Utilizing Research to Enhance Fire Service Knowledge

Kerber, Stephen

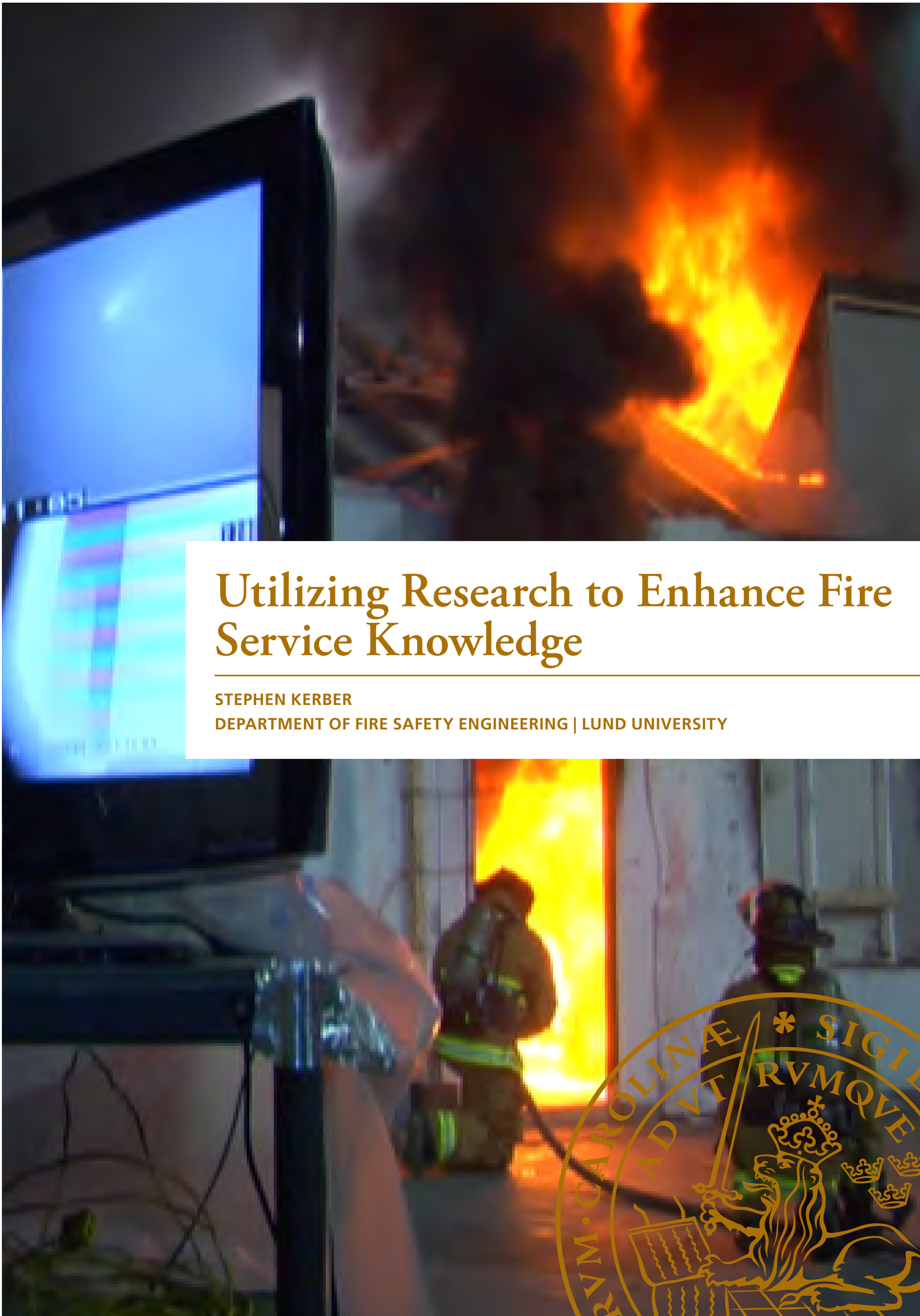
2020

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Kerber, S. (2020). *Utilizing Research to Enhance Fire Service Knowledge*. Lund University, Faculty of Engineering.

Total number of authors:
1



Utilizing Research to Enhance Fire Service Knowledge

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Utilizing Research to Enhance Fire Service Knowledge

Stephen Kerber

DOCTORAL THESIS
by due permission of the Faculty of Engineering, Lund University, Sweden.
To be defended in V:B at 12.00 on Tuesday the 15th of September, 2020.

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Document name
DOCTORAL THESIS

Date of Issue
2020-09-15

Sponsoring organization
Underwriters Laboratories Inc

Title and subtitle
Utilizing Research to Enhance Fire Service Knowledge

Abstract
This thesis explores the fire service workplace through full-scale experiments. Evidence-based information has been developed to be combined with firefighter experience to improve their knowledge of fire dynamics and the cause and effect impact of their tactics on life safety, property conservation, and incident stabilization. Multiple series of experiments examined how residential fire dynamics changed as firefighters deployed tactics such as horizontal ventilation, vertical ventilation, interior fire suppression, exterior fire suppression, and search & rescue. In addition, the fire service improvement model was analyzed and changes are offered. The two main changes include incorporating a foundation of fire dynamics knowledge and utilizing research to fill the existing gaps. Fire dynamics knowledge is imperative to ensure that as firefighters apply their Standard Operating Guidelines (SOGs) at emergency incidents, what is experienced is both reliable and scientifically sound. Further benefits provided by research include understanding the impact of changes in the fire service work environment, better incorporation of evolutions in technology and tools, resolving conflicting experience, and understanding chronic health hazards, implications, and solutions. This integration of science-based knowledge and experience enables the fire service to better evaluate its strategies, tactics, and tasks, ensuring firefighters remain as efficient and effective as possible as they carry out their mission.

Key words
fire dynamics, fire service, fire safety engineering, firefighting, firefighter safety

Classification system and/or index terms (if any)

Supplementary bibliographical information
Report number: 1065
ISRN LUTVDG/TVBB–1065—SE

Language
English

ISSN and key title
1402-3504

ISBN
978-91-7895-555-8 (print)
978-91-7895-556-5 (pdf)

Recipient's notes

Number of pages
296

Price

Security classification
Open

Signature

Date 2020-09-15

Utilizing Research to Enhance Fire Service Knowledge

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Funding Information:
The thesis work was financially supported by Underwriters Laboratories Inc. The majority of the research presented in this text and appended publications was carried out for the Fire Prevention and Safety Grants Research and Development Program, with funding provided through the Department of Homeland Security, Federal Emergency Management Agency Program Directorate Assistance to Firefighters Grant Program.

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ISBN (print): 978-91-7895-555-8
ISBN (PDF): 978-91-7895-556-5
ISSN: 1402-3504
ISRN: LUTVDG/TVBB–1065—SE
Report number: 1065

Printed in Sweden by Media-Tryck, Lund University, Lund 2020

Contents

Acknowledgments

Many people have contributed to shaping this thesis. First of all, I would like to thank my supervisors, Professor Patrick van Hees and Dr. Stefan Svensson, for their guidance, patience, and friendship throughout my PhD studies.

Thanks are due to my colleagues and friends who have mentored me, cheered me on, made me look good, and have had an immeasurable impact on the future of the fire service, including Dan Madrzykowski, Craig Weinschenk, Robin Zevotek, Keith Stakes, Roy McLane, Jack Regan, Joseph Willi, Zoe Susice, Jennifer Williams, Sarah Huffman, Larry Emrie, Josh Crandall, Gavin Horn, Kenny Fent, Denise Smith, Chris Hasbrook, Pravin Gandhi, Bob Backstrom, Tom Chapin, Cara Gizzi, and Terry Brady.

In addition, a number of people have advised me and my team through the years as part of the UL Firefighter Safety Institute Advisory Board, including Derek Alkonis, Charles Bailey, John Ceriello, Sean DeCrane, Jim Dominik, Mike Gagliano, Sean Gray, Bobby Halton, Todd Harms, Ed Hartin, George Healy, Gavin Horn, David Rhodes, Erich Roden, Tim Sendelbach, Jens Stiegel, Stefan Svensson, Adam Thiel, and Peter Van Dorpe.

I would also like to thank my mother, Linda, and my father, Kerby. Finally, thank you Erin, my amazing wife, for your endless support through all the work, travel, relocation, and finalization of this thesis. Without you and your support, none of this would be possible. Last but not least, I want to thank my wonderful sons Owen and Cameron. Although they likely don't know it, they are an incredible motivating factor to do the research that hopefully someday will make their lives safer.

Steve Kerber

Popular Science Summary

Every day, firefighters around the world respond to emergencies to protect the public, property, and environment. As they progress from day one in their career to their retirement, they deserve the best support possible to carry out their mission of saving lives. The good news is that they have hundreds of years of experience to gain knowledge from. The bad news is that as the world continues to evolve, these years of experience may not be as applicable as they were in the past. These changes occur on a regular basis and make it difficult to gain sufficient experience, quickly enough, on all hazards.

Much like firefighting itself, gaining experience in the fire service is complex. It is more than simply going to fires; it is understanding what is going on in front of and around the firefighters, much of which they can not see or feel. Even those things they do observe are impacted by fire's natural growth and decay, the structure, and the actions of other firefighters. No individual at a fire can truly know the entirety of conditions throughout the building. Firefighters simply can never know enough or know it soon enough. Additionally, firefighters cannot afford to wait for experience alone to educate them, because their lives and the lives of others can be at stake.

This research aims to improve firefighter safety by increasing the scientific knowledge of the evolving residential fire environment and its impact on fire service tactics. This goal was accomplished by conducting full-scale fire experiments with the fire service. Four series of experiments were conducted to examine residential fire dynamics and how they change as firefighters deploy tactics such as horizontal ventilation, vertical ventilation, interior fire suppression, exterior fire suppression, and search & rescue. Measurements of gas concentrations and air temperatures allowed calculation of fractional effective dose (FED) throughout the structures, and allowed for an analysis of what tactics, on what timelines, and in what combination improve conditions for any possible trapped occupants and the firefighters tasked with their safe rescue. Additional analysis extended to actions that can be taken by occupants prior to fire department arrival, such as closing doors. Fire service health and safety were also analyzed by utilizing firefighter human subjects during simulated house fires. The goal was to understand the impact of job assignment and the tasks they completed on their thermal and chemical exposure.

More broadly, this research examines the fire service improvement model and identifies how research can play a role to fill knowledge gaps that remain in the traditional model, in which feedback comes only from going to emergen-

cies and gaining fireground experience. Fire service research is needed to better understand and teach fire dynamics to the fire service. With a solid foundation of fire dynamics knowledge, firefighters will gain experience with improved context, and they will have a stronger understanding of the cause and effect relationships of their tactics on the fire environment. Additional benefits that can be provided by research include understanding the impact of changes in the fire service working environment, evolutions in technology and tools, resolving conflicting experience, and understanding chronic health hazards, implications, and solutions.

Seven scientific peer-reviewed research papers are appended to this thesis, and 10 additional research publications are included to meet the research objective. The research described in detail in these publications is assimilated and discussed in the context of the fire service improvement model in the thesis.

Sammanfattning (in Swedish)

Räddningstjänstpersonal över hela världen hanterar dagligen nödsituationer med syfte att skydda eller rädda liv, egendom eller miljö. Under hela sitt yrkesliv förtjänar denna personal det bästa möjliga stödet för att kunna utföra sitt uppdrag. Den goda nyheten är att de har hundratalsår av erfarenhet att bygga sin kunskap på. De dåliga nyheterna är att världen utvecklas och förändras kontinuerligt vilket gör det svårt att snabbt bygga upp erfarenhet.

Att bygga upp erfarenhet inom räddningstjänsten är komplext, eftersom det handlar om så mycket mer än att endast åka på utryckningar; det handlar också om att förstå hela situationen, av vilket det är mycket vi inte känner till. Förutom branddynamiska förhållanden påverkar även situationens karaktäristik och de åtgärder personalen vidtar. Ingen enskild person kan heller känna till alla de förhållanden som råder i en byggnad vid en brand. Räddningstjänstpersonalen kan helt enkelt aldrig veta tillräckligt mycket eller tillräckligt fort, och de har inte råd att vänta på att endast de egna upplevelserna och erfarenheterna ska ge dom tillräckligt med kunskap, eftersom såväl deras egna liv som andra kan stå på spel. Tiden är inte på räddningstjänstens sida.

Detta arbete syftar till att förbättra räddningstjänstpersonalens säkerhet genom att öka kunskapen om den föränderliga bostadsmiljön och dess påverkan på taktiken. Detta har åstadkommits genom att ett antal brandförsök i full skala har genomförts tillsammans med ett antal räddningstjänstorganisationer. Fyra experimentserier har genomförts för att undersöka branddynamik vid bostadsbränder och vad som sker då räddningstjänsten använder horisontell ventilation, vertikal ventilation, invändigt brandsläckning, utvändig brandsläckning och sökning av saknade personer. Mätningar av FED (Fractional Effective Dose) vid brand i byggnad har möjliggjort en analys av vilken taktik, i vilka tidsperspektiv och i vilken kombination som förbättrar förhållandena för eventuella personer i byggnaden och för räddningstjänstpersonal. Ytterligare analyser har tydligt pekat på åtgärder som kan göras av allmänheten före räddningstjänstens ankomst, till exempel att stänga innerdörrar till sovrum inför natten. Även hälsa och säkerhet för räddningstjänstpersonal har undersökts vid simulerade bostadsbränder, där de termiska effekterna samt effekterna av exponering av cancerframkallande ämnen i samband med de uppgifter dessa utför har analyserats.

På ett övergripande plan har detta arbete studerat en modell för hur kunskapsutveckling sker inom räddningstjänsten och belyst hur forskning kan spela en roll i denna modell för att fylla de kunskapsbrister erfarenhet inte kan fylla. Räddningstjänstforskning behövs för att bättre förstå och utveckla kunskapen

kring branddynamik inom räddningstjänsten. Med en solid grund av kunskap om branddynamik kommer räddningstjänstpersonal att få bättre erfarenhet eftersom de då bättre förstår orsaken till och effekten av deras taktik knutet till brandmiljön. Ytterligare fördelar som kan tillhandahållas genom forskningen är att förstå effekterna av förändringar eller variationer i arbetsmiljön, utvecklingen inom metod och teknik, förklara motstridiga erfarenheter och förstå hälsorisker, dess implikationer och lösningar.

Avhandlingen bygger i huvudsak på sju publicerade vetenskapliga artiklar. Resultaten från dessa artiklar presenteras och diskuteras i avhandlingen. Ytterligare tio forskningspublikationer ingår för att uppfylla de krav som ställs på arbetet.

Terminology

Terms used recurrently in the thesis are explained below. The terms are either considered to be unfamiliar with regard to the subject, or needing an explanation in the context of this thesis. Other definitions may exist for these terms, but these are the definitions used in this thesis.

Decontamination: The process of removing contaminants such as soot, particulate, and fireground chemicals to clean fireground tools and equipment and prevent the spread of contamination to other persons or equipment [1].

Door Control: Using a door to limit the amount of air available to the fire, or to isolate a part of the building from the flow path [1].

Fire Attack: The coordinated tasks of delivering an extinguishing agent to the fire and heat, and managing the flow of air, smoke, and heat [1].

Fire Dynamics: The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior [2].

Fire Environment: The surroundings or exposure conditions existing in a structure fire typically characterized by thermal conditions, gas concentrations, and smoke opacity. [3]

Flashover: Transition to a state of total surface involvement in a fire of combustible materials within an enclosure [4].

Flow Path: The volume between an inlet and an outlet that allows the movement of heat and smoke from the higher pressure within the fire area toward the lower pressure areas accessible via doors and window openings.

Fog Nozzle: A nozzle intended for connection to a hose line or monitor to discharge water in either a spray pattern or a straight stream pattern as selected by the operator [1].

Fractional Effective Dose (FED): Ratio of the exposure dose for an asphyxiant to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility [4].

Fractional Effective Dose Rate (FED Rate): The time rate of change of the Fractional Effective Dose. Computed to better understand the impact of the fire service on instantaneous exposure to potential occupants.

Fuel-Controlled Fire: A fire in which the heat release rate and growth rate are controlled by characteristics of the fuel, such as quantity and geometry, and in which adequate air for combustion is available [2].

Horizontal Ventilation: A method of using natural ventilation currents to manage the flow of heat and smoke from the interior to the exterior while entraining fresh air from an intake on the same level of the structure [1].

Positive Pressure Ventilation (PPV): A method of ventilating a room or structure by mechanically blowing fresh air through an inlet opening into the space in sufficient volume to create a positive pressure within and thereby forcing the contaminated atmosphere out the exit opening [5].

Size Up: The ongoing observation and evaluation for factors used to develop strategic goals and tactical objectives [1].

Smooth Bore Nozzle: A nozzle for producing a solid stream of water [1].

Standard Operating Guideline (SOG): A written directive that establishes recommended strategies/concepts of emergency response to an incident [1].

Tactics: Deploying and directing resources on an incident to accomplish the objectives designated by the strategy [1].

Transitional Attack: The application of a fire stream from the exterior of the structure to improve conditions prior to interior fire attack [1].

Ventilation: Circulation of air in any space by natural wind or convection or by fans blowing air into or exhausting air out of a building; a firefighting operation of removing smoke and heat from the structure by opening windows and doors or making holes in the roof [2].

Ventilation-Controlled Fire: Fire where the fire growth is determined by the amount of air available [4].

Vertical Ventilation: Ventilating a point above the fire through existing or created openings and channeling the contaminated atmosphere vertically within the structure and out the top; done with openings in the roof, skylights, roof vents, or similar [5].

Prologue

My advisors suggested that this thesis be easy to read and be told like a story. So, I am going to start with a story on how this thesis came to be and how it is a piece of a much larger story.

One could say that firefighting is in my blood. I grew up in a firefighting family. My father was a volunteer firefighter and is the director of a firefighter training academy, and my grandfather was fire chief of our local volunteer fire department for 27 years and a fire marshal. Growing up in this environment had me spending many hours at the fire station and fire academy. I learned by watching for many years before I could participate in the fire service myself.

That opportunity finally came when I turned 16 years old and was able to join my local volunteer fire department. Now that I could *do*, in addition to watch, it was only natural that I spent my time at the fire station trying to learn as much as possible. I attended the basic firefighter training at the local fire training academy and was qualified as an interior firefighter by age 18. Additional training was available during drill nights at the fire station where I learned the difference between what was taught at the academy and what was expected at the fire station.

Beyond the fire service, I found enjoyment in both math and science. It was only natural that as I was researching my options for college, most of my time was spent looking at engineering schools. During this research, I stumbled upon fire protection engineering. Beyond that, I found about the live-in programs at fire stations in the vicinity of the University of Maryland. I was fortunate to be accepted into the university, and I also received a live-in position at the College Park Volunteer Fire Department (CPVFD). Both of these programs are where the motivation for this research began. To this day, the University of Maryland is the only undergraduate program in fire protection engineering in the United States.

Moving from my rural/suburban volunteer fire department to a suburban/urban department was eye opening and a culture shock. This was my introduction to the wide variety of ways in which fire departments approach their work. Some of these things were obvious due to geographical and equipment differences, and some were not so easily explained. This new department was unique in several facets. Particularly, because it had been staffed for decades by firefighters/university students, ideas of how to operate were constantly being reevaluated as new ideas were shared from members' hometown fire departments. This was so common, however, that the probationary training manual cautioned new recruits from talking about how you did things at home before you learned how and why it was done in CPVFD. In many cases, firefighters spent four years at the department before graduating and moving on, so training and discussion of new ideas was ongoing.

During the day I was gaining knowledge of fire science at the university, and in the evenings, nights, and weekends I was gaining experience by responding to emergencies. This was an excellent combination, but it highlighted some interesting disconnects. The fire service was not always applying or understanding fire science principles, and the university was not always incorporating the fire service in the fire protection engineering system. There was clearly room for improvement. I would push for the fire protection engineering discussions to include fire service response, and for the fire service discussions to include fire science where applicable. This desire to bring both fields together continues to this day and is evident in this thesis and my career.

Another fortunate encounter occurred while I was working part time at the Maryland Fire Rescue Institute (MFRI). MFRI would utilize local volunteer firefighters to assist with running the operations of the academy. One day a group was taking part in a training class doing basic firefighter skills such as putting on personal protective equipment, stretching hose lines, climbing ladders, etc. They did not look like a typical group of firefighters, so I was intrigued. At a break, I spoke with a couple of the students and was introduced to the National Institute of Standards and Technology's (NIST) Firefighting Technology Group. They were predominantly engineers and scientists who were working on fire service related research projects. They were at the academy to experience a typical day of a firefighter. Some of them were University of Maryland graduates, and a couple even had prior firefighting experience at CPVFD. I followed up with these contacts and became a co-op student with the Firefighting Technology Group my junior year. Now I was splitting my time between class at the university, volunteering and living at the fire station, and assisting with research projects at NIST.

I got exposed very quickly to how research was already impacting or had impacted and could continue to benefit the fire service. My first projects were assisting with fire modeling of an incident that killed two firefighters when a backdraft occurred at a hardware store in New York City [6] and trying to better understand the use of positive pressure ventilation (PPV) in the fire service. The PPV research was extensive and occurred across multiple scales of size and geometry. It began with fire modeling [7, 8] and expanded to room fires [9], high-rise building pressure experiments [10], high-rise fire experiments [11, 12], and finally to school building fire experiments [13]. These projects increased my appreciation for firefighting as a complex system with many variables, and that research was a tool that could move the knowledge forward.

Additional projects presented opportunities to work with firefighters all over the world. I continued to see that while the fire was the same (because it always follows the same physics and chemistry principles everywhere), how the fire departments operated could be very different. Additional research I played a significant role in at NIST included the Station Nightclub investigation [14], atrium smoke control [15], and wind driven fires [16, 17].

As I continued to research positive pressure ventilation, Stefan Svensson's name and the research being conducted at the Swedish Rescue Services Agency continued to show up. My research attempted to build on some of his research, which led to an in-person meeting at an Interflam Conference. We learned that our work was similar and that we were alike in our backgrounds (firefighting, fire safety engineering, and research). Leveraging his international contacts, Stefan created the International Fire Instructors Workshop (IFIW). This was a first of its kind gathering where fire researchers and firefighters from all over the world would get in the same room and see what happened. What happened was a sharing of ideas, knowledge, and experience that shrunk the world for me. A group of fire service professionals got to see the benefit of research and ask many questions they wanted answered so that firefighting would be based on science and not opinion. Now I had access to many complex firefighting systems from all over the world and we could openly discuss both similarities and differences in an open-minded environment. This group remains active today, with an annual workshop to share ideas, best practices, and methods to teach fire dynamics in the fire service.

One day Stefan shared with me that he was surprised I did not have a PhD. He has assumed I did. After much discussion and mentoring from Stefan, I decided to enroll at Lund University. I was very intrigued by the fact that the Fire Safety Engineering Program was taught at the Division of Fire Safety Engineering and System Safety. This combination of professors provided an opportunity to expand my knowledge of systems theory and apply it to the fire service. Additionally, Stefan's commitment to advise me has been tremendous. Becoming a student again has been incredibly challenging but also rewarding. I have enjoyed learning how much I do not know, such as the big difference between research reports and peer-reviewed journal articles. Learning that research can improve the fire service if it is performed *with* the fire service has been one of the best experiences of my life.

This educational journey has occurred at the same time as my professional journey. I am certainly not the typical student, but I am proud to be a career student. I was privileged to join Underwriters Laboratories (UL) and afforded the opportunity build a team, the UL Firefighter Safety Research Institute (FSRI). FSRI is dedicated to increasing the knowledge of the fire service through research, education, and outreach. In addition to support from UL, funding opportunities were available through the U.S. Department of Homeland Security Federal Emergency Management Agency Assistance to Firefighters Grant Program. For the first time, significant money was made available for firefighter research. This allowed research approaches at a magnitude and scale that had previously been cost prohibitive. I believe this program has created a golden age of fire service research, continuing to result in high-impact research with the fire service that gets implemented more each day. FSRI has led research in ventilation, suppression, building construction, health, technology, training, fire dynamics, fire investigation, data science, and public safety.

This thesis is a result of decades of dedication to improving the safety, efficiency, and effectiveness of the fire service. If other researchers can take this summary to perform research *with* the fire service in a more effective manner, it is all worth it. This thesis is a story of working toward a safer world by utilizing research to improve the important and complex firefighting system.

Chapter 1

Introduction

Although fundamental combustion research dates back to 1770's France and Lavoisier, fire is a relatively young science that continues to be better understood everyday by researchers around the world. The first book on fire dynamics was not published until 1985 [18], so much is still being learned and applied. The built environment is also complex and continually evolving. At the intersection of fire, the built environment, and emergency response sits the fire service. When fire is no longer being utilized in a controlled manner, the fire service responds to mitigate the emergency. Here, we will specifically focus on fires in the built environment. The fire service system is incredibly complex and varies greatly in its implementation around the world [19].

As society has evolved, the fire service has evolved as well in an attempt to best meet the emergency response needs of society. Because society relies on the fire service to mitigate emergencies and protect the public, it should be obvious that we want to help the fire service be as prepared as possible. The process of helping the fire service understand fire science, evolutions in their workplace (i.e., the built environment), and how their actions interact with both to lead to a successful outcome at emergencies is anything but simple. This research opportunity does not exist because of the lack of theoretical understanding of fire. It exists because of a lack of applied research that links the current understanding of fire dynamics to the fire service's workplace. This thesis will suggest how we may do this more effectively by providing examples of several applied research studies that were conducted with the fire service that resulted in improved firefighter and public safety.

1.1 Thesis Outline

This thesis is organized as follows. In Chapter 2, the background underpinning the thesis is outlined. In Chapter 3, the research objectives described in the first section are iterated and more specific research questions are formulated, and in Chapter 4 the methodology is described. The research contributions are presented in Chapter 5. In Chapter 6 views on research's role in the fire service are presented with examples from the papers. The research contributions and reflections on the methodology, validity and reliability are discussed in Chapter 7. Finally, conclusions from the thesis are presented in Chapter 8, and future research suggestions are shared in Chapter 9. In the Appendix, the seven research papers (which are listed in the next section) are included.

1.2 Appended Publications

I **Analysis of Changing Residential Fire Dynamics and its Implications on Firefighter Operational Timeframes**
S. Kerber
Fire Technology 48(4):865–891, 2012

II **Analysis of One and Two-Story Single Family Home Fire Dynamics and the Impact of Firefighter Horizontal Ventilation**
S. Kerber
Fire Technology 49(4):857—889, 2013

III **Occupant Tenability in Single Family Homes: Part I - Impact of Structure Type, Fire Location and Interior Doors Prior to Fire Department Arrival**
N. Traina, **S. Kerber**, D. Kyritsis, G. Horn
Fire Technology 53(4):1589—1610, 2017

IV **Occupant Tenability in Single Family Homes: Part II - Impact of Door Control, Vertical Ventilation and Water Application**
N. Traina, **S. Kerber**, D. Kyritsis, G. Horn
Fire Technology 53(4):1611—1640, 2017

V **Effect of Firefighting Intervention on Occupant Tenability during a Residential Fire**
S. Kerber, J. Regan, G. Horn, K. Fent, D. Smith
Fire Technology 55(6):2289—2316, 2019

VI **Thermal Response to Firefighting Activities in Residential Structure Fires: Impact of Job Assignment and Suppression Tactic**
G. Horn, R. Kesler, **S. Kerber**, K. Fent, T. Schroeder, W. Scott, P. Fehling, B. Fernhall, D. Smith
Ergonomics, 61:3, 404–419, 2017

VII **Contamination of Firefighter Personal Protective Equipment and Skin and the Effectiveness of Decontamination Procedures**
K. Fent, B. Alexander, J. Roberts, S. Robertson, C. Toennis, D. Sammons, S. Bertke, **S. Kerber**, D. Smith, G. Horn
Journal of Occupational and Environmental Hygiene, 14:10, 801–814, 2017

Paper	Author's contribution
I	The candidate designed and performed the experimental work, analyzed the data, and wrote the paper. The overall contribution was 100%.
II	The candidate designed and performed the experimental work, analyzed the data, and wrote the paper. The overall contribution was 100%.
III	The candidate designed and performed the experimental work, assisted with the analysis, and paper writing. The overall contribution was 40%.
IV	The candidate designed and performed the experimental work, assisted with the analysis, and paper writing. The overall contribution was 40%.
V	The candidate designed the fire dynamics portion of the experimental work, assisted in the performance of the experimental work, led the fire dynamics analysis, and led the paper writing. The overall contribution was 75%.
VI	The candidate designed the fire dynamics portion of the experimental work, assisted in the performance of the experimental work, assisted the with fire dynamics analysis, and paper writing. The overall contribution was 20%.
VII	The candidate designed the fire dynamics portion of the experimental work, assisted in the performance of the experimental work, assisted with the fire dynamics analysis, and paper writing. The overall contribution was 10%.

All papers are reproduced and presented in the Appendix with permission of their respective publishers.

1.3 Related Publications

I **Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Pressure Experiments**
S. Kerber, D. Madrzykowski, D. Stroup
National Institute of Standards and Technology, NISTIR 7412, 2007

II **Evaluating Positive Pressure Ventilation In Large Structures: High-Rise Fire Experiments**
S. Kerber, D. Madrzykowski
National Institute of Standards and Technology, NISTIR 7468, 2007

III **Evaluating Positive Pressure Ventilation In Large Structures: School Pressure and Fire Experiments**
S. Kerber, D. Madrzykowski
National Institute of Standards and Technology, NIST TN 1498, 2008

IV **Fire Fighting Tactics Under Wind Driven Conditions: Seven-Story Building Experiments**
S. Kerber, D. Madrzykowski
National Institute of Standards and Technology, NIST TN 1618, 2009

V **Improving Fire Safety by Understanding the Fire Performance of Engineered Floor Systems and Providing the Fire Service with Information for Tactical Decision Making**
S. Kerber
Underwriters Laboratories, March 2012

VI **Full-Scale Floor System Field and Laboratory Fire Experiments**
S. Kerber
Underwriters Laboratories, March 2012

VII **Basement Fire Growth Experiments in Residential Structures**
S. Kerber, D. Madrzykowski
Underwriters Laboratories, March 2012

VIII **Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes**
S. Kerber
Underwriters Laboratories, November 2015

IX **Cardiovascular and Chemical Exposure Risks in Modern Firefighting**
G. Horn, **S. Kerber**, Fent, K., B. Fernhall, D. Smith
IFSI Research; UL FSRI; NIOSH; UIC Interim Report, January 2016

X **Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices**
R. Zevotek, **S. Kerber**
Underwriters Laboratories, May 2016

Chapter 2

Background

Between 1977 and 2018, 4,646 on-duty firefighter fatalities occurred in the United States [20]. Internationally, data and details on firefighter fatalities exist for some countries (Sweden [21], United Kingdom [22], and 32 other countries [23]). Firefighter injuries and fatalities inside structures remains an important concern. Figure 2.1 shows the death rates of U.S. firefighters inside structures due to structural collapse, fire progress and lost inside is trending upwards. It is believed that one significant contributing factor is the lack of understanding of fire dynamics and how fire service tactics influence fire dynamics [20]. In the same period of time, the number of structure fires decreased by more than half, while the civilian home fire death rate per fire has remained steady [24]. All of these statistics suggest there are significant challenges to fire and firefighter safety.

Madrzykowski [3] explained that for thousands of years humans had been using fire productively and that many had studied aspects of fire, including engineers and firefighters. However, it was not until 1985 that the first textbook on fire dynamics was published [18]. He went on to explain the changes that have occurred in the fire environment, the research that has been conducted, and that it was time to embrace the knowledge of fire dynamics in the fire service. Johansson and Svensson [26] reviewed the use of fire dynamics theory in the fire service. The pair concluded that in 2019, the theoretical status was fair, the potential and need were good, but the use was poor. They suggested that the use of fire dynamics in the fire service could improve with a stronger link between theory and practice in education and training.

Since the formation of the fire service, there has been reliance on experience

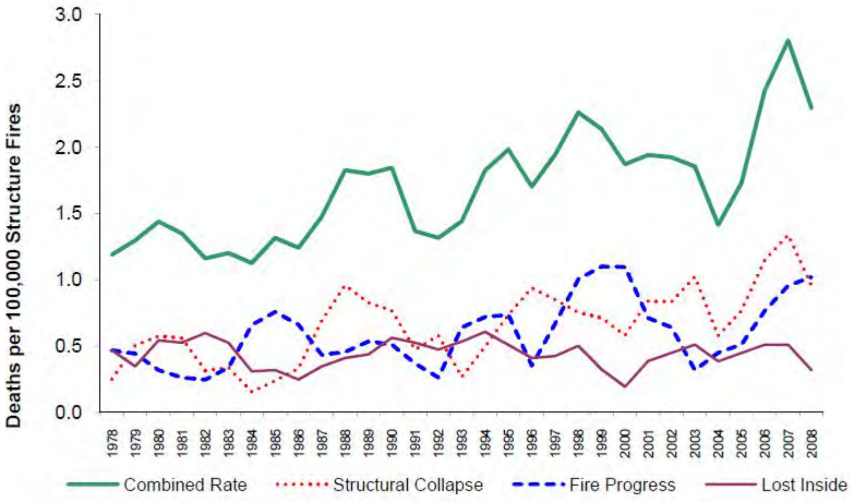


Figure 2.1: Firefighter Death Rates for the Three Major Causes of Fatal Injuries 1977 - 2009 [25].

gained at incidents. Fire service training has relied on this by providing the basics to new recruit firefighters with the expectation that the recruits would learn at incidents through mentorship from an experienced firefighter or fire officer in the field [27, 28]. This mentor would share their knowledge of fire in the fire house and during incidents. This sharing of knowledge would complement the visuals seen by the newer firefighter as they gained their own experience. In the last 40 years, the annual number of structure fires has decreased by 50 percent in the United States, from 1,098,000 in 1977 to 499,000 in 2018 [29]. With such a large decrease in structure fires, the U.S. fire service, in general, is gaining less fireground experience to understand fire progression. Without experience, the fire service is lacking additional (or redundant) feedback mechanisms and suffers from a large gap in the information needed to increase firefighter safety.

The built environment is also evolving which can complicate the applicability of the experience gained by the fire service at incidents. The American Housing Survey conducted in 2017 by the U.S. Census Bureau estimates that 121 million housing units have been built in the U.S. Over 55 million (45%) of those units have been built since 1980. Approximately 77 million are single family detached homes of which 33.5 million (44%) have been built since 1980. Since 1950 an average of 9.9 million new single family detached homes per decade have been built in the United States [30]. The way these homes have been built, materials used to build them, and contents put into them all impact how fires grow and spread. Additionally, many structures have been renovated and refurnished over time.

2.1 Fire Service Desired Outcomes and Challenges

The primary objective of the fire and rescue service is to save and protect people in the event of emergencies. Additionally, the protection of property and environment are important to the fire service. At every incident, the fire service operates to stop additional damage to people and property from the moment they arrive. Control is the overall, comprehensive objective of a fire and rescue operation. It is only through control that the course of events on the fireground can be directed in an intended direction, and it is through the initiation, coordination, and execution of procedures that control is obtained and maintained [19].

There are numerous challenges to the fire service's ability to control emergencies with minimal loss of life and property. First, there are many unknowns to the fire service at every incident, so it is impossible to know exactly how much damage has already taken place prior to their arrival and if additional damage to people and property was prevented as a result of the fire department operation. This makes it challenging to determine if the fire department operations executed were the best ones possible at any given emergency. Therefore, it is hard to connect individuals' or teams of individuals' actions to the success or lack of success of the overall operation. This leads to a subjective analysis of success at an emergency and can lead to misinterpretation of good operations or even worse, the normalization of deviance [31]. Second, due to improvements in fire prevention technology, there has been a significant decrease in the number of fires that require fire service intervention [32]. Combining the decrease in opportunities to gain experience and the challenges associated with knowing what is good experience, many opinions exist in the fire service as to the best tactics, tools, timing, etc., that lead to successful outcomes. Additionally, building technology and building contents evolve which could lead to experience that is no longer correct or becomes dated.

2.2 Fire Service Improvement Model

The fire service has traditionally improved by following a model based on experience [33]. Figure 2.2 shows a suggested iterative model developed by Brunacini describing this experience-based approach to improvement and how fire service operations evolve over time. Standard operating guidelines (SOGs) are the organizational agreement on how a particular activity or series of activities will be performed (i.e., strategy and tactics) at an emergency. The SOGs form the training basis for what is expected of the firefighters. Firefighters subsequently perform actions at an emergency based on their training. After an incident, firefighters ask themselves how well the SOGs/training worked and how well they performed. Revisions to the SOGs are made based on the post-emergency assessments. The more incidents a fire department responds to, the more the SOGs can be refined and evolved.

Figure 2.2: Existing fire service improvement model [33].

This type of model does not evolve well, or at all, if the critique phase is conducted based on incomplete knowledge or misunderstood cause/effect relationships. There is a large amount of complexity on the fire ground [19], so the ability to interpret the big picture to gain valid experience is difficult.

In many cases, experience is based on whether or not a fire was effectively extinguished and what each individual experienced during the incident. It is rare for any specific individual on the fireground to have a complete picture of what every other individual experienced. As a result, an individual who has experienced fire behave a certain way several times may change their behavior or even the department's operating procedures based on an incomplete understanding of the main driver(s) for that particular outcome. Essentially, without a good working knowledge of fire dynamics, they could be guessing on the why and update SOGs in the wrong direction. Further complicating this situation is the fact fireground variables change over time. An example would be a firefighter operating above a basement fire because he has done so many times before and the floor did not collapse under him [34]. The outcome of these incidents would further reinforce existing procedure. Several years later a new floor construction material is introduced that has less mass than the traditional floor system and therefore has the potential to collapse sooner. If that firefighter continues to operate above a basement fire like he has in the past, he has a greater potential of being injured or killed because he did not understand the fire dynamics and structural stability changes associated with the change in building material.

2.3 Research Challenges and Advancements

Fire service research and improved fire dynamics knowledge are important to enhancing the fire service improvement model. Before modifications to the fire service improvement model are presented, it is important to examine both the challenges and advancements that have been made in research. Fire service research has many challenges, but there have also been numerous advancements in the last couple of decades. These advancements have removed barriers present for previous researchers and suggest we can learn and disseminate research results like never before.

Typically, fire science theories are demonstrated at a reduced scale because of space, cost, and time restraints as compared to the full-scale. Scale models, however, have many limitations in their ability to demonstrate fire dynamics [35]. Scaling geometries that do not appear real to the fire service and events that happen on a different time scale makes trusting results from these types of models a challenge for the fire service. Additional challenges of the complex physical phenomenon do not all scale at the same factor, making replication of complex phenomenons challenging at reduced scale. Scale models can be useful to demonstrate fire phenomena but are not as useful of a tool to examine fire service operations [36]. This is the main reason for full-scale experiments: to prove the theory still holds at real scale and allow the fire service to see the cause and effect relationships of their tactics in an environment they accept as representative of what they see in their experience.

The NIST Firefighting Technology Group has utilized computational fire models to examine incidents in which firefighters lost their lives and the fire dynamics were not well understood. The computational model used, Fire Dynamic Simulator (FDS), was developed in 2000 and has been improved over the years by many collaborators. This large eddy simulation software was able to provide quantitative and qualitative insights into fire dynamics [37] better than any prior software. Researchers worked with the fire service to study and recreate incidents of significant impact to the fire service to provide new understanding with this tool. Incidents include the Cherry Road Fire in Washington, D.C. (2 firefighter fatalities) [38], the Houston McDonalds Fire (2 firefighter fatalities) [39], the Keokuk, Iowa Fire (3 firefighter fatalities) [40], the Houston Wind-Driven Fire (2 firefighter fatalities) [41], the Attic Fire in Chicago, IL (1 firefighter fatality [42], and the Charleston Super Sofa Fire (9 firefighter fatalities) [43].

While FDS continues to be actively developed (most recent release is Version 6.7.4 on March 9, 2020) [44], there still exist gaps in the validation-space that are critical to modeling the complex physical phenomena of the residential fireground. The developers have made progress since the last major code release in modeling gas species, specifically carbon monoxide, during ventilation-controlled conditions using multi-step chemical reactions and their fast-chemistry combustion model [45]. However, only experiments with well-characterized gas burners or pool fires are included in the assessment. Predicting gas species from a typical residential fire would require the addition of pyrolysis modeling, which still lacks the appropriate level of validation.

Additionally, FDS does not yet have the capability of modeling firefighting operations such as suppression. FDS does have the ability to model water droplet movement through a sprinkler submodel and one could modify input variables to behave like a hoseline, FDS lacks validation for water distribution with these modifications as well as the complex interaction of water droplets and pyrolysis [45].

The need to conduct full-scale experiments gives rise to an increase in difficulty, complexity, cost, and safety challenges. The larger scale introduces additional variables to control and increases the instrumentation requirements needed to accurately measure the fire dynamics. The number of variables in an actual emergency present a challenge to replicate and bound within a series of experiments. Additionally, fire measurements in full-scale experiments must also withstand harsh fire environments. Measurements such as temperature, gas velocity, gas concentration, and pressure must remain accurate at high temperatures, under moist and sooty conditions, and for long durations. In the fire service's work environment, thermal conditions can change within seconds so measurement frequency is also important [46].

Measurement equipment technology and computer and data acquisition technology have progressed significantly in the past 50 years. In the 1970s, strip chart recorders could track a small number of data channels during an experiment. Additionally, video recording was very expensive and not practical for a fire environment. Today, hundreds of data channels can be recorded at high frequencies (e.g., 1 Hz–10 kHz). Video can be recorded at very high resolution (e.g., 1080p–4k), and camera technology has improved so much that inexpensive cameras can be placed in harsh environments and record remotely.

In addition to measurement science, funding has always been a challenge for fire service research, particularly for full-scale experiments. In 2005, the Department of Homeland Security launched the FEMA Assistance to Firefighters Grant (AFG) program. This program funded research projects up to $1 million, now $1.5 million. A portion of the AFG program is awarded to institutions to conduct research that will generate knowledge to increase firefighter safety. The goal of this research and development grants program is to reduce firefighter fatal and nonfatal injuries and improve firefighter safety, health, and wellness. Since the start of the program, more than 100 projects have been awarded more than $110 million in funding. Research topics ranged from clinical studies designed to understand firefighter physiology to technical studies designed to better understand fire behavior during house fires [47].

It is also difficult to communicate research results to the fire service to keep them up to date with the latest firefighter safety information. In the United States, the fire service is made up of approximately 800,000 volunteers and 300,000 career firefighters [48]. There is no established means to communicate a message to all of these firefighters, and even if there was, they may not listen, understand, or believe the message. In many cases, volunteer firefighters have jobs and family obligations that do not allow them to participate in training the same way career firefighters would during their shifts. Currently in much of the United States, there is also no requirement for firefighters to participate in continuing education. In some cases there is no training requirement at all to become a firefighter [49].

With the increased use of the internet there are new methods to communicate fire service information and knowledge to a large number of firefighters. This avenue has led to several good communication streams, such as sharing near-miss incidents in which firefighters were almost injured or killed, or the latest research findings that impact the fire service through social media and on-line training modules [50]. However, anyone can share their experiences, especially in social media. These experiences can be taken out of context, be untimely, and/or be misleading.

In summary, the major research challenges include utilizing reduced-scale models to demonstrate fire dynamics to influence the fire service, limitations of computational fire models, complexities of full-scale experimentation, limitations of measurement technology, funding and universal communication channels in the fire service.

Chapter 3

Research Objective and Research Questions

As discussed in Chapter 2, the fire service improvement model is incredibly complex and varies greatly in its implementation around the world. However, there is an opportunity to incorporate research into the fire service improvement model to increase firefighter safety, efficiency, and effectiveness.

3.1 Research Objective

The overall research objective is to improve firefighter safety by increasing their scientific knowledge of the evolving residential fire environment and its impact on fire service tactics. Additionally, the fire service improvement model will be analyzed and changes will be suggested to the current fire service improvement model to enhance standard operating guidelines, improve effectiveness and efficiency, and accelerate fire service learning.

Based on this overall research objective, five research questions (RQ) are formulated and discussed in the following section.

3.2 Research Questions

Research Question 1

There has been a steady change in the residential fire environment over the past several decades. At the same time, yearly fire incidence data in the United States suggests a continued tragic loss of firefighter and civilian lives. Combining these two trends results in the first research question.

> RQ1: How has the fire environment changed over the past 50 years and how does it impact firefighter health and safety? (Paper I, Paper VI, and Paper VII)

Research Question 2

A significant contributing factor to some firefighter injuries and fatalities is a lack of understanding of fire behavior in residential structures resulting from the changes that have taken place in several components of residential fire environments, as highlighted in RQ1. The changing dynamics of residential fires as a result of the changes in home size, geometry, contents, and construction materials over the past 50 years add complexity to the fire behavior. Ventilation is frequently used as a firefighting tactic to control and fight fires. In firefighting, ventilation refers to the process of creating an opening so that heat and smoke will be released, permitting the firefighters to locate and attack the fire. If used properly, ventilation improves visibility and reduces the chance of flashover or backdraft. However, poorly placed or timed ventilation may increase the air supply to the fire, causing it to rapidly grow and spread. Therefore, it is important to combine what was learned in answering RQ1 and apply it to quantify the impact of two main types of ventilation used by the fire service in RQ2.

> RQ2: How have the fire environment changes impacted fire service horizontal and vertical ventilation tactics? (Paper II and IV)

Research Question 3

Another primary fire service tactic, and arguably the most important, is suppression (i.e., putting water on the fire). Firefighters have many tactical choices for water application, including interior attack, transitional attack, and exterior-only water application [51–53]. An interior attack typically involves firefighters entering the structure to apply water to the fire from a location where the fire has not yet spread, theoretically cutting off its ability to advance into the uninvolved part of the structure [51]. A transitional attack involves an initial rapid (on the order of 10 s) application of water from the exterior of the structure into the fire compartment to provide the initial knockdown. This initial action holds the fire in check while the same or a second crew transitions to an interior position to fully suppress the fire [52]. The exterior-only attack attempts to completely suppress the fire from the outside of the structure and is typically employed when the structural elements of the building may be compromised and/or when no immediate occupant life safety hazard exists [53].

Each method has advantages and disadvantages. An interior attack presents the highest risk for exposure or collapse danger to the firefighter, while an exterior-only attack keeps the firefighter in a safer position but may present a challenge to accessing the seat of the fire. The transitional attack theoretically reduces the firefighters' initial exposure risk and allows fire crews to operate an interior attack under potentially safer conditions. However, there are concerns that application of water from the exterior may cause detrimental changes to trapped occupants and cause a delay in locating potentially trapped occupants. RQ3 aims to answer whether or not those concerns are valid so that firefighters can make decisions regarding suppression tactics based on scientific evidence.

RQ3: What is the effect of water application from the exterior, as part of a transitional attack or exterior-only water application, on civilian and firefighter safety? (Paper II and IV)

Research Question 4

RQ2 and several previous studies have examined fire service tactics for their effectiveness and efficiency [54–60]. Each of these studies focused on a specific fire service tactic and simulated those tactics in a controlled manner to examine the impact on the fire environment. RQ3 examines the impact of firefighter transitional attack on occupants during a series of experiments. Interior attack and the impact of that suppression technique on toxic gas exposure and occupant tenability was not assessed. This research question includes both interior attack and toxic gas measurements. Additionally, the impact on the tenability of simulated occupants (instrumented mannequin) as suppression, ventilation, and search and rescue occur (remove the simulated occupants from the hazardous environment) needs to be better understood and quantified. Improving the understanding of the cause and effect relationship between tactics and occupant tenability will lead to better fire service decision making. This will be accomplished through the following research question.

RQ4: What is the impact of coordinated fire service intervention (ventilation, suppression, search and rescue) on occupant tenability? (Paper V)

Research Question 5

As discussed in Chapter 2, a primary component of the fire service mission is life safety of firefighters and the public they serve. The response to RQ1 and other research [61, 62] highlights that occupants have less time to escape a fire, which could lead to more people needing to be rescued by the fire service. The status of interior doors (closed versus open) could mean the difference between an occupant who is able to be rescued and one who is not. Additionally, those same doors could be leveraged by the fire service as they perform search and rescue operations to limit their exposure and protect occupants found during their search. The last research question is designed to answer the effect of closed doors on occupant survivability, which could influence fire service tactics.

RQ5: What is the effect of a closed door on occupant survivability? (Paper II, III and V)

These five research questions, along with previously published literature in the area, provide a comprehensive overview of the current status of knowledge for addressing the overarching objective presented above. The research questions are addressed in Chapter 5 with the help of the research presented in the appended papers and related publications.

3.3 Limitations

As with all studies, the current study is subject to several limitations. Recreating all the variables of a fire department response is a challenge due to the complex nature of a fire emergency. Research into the effectiveness of various suppression tactics is not intended to recreate the fire emergency in its entirety but to control as many of the variables as possible to permit an objective comparison.

The number of experiments was limited based on the available budget. The focus of most of this research was limited to residential structures as that is where most traumatic firefighter fatalities and civilian fatalities have occurred in the last 40 years [20]. These projects were not able to test all of the potential tactical choices of firefighting crews; thus it is important to utilize both these research results and fire service experience when making tactical choices. Additionally, the structures, fire service response times, tools and procedures were conducted primarily with United States influence as required by the project funding source. Any application of the results to other countries is dependent on generalizing the results. The influence of this limitation is discussed in Section 4.1. The house fire experiments were limited to content fires. The rooms were lined with two layers of gypsum board so that the fire would not penetrate into the structure.

3.4 Delimitations

Many choices were made in these studies to set the boundaries. Major components of this research were conducted solely in a laboratory facility to control the environmental conditions (wind, rain, temperature, and pressure). During a fire department response, environmental conditions play a role in tactical choices. For example, wind conditions (direction and magnitude) can drive the timing and location of ventilation to either take advantage of or minimize the impact of the wind. Therefore, the results from this research need to be evaluated against the conditions the fire department is faced with on-scene.

There is a multitude of home geometries around the world, however the two house types selected for this study represent common homes built in the U.S. during different time frames. Each was designed by a residential architect and constructed by a residential home builder. The first was a one-story, 112 m^2, three-bedroom, one-bathroom house with eight total rooms. The house was designed to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings. The second house was a two-story, 297 m^2, four-bedroom, 2.5-bathroom (a half bathroom has a sink and toilet but no shower or tub) house with 12 total rooms. The house incorporated features common in early-twenty first century construction such as an open floor plan, two-story great room, and open foyer.

The location of the measurements for occupant survivability were chosen to compare the effects of proximity to the fire, being behind a closed door, and being elevated off the floor. Although these values can be extrapolated to other similar locations within the structure, due to the complexity of the fire environment, they are not representative off all possible locations where an occupant may be located in a residential structure.

Chapter 4

Research Methodology

Two aspects important for fire service research are the research philosophy and the scientific methodology. The research philosophy is focused on doing the research in a way that will have a positive impact on the fire service, and the scientific methodology ensures the research follows a standardized and accepted process that is trustworthy, valid, and reliable. The best research in the world can be conducted but unless it reaches the target audiences in the right way with accurate conclusions, it will fall short in its mission.

4.1 Research Philosophy

The primary principle of the research methodology employed here is to conduct research *with* the fire service and not *for* the fire service. This allows for several important things to occur: 1) Researchers are able to better understand the problems as they are directly addressed from the fire service; 2) the fire service participates in experimental design processes through their role on technical panels to maximize impact of each experiment; 3) researchers can get quick feedback on experimental results from the technical panel to adjust the study as necessary; 4) the fire service has the opportunity to understand the benefits and limitations of the research so that they best share and implement the findings; and 5) researchers and fire service members can disseminate the research findings together with a consistent message. Figure 4.1 shows the components of the research philosophy from start to impact.

Research begins with the engineering team working with a cross representation of the fire service as the key stakeholders as well as other subject matter experts

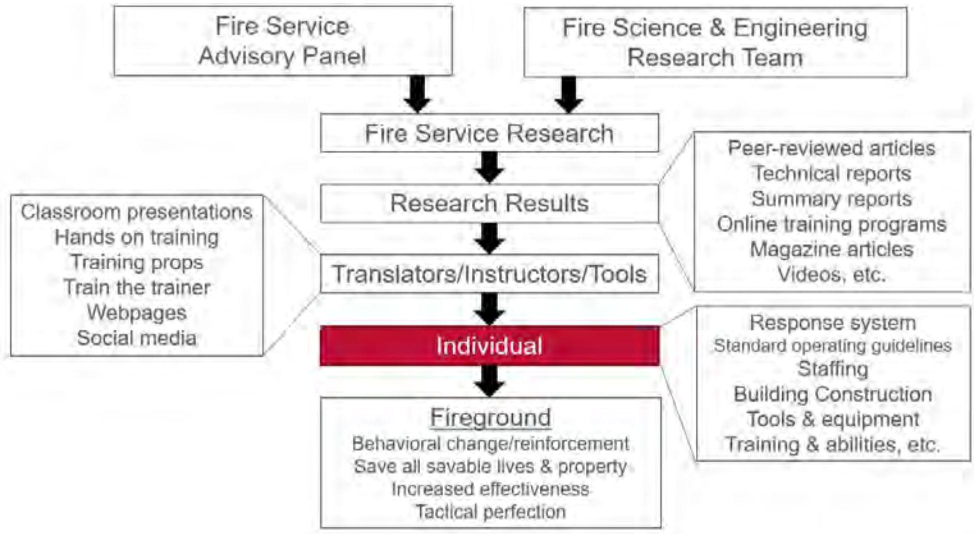


Figure 4.1: Fire service research philosophy.

on the research topic (e.g., the technical/advisory panel). This approach can be challenging because the fire service is very fragmented and diverse. For example, there are close to 30,000 fire departments in the United States alone [48]. Those departments have diverse standard operating guidelines [63] and response hazards. An advisory or technical panel comprised of fire service representatives with diverse attributes helps ensure the project is applicable to as much of the fire service as possible by providing domain-specific guidance to the research team. To develop a diverse set of advisors, attributes such as geographical location, fire department type, rank, years of experience, applicable experience to the research topic, and education level are considered for selection. Additional stakeholders such as academic experts or affiliated fire service groups are also good candidates for a fire service research advisory panel.

An advisory panel can also present challenges. A main challenge is their lack of familiarization with the scientific methodology, fire dynamics, and fire measurement. In the same way researchers learn about fire service needs from the technical panel, researchers should spend time at the beginning of a project explaining the research specific components at the appropriate level of detail. An example of this is an interactive on-line training program designed to teach heat transfer and fire measurements that can be shared with the advisory panel before the first meeting [64]. Another challenge is defining and sticking to a research scope. The panel needs to understand the scope up front so that all decisions, such as adding an experiment, measurement, or new variable, is typically not without a trade-off.

As the research is conducted, it is important to acknowledge that the fire service is comprised of individuals who are most often visual and kinesthetic learners [65] and individuals who are not scientists or engineers (with exceptions, of course). This means that to maximize acceptance and support, the research needs to look real to them and include measurement techniques that are able to easily be visualized, such as video and thermal imaging. Additionally, analysis techniques such as heat maps or overlaying of data on other visuals like floor plans or video can be very effective tools. Although engineering tools can be used to replace realistic fuel loads or scale the building down, these will be met with heavy skepticism and reduce the chances of the research results being implemented by the fire service. In some cases the advisory panel will understand, but the entire fire service must always be considered the ultimate stakeholder.

After the fire service research is conducted and the research results are produced, several factors will lead to the research being implemented successfully. The first is how the research results are shared by the research team. This is followed by how the research is translated, taught, or shared by others as they interpret the research results. Next is how it is received and acted upon by the individuals within the fire service. Finally, how it is implemented on the fireground?

The research team has many options to disseminate the research results. Many depend on the desired audience. Peer-reviewed journal articles are important to subject the research to the scrutiny of other experts in the field, and to confirm the conclusions are accurate based on the experimentation. Technical reports include all of the details and all of the data so that other researchers can expand or replicate the research. Additionally, the technical reports allow anyone to see how the data was analyzed and how the conclusions were drawn. Summary reports are a way to provide the key information from the technical report that are important to a particular audience, such as the fire service, without overwhelming them with all the fine details of the research. On-line training programs can bring the research to life for visual learners (such as the fire service) by supporting the scientific methodology and data with visuals that make the results easy to understand and put them into proper context. Trade magazine articles are a good tool because they can be co-written with the fire service so that they are easy to understand and contain visuals that are useful. Videos are a critical component of the experiments and the dissemination of results, especially for the fire service.

The next layer in the fire service research philosophy is how the research results are translated and delivered to the fire service. This is a critical component of the fire service research philosophy and where the research team has a decreased amount of control. The fire service will commonly say they want the research dumbed down so that they can understand it. This is not the right approach. The research can be simplified or translated well for the target audience without taking away accuracy or context. Care must be taken when developing classroom presentations, hands on training, training props, train-the-trainer programs, webpage material, social media posts, etc., so that research results are not taken out of context. This could result in misunderstanding and misapplication of research results. The best way to do this is for the researchers to work with the fire service and to always have linkage back to the science-based articles, reports, on-line programs, etc. directly produced by the research team.

Finally, the most important component of the philosophy (highlighted in Figure 4.1) is the individual (firefighter, fire officer, fire chief). These are the people who will respond to the fire emergencies and save lives and property. They have to take the new information from the research and apply it to their reality. They need to examine how the research results fit their particular response system, standard operating guidelines, staffing, buildings in their response area, tools and equipment, and the training and abilities of their department. The research will not always exactly match their reality, so they need to interpret the research results to determine if they are going to implement the findings and how they will do so. The research team can also present the results in a way that makes this manageable for the individual.

Following this research philosophy has resulted in fire service research being implemented on the fire ground around the world. Incidents where tactics were performed that were a result of research presented in this thesis have resulted in lives being saved. Chief James Dominik (ret. Wilmette Fire Department) shared "Our Firefighters have been trained based on the learnings from UL's research ... And lives have been saved [66]." There are many other examples where fire departments have taken the research results and modified their SOGs or created guidelines on how to incorporate science-based research [1]. It is also important to recognize that different parts of the world have differences in context. Before research models, methodologies or findings are implemented they must be examined with local stakeholders to ensure proper context.

4.2 Scientific Methodology

While every fire event that the fire service responds to is unique because of the range of fireground variables, the fire dynamics of the event are still bound by fundamental physics which include thermodynamics, heat transfer, and fluid dynamics. As a result, two main pathways exist for capturing the impact of the fire service: Simulate both the fire and fire service interaction with a physics-based model where the output is considered to be an observation of reality within some range of acceptance or conduct experiments and directly measure the outcome. In either case, the methodology begins with a hypothesis to be tested, an assessment of the results, and analysis of results following acceptance.

Computational models have some advantages compared to full-scale experimentation, the primary of which is the low-cost compared to an equivalent full-scale experiment. Additionally, the model can generate full-field output data compared to the discrete measurement locations of an experiment. The computation model can also be used examine a range of fire phenomena beyond what could be safely conducted or measured. Some of the challenges for modeling the fire dynamics and subsequent fire service interactions, as discussed in Section 2.3, are the lack of validation for the pyrolysis of complex fuels and the response to water application from a fire service hose stream. An additional complexity is incorporating the human behavior component of a firefighter actually performing the tactic of interest. There also exists an evolving understanding of the physics of fire dynamics that can only be described mathematically with important assumptions and simplifications that may not apply universally. As a result, with the current state of modeling, the output could carry error bars sufficiently large that would prohibit meaningful comparisons. This is compounded by a stakeholder group (the fire service) who are already biased with a must-see-to-believe mindset.

The scientific methodology chosen to answer these research questions was to conduct full-scale experiments. Conducting full-scale experiments has its own set of challenges. The primary challenge is the cost associated with conducting fire experiments at this scale, which limits the total number of observations that can be made. Therefore, to maximize the impact of a finite set of experiments, careful consideration is given to parameters such as building materials, the fuel load, and the ignition source during each experiment so the impact of specific firefighting operations such as ventilation operations or fire suppression tactics on tenability conditions in structures can be examined. See Figure 4.2 for examples of purpose-built structures utilized in the experimental series conducted for the research in Papers I and II.

(a) Single Compartment Designed For Paper I Experiments

(b) Single Family House Designed for Paper II Experiments

Figure 4.2: Examples of purpose-built structures used for full-scale experiments to support papers I and II.

Experiments also require expertise in measurement science, specifically knowledge of measurement limits and uncertainty, to accurately quantify the fire environment. Measurements of gas temperature, gas velocity, gas concentration, pressure and heat flux were made using common fire science instruments. In some cases the fire service asked questions that required new measurements to be developed. A new method for estimating skin burn risk based on ex-vivo samples of porcine (pig) skin was developed [67]. Laser based measurement methods were developed to examine moisture in the fire environment that could lead to occupant or firefighter steam burns [59, 68].

As the results from experiments are analyzed and presented to the fire service, the confidence in measurements must be quantified and shared. For any measured data (e.g., gas concentration, heat flux, temperature, etc.) is it paramount to recognize that uncertainties exist in the measurements. There are different components of uncertainty in the measured data depending the on the quantity measured. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those evaluated by statistical methods, and Type B are those evaluated by other means [69]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (− a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 99.7%. After estimating uncertainties by either Type A or B analysis, the uncertainties can be combined in quadrature to yield the combined standard uncertainty. Multiplying this combined standard uncertainty by a coverage factor of two results in an expanded uncertainty with a 95% confidence interval [69]. For some components, such as the zero and calibration elements, uncertainties were derived from referenced instrument specifications. For other components, referenced research results and past experience with the instruments provided input for the uncertainty determination.

One particular challenge when utilizing full-scale structures is measuring the impact of firefighter operations on occupant tenability (i.e., the survivability of occupants in the fire environment). In most incidents the fire service does not know the condition of the potential occupants, but the fire service's goal is to improve the occupant's chances of survival with their tactical choices. Occupant tenability was assessed by measuring gas concentrations, heat flux, and gas temperature to examine both the thermal and toxic gas exposure fractional effective dose (FED) based on the method described in ISO 13571 [70]. The irritant-gas, mass-loss, and smoke obscuration models also presented in ISO 13571 were not utilized for this analysis. According to the standard, ashyxiant toxicants, irritants, heat, and visual obscuration are each considered as acting independently. Some interactions are known to occur but are considered secondary [70].

The FED algorithms calculate the time to incapacitation based on an accumulated exposure to either toxic gases or air temperature and heat flux. This methodology provides specified thresholds that are commonly utilized to estimate risk. Based on a lognormal distribution, FED = 0.3 is the criterion used to determine the time for incapacitation of susceptible individuals (11% of the population, including young children, elderly, and/or unhealthy occupants) and FED = 1.0 is the value at which exposure would be considered untenable for 50% of the population. The FED equation for toxic exposure can include a number of products of combustion, but the experiments in this work focused on the most common gases produced at high concentrations during residential structure fires.

As a result, the general N-gas equation was simplified to include the following [71]:

$$FED_{toxic} = (FED_{CO} * HV_{CO_2}) + FED_{O_2} \tag{4.1}$$

In Equation 4.1 [71], FED_{CO} and FED_{O_2} are the doses for carbon monoxide inhalation (CO) and low oxygen (O_2) resulting in hypoxia, respectively, each measured as a function of time. The expression for FED_{CO} is:

$$FED_{CO}(t) = \int_0^t 3.317 * 10^{-5} [\phi_{CO}]^{1.036} (V/D) dt \tag{4.2}$$

where ϕ_{CO} is the CO concentration in parts per million, dt is the time step, V is the volume of air breathed each minute in liters, and D is the exposure dose in percent carboxyhemoglobin (% COHb) required for incapacitation.

Values of V and D vary depending on the level of work being conducted by the occupant. The default case is often taken to be light work (e.g., crawling to evacuate a structure), which corresponds to D = 30% COHb and V = 25 L/min [71]. The uptake rate of CO and other products of combustion can vary considerably with V, and depends on a number of factors, including hyperventilation induced by exposure to CO_2. This increase in respiration rate due to CO_2 inhalation is accounted for in Equation 4.1 [71] by the hyperventilation factor HV_{CO_2}:

$$HV_{CO_2}(t) = exp\left(\frac{0.1903(exp(\phi_{CO_2})) + 2.0004}{7.1}\right) \tag{4.3}$$

where ϕ_{CO_2} is the mole fraction of CO_2. Last, the fraction of an incapacitating dose due to low oxygen hypoxia (FED_{O_2}) is calculated by:

$$FED_{O_2}(t) = \int_0^t \frac{dt}{exp[8.13 - 0.54(20.9 - C_{O_2}(t))]} \tag{4.4}$$

where dt is the time step and C_{O_2} is the O_2 concentration (volume percent).

For several experimental series, an FED analysis was also conducted to examine the impact of thermal exposure to potential trapped occupants. The FED_{heat} tenability limit is commonly used as the expected onset of severe skin pain. FED_{heat} calculated incapacitation from skin exposure to radiant heating and from convective heating [71]:

$$FED_{heat}(t) = \int_0^t \frac{q^{1.33}}{1.33}dt + \int_0^t \frac{T^{3.4}}{5E7}dt \tag{4.5}$$

where q is in kW/m^2 and T is in °C. Equation 4.5 generally applies for temperatures greater than 20 °C.

Traditionally, risk estimates are based on the entire time frame of an exposure. However, the transient exposure experienced while firefighters attempt to affect rescue for a potentially trapped occupant and/or the change in exposure as a result of ventilation/suppression actions is of equal importance. Because FED by definition always increases, the time rate of change of FED–the fractional effective dose rate (FED rate)–is computed to better understand the impact of the fire service on instantaneous exposure. Changes in the FED rate (i.e., what task caused the rate to increase or decrease) allow for clearer dissemination of exposure quantification to stakeholders.

For the fire service, the ability to see fires on a scale that reflects the challenges they face on the fireground, as shown in Figure 4.2, is integral for acceptance. Designing those experiments in such a fashion to isolate the impact of specific tactical choices, quantifying the fire dynamics by using the appropriate instrumentation, and having the fire service participate in the entire process is the methodology that leads to change.

Chapter 5

Research Contributions

The results of the research conducted in this thesis are presented in this chapter. The different data analysis and data collection methods applied in the appended papers were discussed in the Research Methodology Chapter. The research questions and the research objective are addressed with the help of the papers.

5.1 Introduction of the Appended Papers

The seven appended papers are reviewed in this section by presenting the objective and key findings of each paper. Text and figures in this section are, to a large extent, reproduced from the papers, and the reader will of course obtain a more comprehensive understanding of the conducted research by reading the papers themselves.

5.1.1 Paper I: Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Time Frames

The objective of Paper I was to demonstrate some of the ways in which the residential fire environment has changed over the past several decades. These changes have significantly impacted the conditions the fire service will arrive to during fire emergencies and can have a negative impact on their safety. The changes examined included larger homes, larger uninterrupted interior spaces (e.g. open concept floor plans), increased synthetic contents, and changing construction materials. Several experiments were conducted to compare the impact of changing contents in residential houses. Three pairs of experiments showed that a living room with synthetic fuels had flashover times of less than 5 min compared to 30 min with natural fuels after a fire was started with a small flaming ignition on the respective sofa.

The living rooms with synthetic fuels and the living rooms with natural fuels demonstrated very different fire behavior. It was very clear that the natural materials released energy slower than the fast burning synthetic furnished room. The times to flashover show that the a flaming fire in a room with modern furnishings leaves significantly less time for occupants to escape the fire. It also demonstrates to the fire service that in most cases the fire has either transitioned to flashover prior to their arrival and/or became ventilation limited and is waiting for a ventilation opening to increase in burning rate. This difference has a substantial impact on occupant and firefighter safety. This change leads to faster fire propagation, shorter time to flashover, rapid changes in fire dynamics, and shorter escape times.

Floor system collapse times for solid wood joist construction and lightweight construction were also compared. The inferior structural performance of lightweight structural components under fire conditions was demonstrated. Lightweight engineered wood floor assemblies showed the potential to collapse very quickly under well-ventilated fire conditions (Table 5.1). When it comes to lightweight construction, there is no margin of safety. There is less wood to burn, and therefore potentially a shorter time to collapse. The results of these experiments has improved the understanding of the hazards of lightweight construction and assisted incident commanders, company officers, and firefighters in evaluating the fire hazards present during a given incident. The research allowed a more informed risk–benefit analysis when assessing life-safety risks to building occupants and firefighters.

Table 5.1: Floor system description and collapse times

Floor Structural Element	Ceiling	Allowable Deflection L/240 (min:sec)	Firefighter Breach (min:sec)
2 x 10 Joist	None	3:30	18:35
Wood I Joist	None	3:15	6:00
2 x 10 Joist	Lath and Plaster	75:45	79:00
2 x 10 Joist	Gypsum Wallboard	35:30	44:40
Wood I Joist	Gypsum Wallboard	3:30	26:43
Metal Gusset Truss	Gypsum Wallboard	20:45	29:00
Finger Joint Truss	Gypsum Wallboard	24:00	26:30

Additional experiments described in this paper demonstrated that the failure time of wall linings, windows, and interior doors have decreased over time. The failure times could impact fire growth and subsequently firefighter tactics. Each of these changes alone may not be significant, but the all-encompassing effect of these components on residential fire behavior has changed the incidents the fire service responds to. This analysis examined the change in fire dynamics and the impact on firefighter response times and operational time frames. Figure 5.1 provides a comparison between typical fire service response times, and the time to flashover and the time to collapse for modern and legacy construction types.

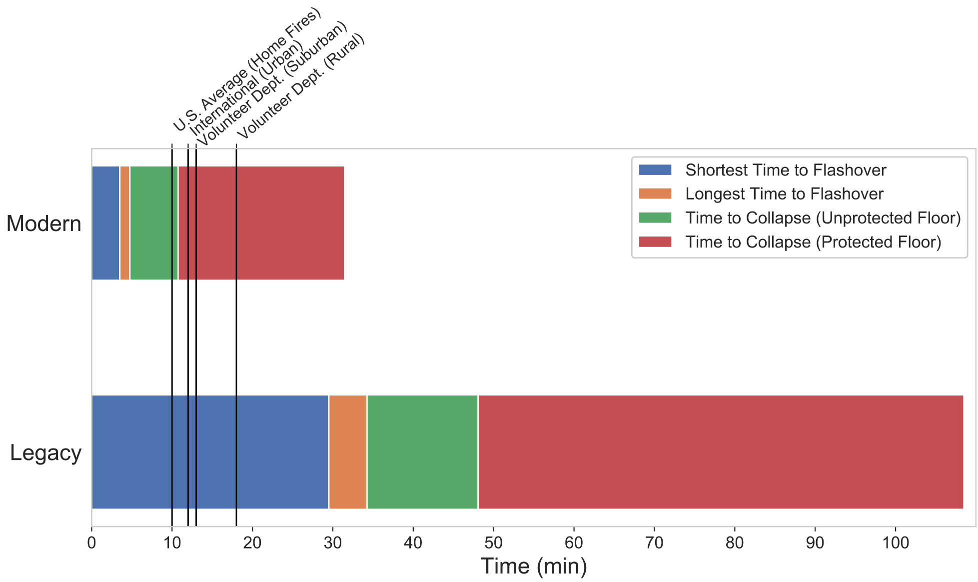


Figure 5.1: Fire service arrival times versus fire development and collapse times.

The overarching conclusion of Paper I is that as society continues to make changes to building materials, whether it is the desire to be environmentally conscience and/or to increase profit, the fire environment will continue to change. If the current trends continue, it will not be in favor of firefighter safety. Therefore, it is important that firefighters continually study changes to their operating environment and the resulting impact on their safety and tactics. Of foremost importance, the firefighter must understand the conditions of the structure to which they arrive. These conditions are likely different than several generations ago. Fire conditions can change rapidly due to under-ventilated fire conditions, and floor systems can collapse quickly and with little warning. Operating conditions need to be constantly monitored to understand the impact of the tactics used so change can occur if needed. Ultimately, if the fire environment has changed, then tactics need to be reevaluated to have the greatest opportunity to be most effective on today's fires.

5.1.2 Paper II: Analysis of One- and Two-Story Single Family Home Fire Dynamics and the Impact of Firefighter Horizontal Ventilation

Paper II builds on Paper I by characterizing the modern fire environment in two representative homes while also examining fire service horizontal ventilation tactics. Two houses were constructed inside a large fire facility. The first was a one-story, 112 m^2, three-bedroom, one-bathroom house with eight total rooms (see Figure 5.2). The second house was a two-story, 297 m^2, four-bedroom, 2.5-bathroom (a half bathroom has a sink and toilet but no shower or tub) house with 12 total rooms (see Figure 5.3). The second house featured a modern open floor plan, a two-story great room, and an open foyer. Fifteen total experiments were conducted in the structures where both the number and location of ventilation openings were varied.

Figure 5.2: 3D rendering of the one-story house. The fire icon indicates the location of ignition.

Ventilation scenarios included opening only the front door, opening the front door and a window near the fire, opening the front door and a window remote from the seat of the fire, opening a window only, and opening a window above the fire floor (only in the two-story structure). One scenario in each house was conducted in triplicate to examine repeatability. Potential occupant tenability was quantified to provide knowledge to the fire service so they could assess their horizontal ventilation standard operating guidelines and training content.

The fires in both houses produced ventilation-controlled conditions, which was necessary to assess the different ventilation practices of the fire service. Tenability in these two homes was limited for occupants based on the fractional effective

(a) First Floor (b) Second Floor

Figure 5.3: 3D rendering of the two-story house. The fire icon indicates the location of ignition.

dose (FED) methodology from ISO 13571 [70]. As a result, it was shown that the possibility of savable lives behind closed doors should be considered by the fire service in their risk analysis. The results of this series of experiments again highlighted that when a flaming furniture fire occurs in a home, occupants have a short time to evacuate safely. This outcome further highlighted the importance of smoke alarms and residential sprinkler systems to increase occupant safety.

Empirical fire experiment data was developed to demonstrate fire behavior resulting from one- and two-story home fires and the impact of ventilation opening locations during fire service operations. This data has been used to provide education and guidance to the fire service in appropriate use of ventilation as a firefighting tactic that will result in mitigation of the firefighter risk associated with improper use of ventilation.

Consider the data presented in Figure 5.4 from a living room fire in the single story structure. Temperatures in the structure rose following ignition, and prior to any ventilation (at approximately 350 s) the temperatures began to decay as the conditions within the structure became ventilation controlled. Ventilation to the structure in the form of opening the front door and living room allowed additional oxygen to reach the fuel and resulted in fire growth and higher temperatures. Also note that the bedroom 3 temperatures remained near ambient levels because the temperature sensors in that room were isolated from the main structure by a closed door.

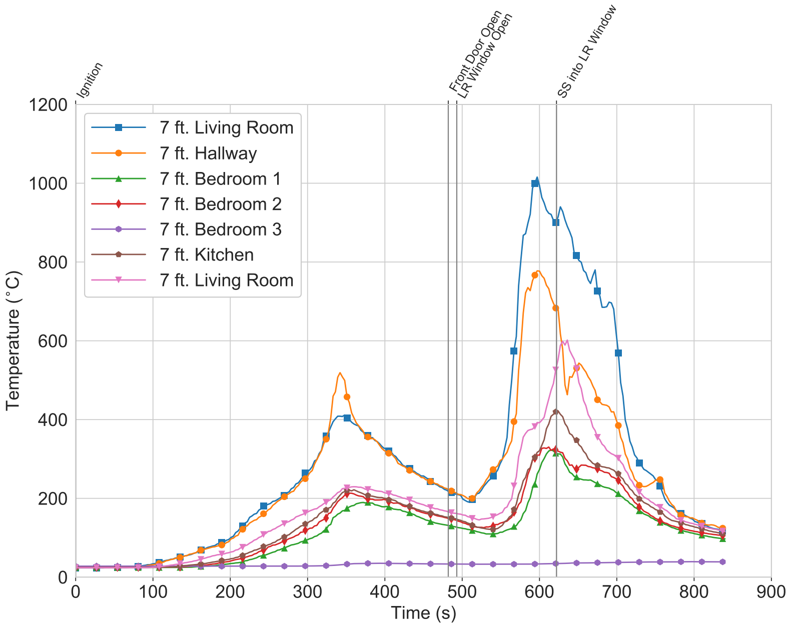
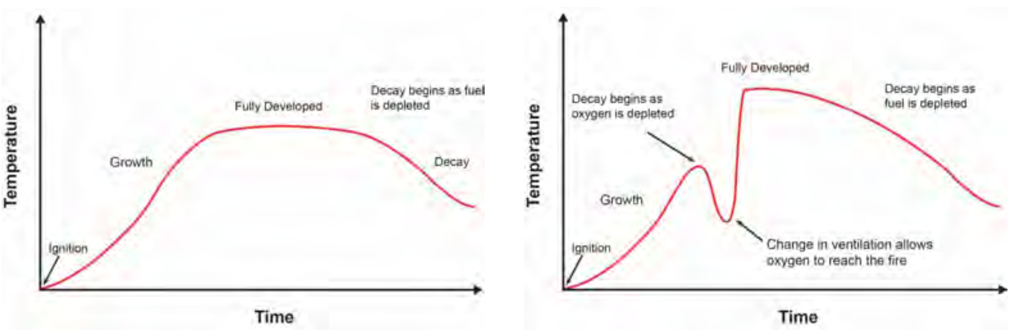


Figure 5.4: One-story house temperatures 2.1 m above the floor with the front door open, followed by the near window. Suppression occurred via straight stream through the open window.

The main conclusions from Paper II were the speed at which fires in homes become ventilation controlled, and the importance of the fire service understanding the impact their horizontal ventilation has on the fire dynamics and survivability within the home. This data supports the ideal ventilation-controlled fire model as opposed to the ideal fuel-controlled model that the fire service has been taught (see Figure 5.5).



(a) Ideal Fuel-Controlled Model **(b)** Ideal Ventilation-Controlled Model

Figure 5.5: Basic models of fuel-controlled and ventilation-controlled fires.

5.1.3 Paper III: Occupant Tenability in Single Family Homes: Part I—Impact of Structure Type, Fire Location, and Interior Doors Prior to Fire Department Arrival

Paper III built on Paper II by examining fires in the same home geometries, but with additional fire locations: bedrooms and kitchens. Paper II only examined living room fires in the one-story house and family room fires in the two-story house. The objective of Paper III was to examine occupant tenability prior to fire department intervention, while Paper IV examined the impact of fire service intervention. Due to the large amount of research aims and data, this analysis was split into two papers, Part I (Paper III) and Part II (Paper IV). Additionally, a legacy/natural-fuel experiment was conducted in the one-story house, which expanded the Paper I research by extending the room fire experiment to a house fire experiment in order to compare tenability and fire department intervention.

This paper describes an experimental investigation of the impact of structure geometry, fire location, and closed interior doors on occupant tenability in typical single family house geometries using common fuels from twenty-first century fires. Two houses were constructed inside a large fire facility: a one-story, 112 m^2 three-bedroom, one-bathroom house with eight total rooms, and a two-story, 297 m^2 four-bedroom, 2.5-bathroom house with 12 total rooms. These homes were built to be as identical as possible to the houses used in Paper II. The only difference was these houses had a roof ventilation system built above the living room in the one-story house and above the family room in the two-story house to allow for remote roof ventilation. Seventeen experiments were conducted with varying fire locations. In all scenarios, two bedrooms had doors that remained open while the third bedroom door remained closed. The closed-door bedroom was immediately adjacent to an open-door bedroom. Temperature and gas measurements at the approximate location of a crawling or crouching trapped occupant (0.9 m from the floor) were utilized with the ISO 13571 fractional effective dose (FED) methodology to characterize occupant tenability up to the point of firefighter intervention.

The FED values for the fire room were higher for heat exposure than for toxic gases, while target rooms reached the highest FED due to CO/CO_2 exposure. The closed interior door impeded FED rise; the worst case scenario resulted in a 2% probability of receiving an incapacitating dose. In contrast, the worst-case scenario for an open bedroom resulted in a 93% probability of receiving an incapacitating dose. In seven of the 17 experiments, the closed interior door resulted in a less than 0.1% chance of an occupant receiving an incapacitating dose prior to firefighter intervention. For the single-story structure, Table 5.2 shows the maximum FED value for both the open (bedroom 2) and closed (bedroom 3) bedrooms as well as the FED ratio between the rooms. Additionally, for each experiment the main FED contributor was identified to highlight the type of hazard a potential occupant was exposed to.

Table 5.2: Maximum FED Values and FED Ratios Comparing Open and Closed Bedroom FED in the Single-Story Structure

Room of Fire Origin	Experiment	Bedroom 2 (Open)	Bedroom 3 (Closed)	FED Ratio
Living Room	1	4.41 CO	0.01* CO	441
	3	4.51 CO	0.11 CO	41
	5	1.85 CO, BR1+	0.05 CO	37
	7	1.79 CO	0.01* CO	179
	15	0.50 Temp	0.01* CO	50
	17#	0.37 CO	0.01* CO	37
Bedroom 1	9	6.06 CO	0.08 CO	179
	11	0.46 CO	0.01* CO	46
Kitchen	13	0.51 CO	0.07 CO	7.3

* For the closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide a lower-bound estimate.
+ Bedroom 1 acted as the open bedroom.
# Denotes legacy furniture.

For the two-story structure, Table 5.3 shows the maximum FED value for both the closed (bedroom 2) and open (bedroom 3) bedrooms as well as the ratio between the rooms. Additionally, for each experiment the main FED contributor was identified to highlight the type of hazard a potential occupant was exposed to. In experiments where the contributions were similar, both factors were listed.

Table 5.3: Maximum FED Values (gas and temperature) and FED Ratios Comparing Open and Closed Bedroom FED in the Two-Story Structure

Room of Fire Origin/Experiment		Bedroom 2 (Closed)	Bedroom 3 (Open)	FED Ratio
Family Room	2	0.01* CO/Temp	0.64 Temp	64
	4	0.01* CO/Temp	0.46 Temp	46
	6	0.05 CO	0.55 Temp	11
	8	0.04 Temp	0.70 Temp	17.5
	12	0.03 CO	0.42 Temp	14
Bedroom 3	10	0.05 CO	8.5 CO, BR1+	170
	14	0.03 CO	5.5 CO, BR1+	183
Kitchen	16	0.13 CO	0.47 CO	3.6

* For the closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide a lower bound estimate.
+ Bedroom 1 acted as the open bedroom.

Prior to firefighter intervention, fires in the single-story structure resulted in a larger threat to occupant tenability than similar fires in the two-story structure due to the lower amounts of available oxygen and smaller volume for the toxic gases to fill. These two factors led to increased carbon monoxide and carbon dioxide concentrations prior to firefighter intervention. In many of the single-story experiments, the FED values prior to firefighter intervention were larger than 1, even in the non-fire rooms. In the single-story structure, gas exposure was the highest risk for target rooms, while thermal exposure posed a larger risk in the corresponding bedrooms in the larger two-story structure. Importantly, the median thermal FED value was 46 times higher for occupants in open bedrooms than occupants behind closed doors. Paper III provides further understanding of the time lines for tenability in common residential structure fires. This reinforces that there are savable lives at house fires, and that fire service size-up should consider that closed interior doors may provide protection in places not visible from the exterior of the structure.

5.1.4 Paper IV: Occupant Tenability in Single Family Homes: Part II: Impact of Door Control, Vertical Ventilation and Water Application

Paper IV extends Papers II and III by examining the impact of fire service tactics such as front door ventilation, vertical ventilation, and water application on occupant tenability. Seventeen experiments were conducted that varied fire location, ventilation locations, the size of ventilation openings, and suppression techniques in the same structures and series of experiments as Paper III. The results of these experiments examined potential occupant and firefighter tenability and provided knowledge the fire service can use to examine their vertical ventilation and exterior suppression standard operating guidelines and training content.

In these experiments, the impact of front door ventilation on toxic gases exposure was minimal, because the toxic gases FED rate actually increased after front door ventilation for several experiments. After vertical ventilation, or the hole in the roof was opened, there was a 30% reduction in the toxic gases exposure rate in two of the one-story structure experiments. Overall, prior to flashover the changes in toxic gas FED rate values (5%–50%) in the structure were minimal compared with the changes in heat exposure FED rate (a 500+% increase for heat exposure FED rate values after front door ventilation). There was not one ventilation hole size used in these experiments, however, that slowed the growth of the fire. After vertical ventilation was initiated, fires transitioned to flashover and fully developed fire conditions more quickly than scenarios without vertical ventilation. Once water was applied to the fire, the larger the ventilation hole and closer it was to the fire, the more products of combustion exhausted out of the structure, causing temperatures to decrease and visibility to improve.

Water application was also shown to reduce the thermal risk to occupants 60 s after water application by one-third on second floor rooms of the two-story structure and at least one-fifth on the first floor rooms of both structures. Water application also resulted in improved conditions for firefighters working on the interior of the structure. To visualize temperature reduction in non-fire rooms due to a straight stream applied directly to the fuel source, the change in non-fire room temperature as a function of the compartment temperature immediately prior to water application are shown in Figure 5.6.

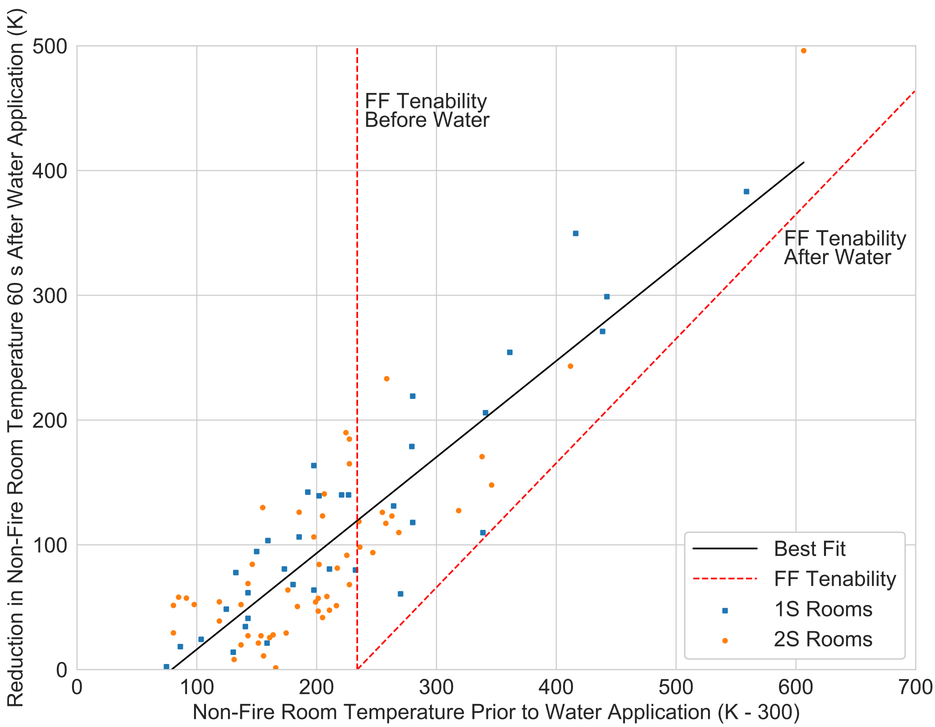


Figure 5.6: Effect of water application on firefighter tenability. The vertical dotted line shows the firefighter tenability criteria prior to water application, and the slanted dotted line shows the firefighter tenability criteria 60 s after water application. The solid line is the best fit line for the data set.

The data presented in Figure 5.6 comes from every straight stream water application during the 17 experiment study. When water was applied with a straight stream, temperatures were always reduced in the non-fire rooms (positive values on y-axis). The more positive the temperature reduction, the greater the value on the y-axis. The largest effects were in the rooms with higher initial temperature (larger values along the x-axis). The x-axis is offset by the ambient conditions (i.e., initial temperature). The higher starting temperatures were typically those measured in rooms closer to the fire room. On the plot is an overlay of the criteria for firefighter thermal tenability threshold of 260 °C (533 K), based on the design temperature for firefighter PPE [72]. Note the 300 K offset, so the tenability line is at 233 K. The data left of the vertical line corresponds to non-fire rooms that were tenable for firefighters before water application (n = 67). Data points between the vertical tenability line and inclined tenability line represent compartments where temperature was initially larger than the temperature threshold, but, 60 s after water application, the temperature was below the temperature threshold (n = 25). Data points to the right of the respective inclined tenability line would represent rooms where the temperature remained above the temperature threshold both before and 60 s after water application (n = 0). Temperatures in every non-fire room 60 s after straight stream water application were below the 260 °C threshold for firefighters.

Key findings from Paper IV were that venting a ventilation-controlled structure fire can result in conditions that either did not improve occupant tenability or, at worst, significantly reduced occupant tenability. Vertical ventilation size of 1.4 m^2 and 2.9 m^2 above the ventilation-controlled fire did not improve conditions for occupants in the adjacent bedrooms. On the other hand, water application improved conditions for simulated occupants in both the one-story and two-story houses.

5.1.5 Paper V: Effect of Firefighting Intervention on Occupant Tenability during a Residential Fire

Paper V expands on the conclusions detailed in the previous papers and introduces human subject testing as an opportunity to better understand coordination of firefighting crews as well as the impact of firefighting tactics on thermal burden and chemical exposure to potential occupants. These experiments were conducted in partnership with the Illinois Fire Service Institute (IFSI) and the National Institute for Occupational Safety and Health (NIOSH). The impact of firefighting intervention on occupant tenability was investigated to provide actionable guidance for selecting firefighting tactics based upon empirical rather than anecdotal evidence. Twelve fire experiments were conducted utilizing a full-sized residential structure to assess the impact of firefighting tactics on occupant exposure. The layout of the structure including the location of occupants is shown in Figure 5.7.

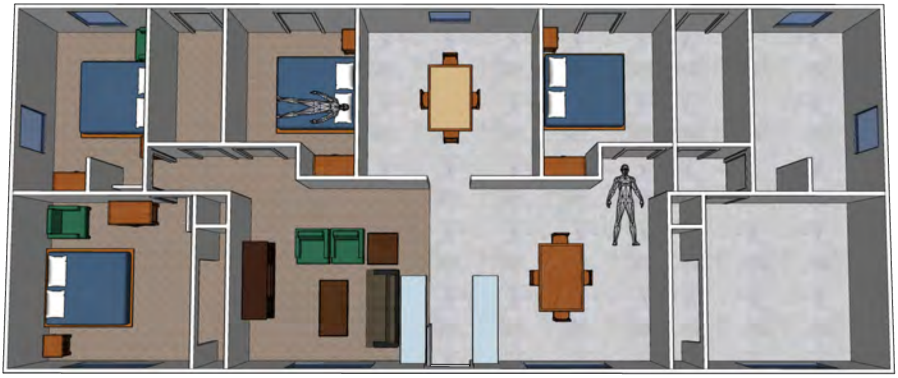


Figure 5.7: Layout of burn structure and location of occupants.

Six groups of firefighters recruited from fire departments throughout the country participated in two experiments each. Two attack tactics were examined: 1) interior attack, with water applied from the interior while a search team searched for simulated trapped occupants, and 2) transitional attack, with exterior water application before transitioning to the interior. In all scenarios, a two-person search team coordinated a search for simulated trapped occupants. Gas concentration and temperature measurements were analyzed using a fractional effective dose (FED) approach to determine the impact of fire attack tactics on the exposure for potential trapped occupants. Water application by the fire attack teams resulted in a rapid drop in temperatures throughout the structure, followed by a decrease in the FED rate. There was no significant difference between the magnitude of the temperature decrease or the time for FED rate to decrease between a transitional attack and an interior attack.

By definition of FED, as described in Section 4.2, the toxic exposure of occupants continued to increase as the removal times for occupants increased. However, the rate of increase slowed following suppression. An analysis of the occupant tenability data showed the most threatened occupants were not always closest to the seat of the fire. Occupants near the fire but isolated, such as those behind a closed door, received a lower exposure. As such, the results emphasized the need for rapid removal of occupants and coordination of suppression and ventilation tactics to limit toxic exposure.

Common firefighting texts [73, 74] suggest areas close to the suspected seat of the fire should be searched first, because occupants trapped in these areas are exposed to the greatest risk. In these experiments, unprotected occupants trapped in the near hallway were indeed at greatest risk of thermal exposure, but this area was also the least likely location to find a tenable occupant. The other locations, while likely to reach untenable conditions for many occupants by the end of simulated activities, experienced significantly lower FEDs at the time of intervention. Figure 5.8 shows the FED values in the dining room and hallway at the time the first occupant was found. These locations are approximately equidistant from the front door, and therefore can be used to assess differences if the search team first went toward the fire and found an occupant compared to a location on the opposite side of the structure.

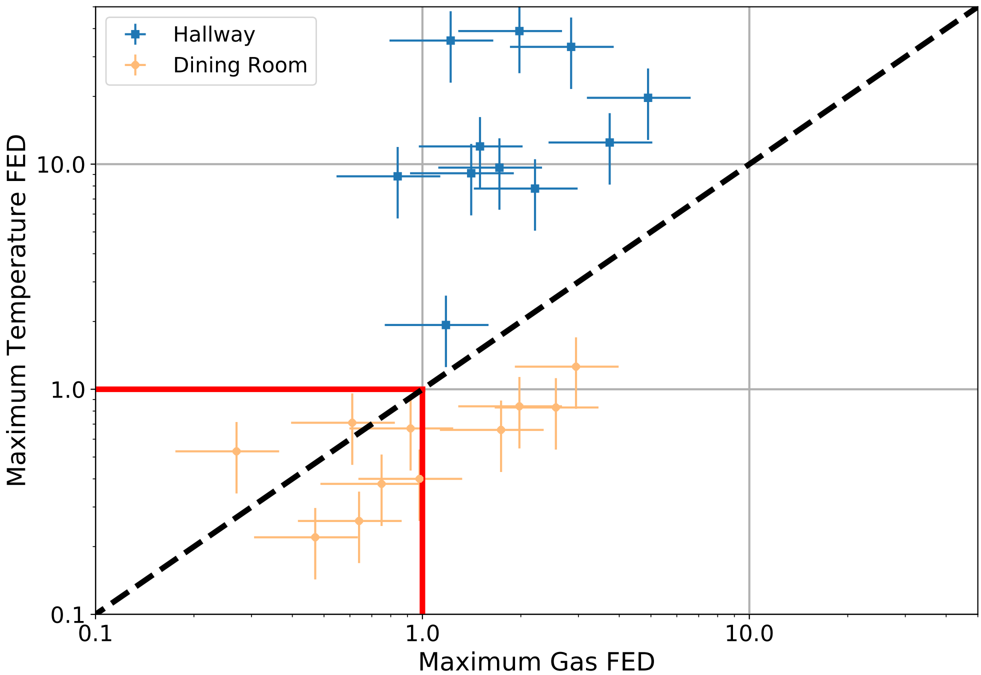


Figure 5.8: Near Hallway vs. Dining Room FED values at time of intervention. FED_{gas} is shown on x-axis and FED_{temp} is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population (1.0), Error bars represent the experimental uncertainty.

In these experiments, by searching away from the fire, the team was more likely to find a viable occupant than when the search team first moved toward the fire. Although it is not possible to conclusively determine lethality at a specific point in the structure from the data collected in this study, it is evident that the occupant found next to a post-flashover compartment fire had a higher risk of sustaining lethal burn injuries or receiving a lethal dose of toxic gases than one located remotely in the structure, as shown in Figure 5.8. Occupants trapped close to the fire room should not be abandoned or neglected, but high priority should also be placed on the potential for viable occupants trapped remote from the seat of the fire that may also of need of rapid removal. The search method employed by firefighters on the fireground is ultimately dependent on local policies and procedures, and the circumstances of the specific incident.

5.1.6 Paper VI: Thermal Response to Firefighting Activities in Residential Structure Fires: Impact of Job Assignment and Suppression Tactic

This paper reports on measurements to characterize the thermal burden experienced by firefighters in different job assignments who responded to controlled residential fires with typical furnishings utilizing the same series of experiments as Paper V. Firefighters' thermal burden is generally attributed to high heat loads from the fire and metabolic heat generation. These sources of thermal burden can vary between job assignments and suppression tactic employed. Utilizing a full-sized residential structure, firefighters were deployed in six job assignments utilizing two attack tactics: 1) water applied from the interior or interior attack; and 2) exterior water application before transitioning to the interior, or transitional attack.

Heat stress is one of the most common challenges firefighters routinely encounter. Because firefighters perform strenuous work while wearing heavy, insulating personal protective equipment (PPE), a rise in body temperature almost always accompanies firefighting activity. High heat exposures from the fire can also add to the heat stress experienced by firefighters. The physiological and thermal strain of firefighting activities have been documented based on simulated fireground work. Changes in core temperature associated with firefighting activities have been reported by several research groups [75–78].

Firefighting involves strenuous work that leads to maximal or near-maximal heart rates (HR) and, in some cases, rapid changes in core temperature (T_{CO}). Studies led by Barr [79] and Horn [80] reported average core temperature changes of 0.70 °C during short bouts of firefighting activity typical of residential room and contents fires. The researchers noted that repeated bouts of firefighting or the use of multiple SCBA cylinders of air would be associated with further increases in body temperature.

It is important to note, however, the vast majority of work performed characterizing the thermal stress of firefighting has occurred during training fires or in controlled laboratory conditions. Training fires differ considerably from residential fires in terms of the geometry of the structure, building materials, and fuel loads. Because of these factors, firefighters may experience different thermal environments, as well as different chemical exposures, during actual fires in residential buildings than in a training burn. Recent measurement of ambient temperatures inside common structure fires have further detailed risks posed by firefighting activities in modern structure fires [81].

When firefighters respond to structure fires, heat transfer from the environment to the firefighter can be affected by both job assignment and suppression tactic. Firefighters performing different job assignments experienced different ambient conditions and had different thermal responses. Firefighters who performed the most strenuous work had the highest skin and core temperatures, regardless of ambient conditions in which they were operating. Firefighting tactic had a significant effect on environmental conditions encountered by firefighters operating inside the structure.

Table 5.4 provides a summary of the maximum and average temperatures experienced by inside attack and inside search job assignments for both interior attack and transitional attack. Helmet temperatures were measured with a portable temperature sensor and data acquisition system affixed to the front of the helmet. For comparison purposes, the average working temperatures measured inside the structure during overhaul operations and exterior temperatures experienced by the outside operations are also presented. The data shows significantly lower maximum and average temperatures for the inside attack crews when they used a transitional attack compared to interior attack ($p = 0.006$ each), with no significant impact from the tactical choice on the inside search crew's thermal exposures (although the average temperature exposure difference was borderline significant, $p = 0.075$).

Table 5.4: The mean (SD) of maximum and average helmet mounted temperature measurements collected from the nozzleman on the attack team and the lead search team member (n=12).

Measure	Job Assignment	Interior Attack	Transitional Attack	Significance
Helmet Temperature (°C)				
Maximum	Inside Attack	191.0 (48.6)	95.7 (54.9)	p=0.006
	Inside Search	63.2 (13.0)	54.7 (101)	ns(0.245)
Average	Inside Attack	57.6 (7.0)	42.2 (7.8)	p=0.006
	Inside Search	39.7 (4.6)	34.9 (3.9)	ns(0.075)
Ambient Temperature (°C)				
Average	Overhaul	25.0 (3.0)	26.2 (2.8)	ns(0.375)
	Outside	19.2 (1.2)	19.8 (1.4)	ns(0.505)

Note: For Overhaul and Outside job assignments, reported temperatures are the average hallways temperatures (1.5 m) during overhaul and exterior temperature through the scenario, respectively.

Table 5.5 provides a summary of the mean values for arm and neck skin temperature as a function of job assignment performed and firefighting tactic employed. Arm and neck skin temperature was monitored with a patch that communicated with a data logger located in the firefighter's bunker coat. A benefit of lower ambient temperatures during transitional attack was lower neck skin temperatures for the attack firefighters. Neck skin temperatures for inside attack firefighters were ∼0.5 °C lower when the transitional tactic was employed. However, the reduced ambient and neck skin temperature for firefighters operating inside the structure did not translate to reductions in core body temperature during transitional attack (Tables 5.5 and 5.6).

Table 5.5: The mean (SD) of the maximum skin temperature for firefighters operating in different job assignments and attack tactics.

Job Assignment	Interior Attack	Transitional Attack	N
Maximum Arm Skin Temperature (°C)			
Outside Command/Pump	36.14 (1.32)	36.09 (1.36)	8
Outside Vent **	37.65 (0.71)	37.76 (0.62)	8
Inside **	37.51 (1.07)	37.20 (0.82)	16
Overhaul **	37.65 (0.76)	37.96 (0.43)	15
Total	37.35 (1.09)	37.35 (1.02)	47
Maximum Neck Skin Temperature (°C)			
Outside Command/Pump	36.40 (1.24)	36.20 (1.18)	8
Outside Vent**	37.72 (0.15)	37.67 (0.54)	8
Inside **	37.67 (0.76)	37.21 (0.63)	16
Overhaul **	37.81 (0.99)	38.06 (0.46)	15
Total	37.50 (0.99)	37.39 (0.93)	47

* Significantly different than Outside Command/Pump ($p<0.05$)
** Significantly different than Outside Command/Pump ($p<0.001$).

Table 5.6 provides the mean values for the maximum core temperature and core temperature change by job assignment and firefighting tactic. Core temperature was measured with a small disposable core temperature sensor capsule, which is designed to pass through the body and be eliminated in feces within approximately 24 h. While the sensor was in the GI tract, it transmitted temperature information to the remote recording device. Although there was no main effect of tactical choice on core temperature response, there was a main effect of job assignment for both maximum core temperature and rise in core temperature. Firefighters assigned to overhaul had the highest core temperatures, followed by outside vent. Although inside firefighters' maximum core temperatures were slightly higher in magnitude, they did not differ significantly from the outside command firefighters.

Table 5.6: The mean (SD) of the maximum core temperature and core temperature changes for firefighters operating in different job assignments and attack tactics.

Job Assignment	Interior Attack	Transitional Attack	N
Maximum Core Temperature (°C)			
Outside Command/Pump	37.81 (0.40)	37.68 (0.26)	8
Outside Vent **	38.63 (0.37)	38.54 (0.42)	8
Inside	37.91 (0.21)	37.99 (0.43)	16
Overhaul **	38.88 (0.38)	38.81 (0.58)	15
Total	38.32 (0.57)	38.29 (0.58)	47
Core Temperature Change (°C)			
Outside Command/Pump	0.85 (0.31)	0.64 (0.24)	8
Outside Vent**	1.84 (0.49)	1.64 (0.41)	8
Inside *	0.93 (0.27)	1.15 (0.55)	16
Overhaul **	1.74 (0.46)	1.77 (0.48)	15
Total	1.33 (0.58)	1.34 (0.61)	47

* Significantly different than Outside Command/Pump ($p<0.05$)
** Significantly different than Outside Command/Pump ($p<0.001$).

The main conclusions from this paper were that rapid elevations in skin temperature were found for all job assignments other than outside command. Significantly higher core temperatures were measured for the outside ventilation and overhaul positions than the inside positions ($\sim$ 0.6–0.9 °C). Thus, it is important that firefighters wearing fully encapsulating PPE and working on the fireground be provided rest, recovery, and rehab based on intensity and duration of work, regardless of tactic utilized or the apparent risk from their ambient conditions alone.

5.1.7 Paper VII: Contamination of Firefighter Personal Protective Equipment and Skin and the Effectiveness of Decontamination Procedures

Utilizing the same series of experiments as Papers V and VI, this paper focused on quantifying some important fireground chemical exposures that may impact the carcinogenic risk of firefighting. Firefighters' skin may be exposed to chemicals via permeation/penetration of combustion byproducts through or around personal protective equipment (PPE), or from the cross-transfer of contaminants on PPE to the skin. Additionally, volatile contaminants can evaporate from

PPE following a response and be inhaled by firefighters in the apparatus cab, personal vehicle, or fire stations depending on how and where they are stored and transported. Using polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) as respective markers for non-volatile and volatile substances, the contamination of firefighters' turnout gear and skin following controlled residential fire responses was investigated.

Participants were grouped into three crews of 12 firefighters. Each crew was deployed to a fire scenario (one per day, four total) and then paired up to complete six fireground job assignments. Wipe sampling of the exterior of the turnout gear was conducted pre- and post-fire. Wipe samples were also collected from a subset of the gear after field decontamination. Field decontamination was carried out after firefighters had doffed their gear and post-fire off-gas and surface sampling had taken place. For dry-brush decontamination, an industrial scrub brush was used to scrape debris and contaminants from the gear. For air-based decontamination, an air jet provided by a modified electric leaf blower was directed over the entire surface of the turnout jackets and pants to remove contaminants. For wet-soap decontamination, the investigator prepared a 7.6 L pump sprayer filled with a mixture of water and ∼10 mL of dish soap. The investigator pre-rinsed the gear with water, sprayed the gear with the soap mixture, scrubbed the gear with soap mixture using an industrial scrub brush, and then rinsed the gear with water until no more suds remained. VOCs off-gassing from gear were measured pre-fire, post-fire, and post-decontamination.

PAH levels on turnout gear increased after each response and were greatest for gear worn by firefighters assigned to fire attack and search and rescue activities. Figure 5.9 provides a summary of the percent change in PAH levels from post-fire to post-decontamination by decontamination (air, dry-brush, and wet-soap). The whisker plots show the minimum and maximum values as well as the quartiles of the data. The main conclusions from this paper were that field decontamination using dish soap, water, and scrubbing was able to reduce PAH contamination on turnout jackets by a median of 85% (Figure 5.9). Off-gassing VOC levels increased post-fire and then decreased 17–36 min later regardless of whether field decontamination was performed.

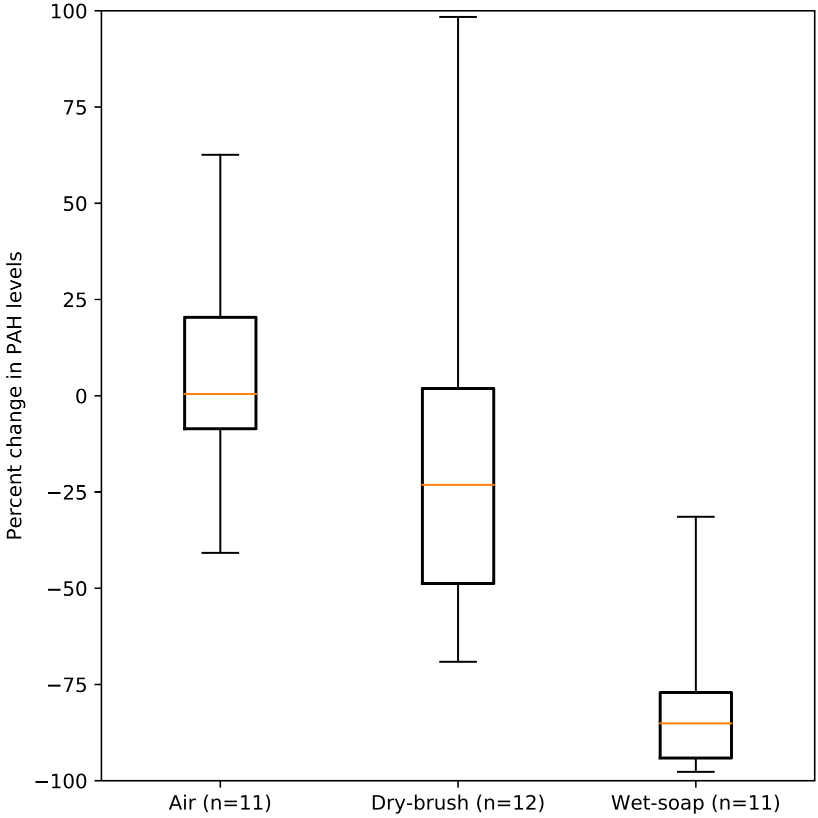


Figure 5.9: Box and whisker plots showing the percent difference in PAH levels measured on turnout jackets before and after decontamination. The minimum, 25^{th} percentile, median, 75^{th} percentile, and maximum values are provided.

Wipe sampling of the firefighters' hands and neck was conducted pre- and post-fire and additional wipes were collected after cleaning neck skin. Median post-fire PAH levels on the neck were near or below the limit of detection (<24 μg/m^2) for all positions. For firefighters assigned to attack, search, and outside ventilation, the 75th percentile values on the neck were 152, 71.7, and 39.3 μg/m^2, respectively. Firefighters assigned to attack and search had higher post-fire median hand contamination (135 and 226 μg/m^2), respectively) than other positions (<10.5 μg/m^2). Cleansing wipes were able to reduce PAH contamination on neck skin by a median of 54%.

5.2 Addressing the Research Questions

The five research questions presented and discussed in Chapter 3 are addressed in this section with the help of the appended papers. Research question 1 provides a foundation for the rest of the research and is addressed in Paper I. The firefighter health and safety component of research question 1 is also addressed with Papers VI and VII. Research question 2 examines fire service ventilation and was addressed in Papers II and IV. Research question 3 focuses on fire service suppression and was also addressed by Paper IV. Research question 4 examines the complete fireground and builds on research questions 1–3 with occupant tenability as the measurement of success, utilizing Paper V. Research question 5 is addressed by comparing open and closed bedrooms during the experiments in Papers II, III, and V.

RQ1. How has the fire environment changed over the past 50 years and how does it impact firefighter health and safety? (Paper I, Paper VI, and Paper VII)

Paper I focused on two main changes in the fire environment; 1) the introduction and evolution of synthetics in furnishings and building materials, and 2) advancements in construction materials and practices. Both of these changes have allowed fire to grow and spread faster and resulted in the potential for structural collapse sooner than legacy materials and methods. These changes have had a negative impact on firefighter risk. Synthetic furnishings have had a significant impact on the fire growth rate, which has resulted in the potential for flashover conditions (pending the availability of oxygen) prior to average fire service arrival times. Additionally, the fire service commonly arrives to ventilation-controlled fire conditions where additional ventilation can result in rapid changes in fire dynamics and negatively impact firefighter safety.

Paper I described how advancements in construction materials, including the use of synthetics in building materials, have allowed for floor and roof system components that span longer distances and use less mass in their design. These two changes have resulted in shorter times to collapse. Once the fire impinges on the roof and floor systems, collapse can occur much faster than the same conditions on a solid wood joist lumber roof and floor system.

The study described in Paper VI examined the thermal conditions in a house fire and how those conditions impact a firefighter's skin and core temperatures. A faster growing fire in today's residential structures will release more energy and more combustion products (i.e., smoke) into the structure in a shorter period of time. That energy gets transfered to the environment, heating up the surroundings and raising the temperature to higher values that were not common in the same time frame for natural fuels. The end results are more challenging conditions that require fire attack and search and rescue to take place in zero visibility, high-temperature conditions. These conditions may require additional metabolic work that, combined with higher environment temperatures, results in elevated skin and core temperatures. Increased skin and core temperature can lead to an increased physiological and thermal strain for operational firefighters.

The increased use of synthetic materials in furnishings and building materials results in more incomplete combustion, which contributes to fire environment chemicals such as PAHs and VOCs, some of which are known or possible carcinogens. Paper VII reports the magnitude of firefighter PPE, neck skin, and hand skin contamination with PAHs during firefighting. The International Agency for Research on Cancer (IARC) classified occupational exposure as a firefighter as possibly carcinogenic to humans (Group 2B) [82]. Since this determination was made in 2010, a number of epidemiology studies continue to find elevated risks of several cancers in firefighters [83].

Over the past 50 years, the increased use of synthetics in home construction and contents have led to an increase in ventilation-controlled fire conditions. These conditions can result in rapid changes in fire dynamics, shorter times to collapse, and increased exposure hazards. All of these changes negatively impact firefighter health and safety. In response, the fire service should evaluate and evolve tactics and hygiene procedures.

RQ2. How have the fire environment changes impacted fire service horizontal and vertical ventilation tactics? (Papers II and IV)

Paper II (horizontal ventilation) and Paper IV (vertical ventilation) provide evidence that the timing and coordination of ventilation are very important due to the ventilation-controlled conditions the fire service commonly arrives to as a result of the fire environment changes discussed in research question 1. It is important for the fire service to understand the basic fire dynamics principle that gases flow from high pressure to low pressure. As a fire grows in a compartment, hot fire gases expand, resulting in an increase in pressure. When a ventilation opening is made (doors, windows, roof), a low-pressure exhaust is created allowing gases to flow toward the low-pressure outlet.

Any new opening creates a flow path in the structure. A flow path is the volume between an inlet and an outlet that allows the movement of heat and smoke from the higher pressure within the fire area toward the lower pressure areas accessible via openings in the structure. When the fire service makes ventilation changes to a structure, the flow of gases can either be used to their tactical advantage or their detriment. Paper II developed empirical fire data to demonstrate fire behavior resulting from one and two-story home fires and the impact of ventilation opening locations during fire service operations. If air is added to the fire by changing the ventilation and water is not applied in the appropriate time frame, the fire gets larger and safety decreases. The average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yielded 100 s for the one-story house and 200 s for the two-story house. In many of the experiments, the time from the onset of firefighter untenability until flashover was less than 10 s. This data provides the first quantifiable evidence of the necessary rate of coordination a fire attack should employ to mitigate the potential increase in risk from ventilation prior to water application.

These times established important benchmarks that can be used to understand many fire scenarios beyond these two structures and this experimental methodology. Additional variables such as structure size, fuel loading, distance from flow path inlet and outlet to the fire, and ventilation opening sizes will impact these important fire service tactical times. Utilizing a knowledge of fire dynamics principles, firefighters can understand how these different variables will apply to the incidents they respond to, to improve their prediction of cause and effect relationships of the tactics they choose to deploy. This data has been used to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic to mitigate the firefighter injury and death risk associated with improper use of ventilation.

RQ3. What is the effect of water application from the exterior, as part of a transitional attack or exterior-only water application, on civilian and firefighter safety? (Papers II and IV)

The focus of Paper II was to examine ventilation, but after ventilation the fire was allowed to progress beyond flashover and the fires were extinguished to prepare for the subsequent experiments. Suppression was done by flowing water into the post-flashover rooms fires from the exterior of the houses. Data recorded during suppression indicated that suppression improved conditions throughout the house, although fire service feedback based on their experience suggested conditions should have worsened inside the house beyond the fire room [84]. The fire service has referred to this phenomena as "pushing fire [85]."

To examine water application and "pushing fire" in more detail, the experiments in Paper IV were designed and instrumented to examine the impact of suppression from the exterior on civilian and firefighter safety. Two common types of fire service nozzles (fog-spray pattern and smooth bore-solid stream) were utilized for the experiments, and fires at ground level and on a second floor were extinguished. In every experiment, air temperatures in all fire and non-fire rooms never increased as a result of fire or hot gases being displaced from the fire room to a non-fire compartment. In each case, the risk from the post-flashover fire to the occupant, located outside the fire room, was reduced. Water application was shown to reduce the thermal risk to simulated occupants or firefighters who could be in adjacent rooms from the post flashover fire room 60 s after water application to one-third the original values in the second floor rooms of the two-story structure and by at least one-fifth of the original values in the first floor rooms of both structures.

RQ4. What is the impact of coordinated fire service intervention (ventilation, suppression, search and rescue) on occupant tenability? (Paper V)

The impact of coordinated fire service intervention of suppression and ventilation on conditions during the rescue of two simulated occupants is described in Paper V. Measurements made at the simulated occupant locations allowed quantification of the impact of coordinated fire attack activities on the FED rate and overall FED. After water was applied, whether from the interior or the exterior, the FED rate in open areas of the structure began to decrease after the front door was opened, providing ventilation. The highest FEDs were close to the fire room due to the high temperatures from the flows escaping the fire rooms and the high concentration of products of combustion in the smoke near this area.

There was no statistically significant difference in the times to locate or remove the occupants between the transitional attack method versus the interior attack method. This could indicate there was not a noticeable improvement in visibility as a result of the early water application in the transitional attack experiments that aided the search team in finding the occupant more rapidly.

Although suppression slowed the production of products of combustion, the expulsion of products of combustion from the structure is a time-dependent process. The rate at which smoke is exhausted and visibility is improved is related to the time of suppression, the methods of ventilation used, the wind speed and direction, and the number, location, and area of ventilation openings. Although ventilation prior to suppression can increase the burning rate of the fire and thus increase the production rate of toxic gases, ventilation closely coordinated with suppression is important for timely evacuation of products of combustion.

Although the FED rate was decreasing in the time the search crew took to find and remove the occupants, the occupants would still be exposed to high concentrations of toxic gases. Even though the magnitude of the hazard was decreasing, the FED of any occupant would continue to increase until they were removed from the structure. It follows that once an occupant is found, the gas and/or thermal exposure to the occupant will continue to increase during the removal process, as long as the occupant is still breathing and/or exposed to environments with high enough temperatures to increase burn risk. These measurements emphasize the importance of rapid removal of occupants located during the search in an effort to minimize the toxic exposure of these occupants. Depending on the conditions within the structure, the location of the occupant within the structure, and the knowledge of the search company of alternative means of egress, the ideal path for occupant removal may be out of an opening separate from the one the search team entered through, such as a rear or side door, or even through a window or down a ladder. This emphasizes the importance of situational awareness among the members of the search company and coordination of occupant removal.

In summary, assuming a ventilation-controlled fire in a house:

1. Effective suppression will convert the ventilation-controlled fire to a fuel controlled fire and reduce the FED rate for any trapped occupants.
2. Once it's a fuel-controlled fire, ventilation will begin to let out more products of combustion than are being created, which will continue to lower the FED rate for any trapped occupants and improve visibility for the fire service.
3. Occupants need to be located and removed from the house to stop the accumulation of their FED to give them the best chance of survival.

Coordinating a fire service intervention with these key steps is likely to lead to a positive impact on occupant tenability.

RQ5. What is the impact of a closed bedroom door on occupant survivability? (Papers II, III, and V)

The fire service has to continually size-up a fire scene to prioritize efforts for deployment of their resources to rescue trapped occupants. During all of the experiments reported on in Papers II, III, and V (in 44 full-scale house fire experiments), there was an instrumented closed bedroom adjacent to an open bedroom. The instruments were placed at locations where occupants could be potentially situated in the bedrooms, assuming they remained still for the duration of experiment and did not self evacuate. Comparing the thermal and gas concentration FEDs yielded a clear conclusion: An occupant with a closed door between them and the fire has a much better chance of surviving these room and contents fires versus an occupant in a bedroom with the door open. In the initial studies reported in Paper II, all of the open bedrooms reached thermal and gas concentration FEDs of 1.0 or higher, while all of the closed bedrooms remained below an FED value of 0.3. In experiments conducted for Paper III, the closed bedroom door significantly limited FED rise, with the worst-case scenario resulting in a 2% probability of receiving an incapacitating dose compared to the worst-case scenario for an open bedroom of 93% probability of receiving an incapacitating dose. The occupant tenability analysis in Paper V showed that the most threatened occupants were not always closest to the seat of the fire; occupants near the fire but behind a closed door received the lowest exposure. The fire service can utilize this information to improve their search and rescue and size-up tactics and to understand that occupants located behind closed doors will have a better chance of survival.

With data showing the speed at which fire grows and spreads (Papers I–V) and the importance of a closed door on the survivability of people during a house fire (Papers II, III, and V), UL FSRI launched a public education campaign. This campaign, executed *with* the fire service, has utilized several marketing strategies to reach the public in an effective way to change their perceptions and behavior when it comes to closing bedroom doors. The key messages are to 1) have working smoke alarms on every level of the home, inside every bedroom, and outside of every sleeping area; 2) have an escape plan that includes closing doors on the way out of the house; and 3) Close Before You Doze – that is put that door between you and a potential fire before you go to sleep at night to buy you that valuable time to escape or be rescued by the fire service. More information and free resources are available at https://closeyourdoor.org [86].

5.3 Addressing the Research Objective

This research aims to improve firefighter safety and effectiveness by increasing their scientific knowledge of the evolving residential fire environment and its impact on fire service tactics. Papers I, VI, and VII showed how the fire environment has evolved and that the more condensed fire time line can have a significant impact on firefighter tactics, safety, and health. Papers II, III, IV, and V examined fire service tactics commonly deployed in emergencies with a modern fire environment and how they can be combined to result in the best possible outcome of life safety and property conservation.

It is important that fire service research fits within the fire service system in order for a positive impact to occur. Modifications are suggested to the traditional fire service improvement model as shown in Figure 5.10 to enhance SOGs, improve effectiveness, efficiency and accelerate fire service learning. The proposed modification suggests that the improvement model should be grounded on a foundation of fire dynamics knowledge. Fire dynamics is the study of how chemistry, fire science, material science, and the mechanical engineering disciplines of fluid mechanics, thermodynamics, and heat transfer interact to influence fire behavior. In other words, fire dynamics is the study of how fires start, spread, and develop.

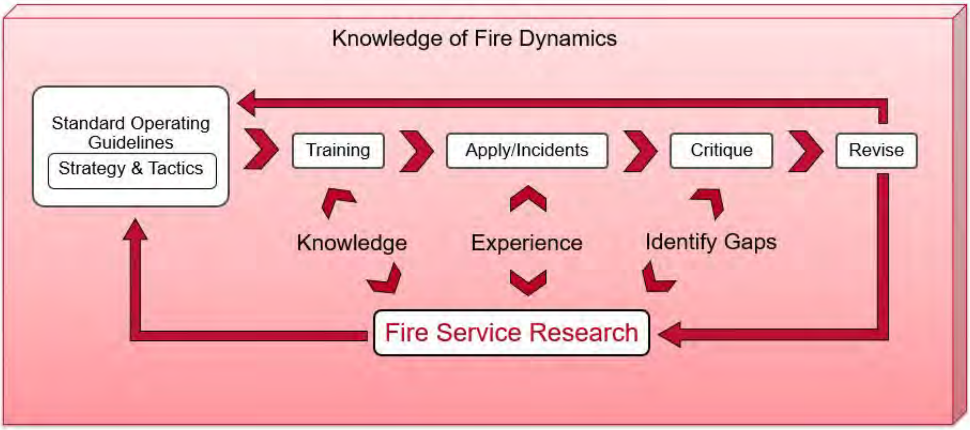


Figure 5.10: An improved fire service improvement model highlighting the importance of fire dynamics knowledge and fire service research.

Knowledge of fire dynamics is paramount for the fire service to gain valid experience that can be used to understand what went correctly and/or incorrectly with respect to the strategies and tactics employed at an incident. Fire dynamics knowledge is also essential during the critique stage of the model so that individuals can combine their experiences to form a more complete picture of the fire incident with a consistent/uniform basis. When trends get linked together after several incidents, a revision may be necessary to the current standard operating guidelines.

In the traditional model, if changes are deemed necessary due to experience, the changes could be attempted in training. However, there is little to no opportunity to safely replicate realistic conditions in training, especially ventilation-controlled fire conditions. Therefore, what changes seemed correct in training may not provide the desired outcome when applied at incidents, especially if firefighters lack understanding regarding the basis for proposed changes.

Fire service research is needed to bridge this gap. Fire service researchers must work with the fire service to utilize their experience to conduct experiments that create realistic conditions. It is also important for researchers to control the appropriate variables so that tactical choices can be better understood. This helps firefighters and fire officers understand how their choices will impact the outcome of an incident.

The place to initially experiment with tactics should not be at incidents but rather in research. For example, consider a bedroom fire in the rear of a house. The fire was extinguished by a firefighting crew comprised of seven individuals, and an unconscious civilian was rescued from an adjacent bedroom with serious but non-life threatening injuries. Had there been no fire service response, the result would likely have been the death of the civilian because they could not self rescue and the fire would have consumed the house. Considering the alternative, the outcome with the fire service was therefore successful, but was it as successful as it could have been? Did the firefighting tactics implemented result in the least amount of harm to the civilian, the least amount of damage to the house and least amount of impact on the environment? It would be impossible to measure this during an actual incident, but this can be measured in research where multiple tactical approaches to the same scenario can be quantified. As research provides answers to fire service questions like these, the knowledge gained can be applied and tuned in training. This iterative process could influence the actions and decision making of the firefighters, which could result in better outcomes in the future.

Chapter 6

Views on Research's Role in the Fire Service

It is important that fire service research fits within the fire service system in order for a positive impact to occur. There are many uses for research in the fire service improvement model. Figure 6.1 highlights the areas in which research can contribute to the fire service improvement model. The following sections examine several of them in detail supported by the research both by the author as well as other researchers. All of this research is influenced by fire service experience and their ever-evolving work environment. Additionally, views are presented on how the research can be implemented, and how impact may be measured.

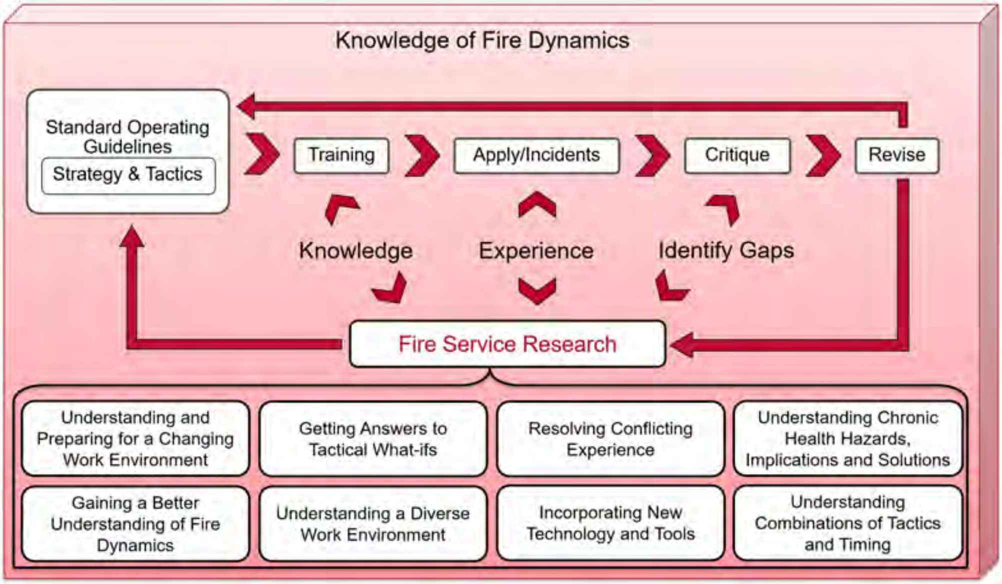


Figure 6.1: An improved fire service system including component areas of research.

6.1 Understanding and Preparing for a Changing Work Environment

Although the physics of fire development has not changed over time, the fire environment (i.e., the firefighter's workplace) has evolved. Several factors, including home size, geometry, contents, and construction materials, have substantially changed over the past 50+ years. Each of these changes may have individual or singular impacts, but the all-encompassing effect of these components on the fire environment has changed the incidents the fire service responds to. Figure 6.2 from Paper I shows each of these components and how they combine to change fire behavior. As society continues to make changes to building materials as a result of the desire to be environmentally conscious, provide cost effective housing, and increase profit, the fire environment will continue to change. If the current trends continue, it will not favor firefighter safety. Therefore, it is important that firefighters and researchers study this new fire environment and its impact on their safety and tactics.

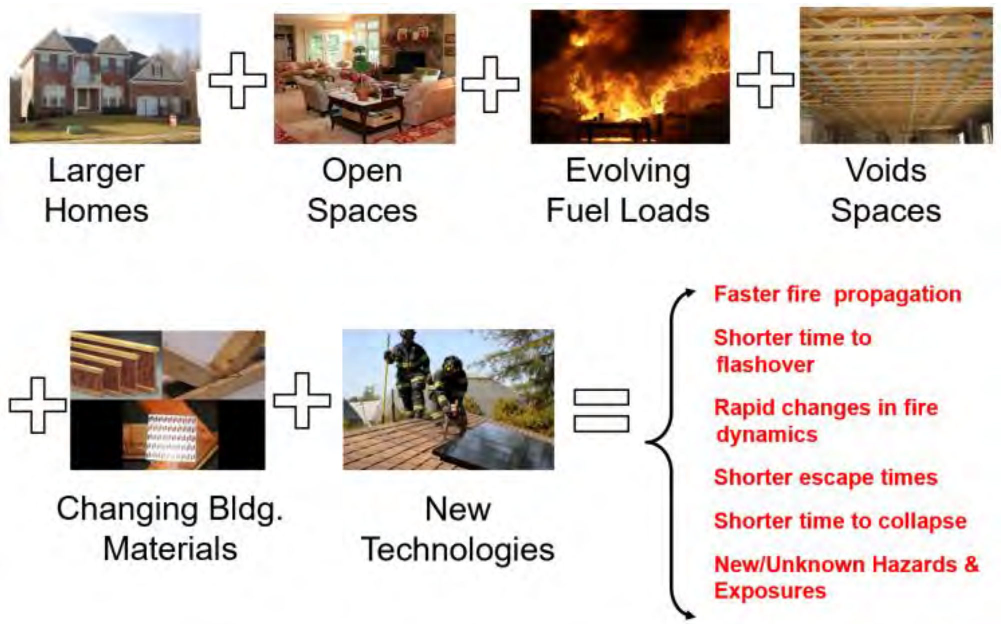


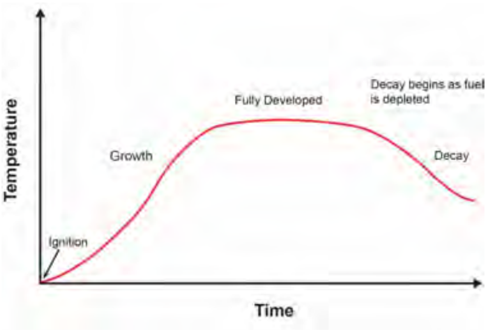
Figure 6.2: The components of the changing fire service work environment.

A key component of firefighter safety is understanding the conditions firefighters arrive to are very different than several generations ago. Fire conditions can change rapidly due to under-ventilated fire conditions (Paper II), and floor systems can collapse quickly and with little warning (related publications VI and VII). Operating conditions need to be constantly monitored to understand the impact of the tactics used, and the potential need to change them. Ultimately, if the fire environment has changed, tactics need to change or be reevaluated to have the greatest opportunity to be most effective on today's fires. Additionally, the fire service and researchers should participate in the codes and standards processes to play a role in the safe adoption and implementation of new technologies and construction practices.

6.2 Gaining a Better Understanding of Fire Dynamics

Fire dynamics knowledge can be improved by changing the way fire dynamics is integrated into fire service education. If they follow the existing training materials created based on NFPA 1001 [27], U.S. firefighters receive approximately 3 hours of fire behavior training that is delivered in a classroom with no hands-on or laboratory learning. Some fire departments in the United States and internationally do much more, while some do none. This training is usually not well-connected to the fire ground. Firefighters are often left to try to connect the principles of fire dynamics to their tactics without much supporting evidence.

It is important the fire service understands the physics and chemistry encompassed in fire dynamics concepts such as flashover, ventilation limits, impacts of ventilation, lower explosive limits, smoke is fuel, the fire triangle, and others. Often, these can be demonstrated utilizing small-scale or bench-top models or demonstrations. For example, Figure 6.3 presents two idealized charts to help understand the impact of ventilation on fire growth. A small-scale model of a single compartment with a door can allow students to visualize how a fire transitions to ventilation controlled once the door is closed and the source of oxygen is removed. Another example is a candle. A candle alone can help demonstrate some of these concepts (e.g., smoke is fuel and fire triangle), but the concepts must also be connected to the full-scale at some point to further improve a firefighter's knowledge.



(a) Ideal Fuel-Controlled Model

(b) Ideal Ventilation-Controlled Model

Figure 6.3: Basic models of fuel-controlled and ventilation-controlled fires.

Additionally, research has been conducted to connect important fire dynamics concepts to the fire ground by producing data and visuals that demonstrate the cause and effect relationship of firefighter tactics to their desired outcomes of life safety and property conservation. Studies on horizontal ventilation (Paper II), vertical ventilation (Paper IV and related publication VIII), wind-driven fires (related publication IV) [16], and basement fires (related publication V) are examples of research conducted *with* the fire service to increase their knowledge of fire dynamics.

It is further important for the fire service and researchers to partner during significant incident reviews and recreations. Learning from incidents that result in line-of-duty deaths or near misses provide lessons that can be shared across the fire service to help prevent future incidents with negative outcomes. Incorporating fire dynamics knowledge into these investigations and recreations allows for science to be connected to firefighter experience, which has the potential to make sure accurate lessons are learned and communicated [38, 40, 42, 87–89].

6.3 Getting Answers to Tactical What-Ifs

There is a saying in the fire service that "no two fires are the same." This is technically accurate, but connecting the similarities and differences of fires has led to the collective experience of the fire service. Without a foundation of fire dynamics knowledge, the experience can be misleading. A further complication is that firefighters do not get a second chance at a fire to try something different and subsequently compare the outcomes. For example, imagine a firefighting crew arrives at a house fire with fire coming from a front window and they choose to advance a hoseline into the front door of the house and extinguish the fire. The firefighters may wonder if the outcome could have been better (less damage, quicker suppression, etc.) if they deployed a different set of tactics or coordinated them differently. This opportunity is not possible in reality, but it is possible in research. An identical (or as close as possible) home with identical furnishings can be ignited in an identical way to try many different sets of tactics. The outcomes can be measured with instrumentation to examine occupant tenability, property damage, and firefighter safety. Studies examining horizontal ventilation (Paper II), vertical ventilation (Paper IV and related publication VIII), positive pressure ventilation (related publication X), attic fire suppression [57], fire attack [59], and basement fire attack [60] utilized this method to directly compare different firefighter-defined sets of tactics.

6.4 Understanding a Diverse Work Environment

Firefighters operate in a diverse work environment. One day they may be assigned to a station that has a response area made up of single-family homes, and the next day they could be responding to high-rise buildings or unique hazards such as tunnels [90] or wildland [91, 92]. Research and broad dissemination of research results can educate the fire service to assist their preparation to respond to a diverse work environment. As an example, research on high-rise (related publications I and II) and school (related publication III) fire dynamics provided data on how fires grow and spread in these types of structures. Most firefighters would not have previous experience going to these types of fires, but many have the potential to respond to these types of fires.

6.5 Resolving Conflicting Experience

Firefighters can have conflicting experience on particular types of fires or with the use of particular tactics. Research can be used to understand the conflicts. For example, a firefighter who utilized a transitional attack in which they flowed water for short period of time could have a very different result than a firefighter who flowed water for a longer period of time or flowed water with a poor technique. Each firefighter may form an opinion on their experience that carries through the rest of their career. Research can isolate the variables to provide a clear comparison of techniques so the firefighters understand the benefits and limitations of water application and technique during a transitional attack. Transitional attack and interior attack were compared based on their impact on occupant tenability to provide objective input to the example above (Paper V) [93]. Large amounts of data can also be combined to gain additional insights from incident responses. A study examined the relationship between the water flow rate applied by the fire service to the area of the fire and found that there were three distinct approaches or modes of firefighting, and each can be categorized by ranges of flow rates [94]. Additionally, several tactics could appear to provide equally positive results. Experiments could be designed to examine any scenario and tactics to compare the outcomes to a defined set of good or bad outcomes, such as FED of occupants, safety and exposure of firefighters, percentage of structure saved, etc. These outcomes must be weighed against the resources required to achieve them, such as the number of firefighters, tools, training, equipment, timing, etc. Only after this comparison is it realistic to resolve conflicting experiences.

6.6 Understanding Chronic Health Hazards, Implications, and Solutions

Research is necessary to understand the chronic hazards of firefighting. Among the most pressing health concerns in the fire service are sudden cardiac events and firefighting-related cancers. However, relatively little fire safety information exists on the cumulative exposures firefighters face while they work on the fireground and participate in training exercises. Many studies have been conducted and are underway by teams of researchers to better understand these hazards and what can be done to prevent or control them (related publication IX) and [95–100].

Figure 6.4 shows pathways from firefighting to two negative health outcomes, cancer and sudden cardiac events. The act of firefighting includes exposure to products of combustion and heat. The products of combustion are composed of toxic gases and particulate. Those particulates and chemicals can be deposited on the firefighter PPE and onto the skin of the firefighter. The heat generated by the fire increases the environmental temperature in the structure, heats the firefighter's PPE and skin, and can increase the core temperature. The firefighter exposed to products of combustion and heat could have several primary physiological responses, including changes in cardiac electrical function, vascular function, blood pressure, blood chemistry, blood coagulation, and metabolites in breath and urine.

Better understanding of these responses could lead to a better understanding of firefighter cancer and sudden cardiac events and how to prevent to reduce their incidence. Studies have examined the impact of job assignment on exposure (Paper VI), the effectiveness of different kinds of decontamination (Paper VII), effectiveness of skin cleaning (Paper VII), and the physiological recovery of firefighters after firefighting [76]. A foundational component to understanding all of these health hazards, implications, and solutions is knowledge of fire dynamics and the fire service's workplace. Utilizing fire measurements and fire dynamics knowledge provides the foundation for studies like these and helps translate information to the fire service. The more research performed on this complex system, the more that can be understood and the more lives that will be saved.

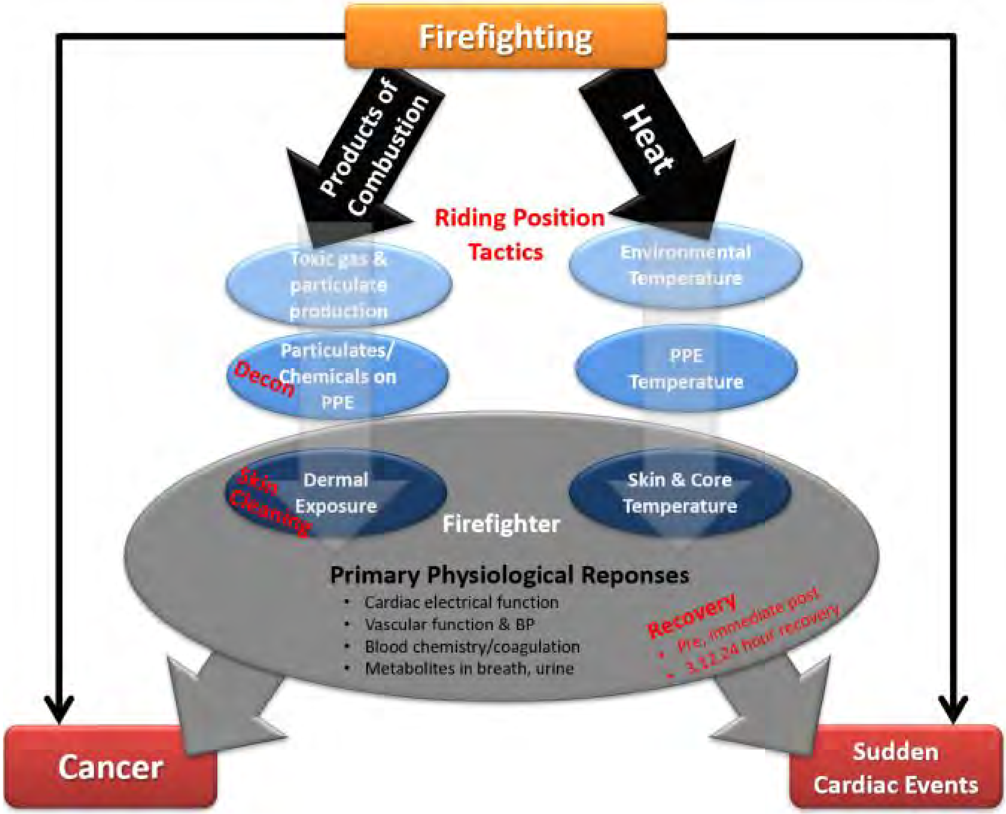


Figure 6.4: A comprehensive model of Cardiovascular and Chemical Exposure Risks in Modern Firefighting [95]

6.7 Incorporating New Technology and Tools

As needs arise, technology evolves and new tools get introduced to the fire service work environment. While intentions are good, technological advancements can mean new challenges for the fire service. Commonly, the fire service has to figure out new tools and technology on their own, either on the training ground, or on the fireground. Both of these options present challenges when the tool or technique is intended to be used at emergency fire incidents. The training ground is not able to fully replicate the fireground and the fireground is a bad place to experiment with new tools because the lives of civilians and firefighters are at stake. A better way to test the benefits and limitations of new tools is with research.

A research experiment can get as close as possible to replicating the conditions in which a new tool will have to operate while not placing the user or civilians in danger. For example, positive pressure ventilation (PPV) fans were placed in service throughout the fire service in the 1980s. Several bad outcomes and line of duty deaths were linked to the use of PPV fans [101–103]. Research studies in the 2000s were conducted by the University of Texas [104], the Swedish Rescue Services Agency [54], SP [105], and NIST [7, 9]. Research studies as late as the 2010s were still examining the benefits and limitations of this tool (related publications I, II, III, and X).

Additionally, as PPE has evolved, new materials and advancements in technology have offered improved protection to the firefighter from thermal hazards and toxic gases. Since the 1960s new materials have been introduced into the fire service. Additionally, evolutions in self-contained breathing apparatus, personal alert safety systems [106], and escape rope systems [107] have advanced with research [3].

Research can provide answers to the fire service on how to deal with these challenges before they encounter them during emergencies. Technologies such as solar panels have become popular around the world, but they also fail, which has resulted in fire service responses. It is not acceptable to have a firefighter be injured or killed because they did not know how to safely mitigate a solar panel fire. At the same time, a business with a solar panel system on the roof should not have to watch their building burn because the fire service did not know how to safely mitigate the incident. These potential and predictable incidents can be examined in research to determine how to best resolve them before they occur. The results can be disseminated to the fire service so they can be prepared with the knowledge to respond to the incidents and bring them to a successful outcome. A study on firefighter safety and solar panel systems examined several potential challenges that could face the fire service [108].

6.8 Understanding Combinations of Tactics and Timing

On the fireground, tactics such as suppression, ventilation, and search are often executed in parallel. How concurrent tactics are executed and timed depends on the structure, conditions, staffing, and other variables. It is very difficult to understand the outcomes of these tactics and what is the best combination during emergencies. In research, these combinations and their coordination can be examined, including the potential impact on civilian and firefighter safety. Early studies investigated tactical patterns and the challenges of coordination [19, 55]. Studies have examined the combination of suppression and ventilation during single family home bedroom fires [59] and basement fires [60]. These have resulted in improved understanding of how flow paths can be used to assist or hinder fire suppression. When ventilation changes are made to a structure, the flow of gases can either be used for tactical advantage or for detriment. The timing of these actions is also critical because the same actions done at different time frames could result in very different outcomes.

6.9 Implementation of Research Results

Effective implementation of research results into the fire service is a continued partnership between the fire service and fire researchers. It requires many different approaches. Ultimately, without implementation, the effort put into the research and the knowledge gained could be lost or wasted. Changing the status quo requires knowledge, consistent, digestible communications, and understanding the politics and the complexities of the fire service.

It is of foremost importance to ensure the research results are easily accessible and disseminated in a user-friendly and transparent manner. Websites, e-learning modules, and videos are all good ways for the individual firefighter to review the material on their own time and at their own pace. Examples of each of these outreach methods can be found at https://ulfirefightersafety.org [50]. At the department level, lesson/drill plans, manipulative drills, promotional exam questions, required reading, and sample SOGs are all tools that can assist the implementation of research results.

At the national and international level, research results should be shared with training organizations and publishers that write the training manuals used and referred to by the fire service. Additionally, research results should be worked into standards and guides because these documents are usually the references that training materials are based on. Finally, partner organizations and their conferences are an excellent way to share results so that firefighters, fire departments, and membership organizations endorse the research results and support their implementation.

There is an opportunity to implement fire research and fire dynamics into fire service training, including hands-on training. Today, fire dynamics is included in classroom training and is not well tied to actual fireground activities. In the classroom, fire dynamics principles could be incorporated into the other subjects, such as forcible entry, ventilation, suppression, search, etc. Additionally, classroom learning should incorporate practical fire service research to reinforce the why in addition to the how. It should be visual and incorporate actual incident video with experiment video as well as line-of-duty death and close-call case studies.

Hands-on training can also be supplemented at many different scales. Small-scale fire demonstrations are very useful to teach the basics of fire dynamics. Candle demonstrations can show principles of ventilation, pressure, and burning gases. Doll houses show additional principles of ventilation-controlled fires, suppression, and the impact of ventilation tactics [109]. Steel container props can introduce students to compartment fire dynamics and help them visualize important concepts such as burning gases and the impact of ventilation [110]. Purpose-built burn buildings can combine tactics with fire dynamics. These props still require good instructors with fire dynamics knowledge because the environment will not respond the same way as the fireground due to safety constraints of the building and the fuels. Even with the limitations, however, burn buildings can be a very useful fire dynamics educational tool. Finally, acquired structures and/or demonstration structures expand training to a real-scale, which allows students to see the impact of ventilation, impact of suppression, and other important fire dynamics principles while watching versus being involved in task-level execution [111]. As long as it is for demonstration purposes only, real fuels can provide valuable lessons to students as they can watch the fire react to changes in ventilation or the application of water from the exterior.

Another important component of implementation is continuing education. This should be incorporated into the fire service system to account for changes in the fire environment as well as updated research results based on fire service experience occurring all over the world. Most fire departments in the United States have no required continuing education [49].

6.10 Measurement of Impact

Fire service impact can be very difficult to measure and therefore quantifying the impact of fire service research is also challenging. It would be nice if we could say that Fire Department “X” saved “Y” lives and “Z” amount of property before the research was conducted, and after the implementation of research results, those numbers decreased by a measurable percent. Currently, that is not the case. The Los Angeles County Fire Department conducted a pilot study to assess the value of changing their standard operating procedures and training as a result of fire dynamics research. They compared a time period of eight months before and after they changed their SOGs and trained their firefighters. The results are shown in Figure 6.5. Based on this analysis, it could be concluded that although the amount of structure fires remained fairly constant, the property loss, content loss, and firefighter burn injuries decreased in a measurable way. This data would require more analysis to determine if implementing the research results was truly a significant factor in these outcomes and if the changes were sustained or due to natural fluctuations, but the high-level comparison is positive. Future analysis could examine this data further to see if burn injury decreases can be attributed to changes in tactics, and if the burn injuries are less severe, which would cost the department less money and justify the cost of the training.

2013 vs. 2014 Comparison

LOSS and INJURIES DECREASED

August 1, 2014

RTW/NFIRS Data

Timeframe	Before Training 1/1/2013 – 8/1/2013	After Training 1/1/2014 – 8/1/2014
Structure Fires	1352	1356
Property Loss	$36,075,678	$33,422,260
Content Loss	$13,759,940	$11,233,966
FF Burn Injuries	22	12

Figure 6.5: The Los Angeles County Fire Department's assessment of research-influenced training change [112].

Another method to characterize the impact of the fire service was developed by Runefors [113]. He assessed the rescues performed by fire departments in Sweden in 2017 utilizing incident reports and interviews. The cases were also compared with fatal fires, revealing that the odds of successful rescue increased, for example, if the fire occurred in an apartment building or if the response time was short. He used this data to create an algorithm to calculate the probability of a successful rescue depending on the capability of the fire service. This methodology could be expanded to examine the chance of successful outcomes based on the tactics deployed or level of fire dynamics knowledge of the fire departments.

Chapter 7

Discussion

This chapter provides a reflection on the applied methods and the quality of the research, which is discussed in relation to the concepts of validity and reliability. Validity relates to the accuracy of the research, or if the study measures what is intended. Reliability relates to the reproducibility of the results. The generalization of the results is also discussed.

7.1 Reflecting on the Methods

All the research presented in this thesis was done at full-scale, which provided excellent insight and knowledge. There were also challenges and missed opportunities that provide the basis for recommended future research efforts. In Paper I, living room fires were compared utilizing different fuels and a flaming ignition source on a sofa to build a representative fire timeline. This timeline could have been further defined by examining different ignition scenarios, such as other locations on the sofa, other items in the room, or other rooms such as kitchens or bedrooms. Kitchen and bedroom fires were conducted as part of Paper III. Additionally, the door burn-through experiments should have included a solid-core door that did not have decorative panels in order to bound the analysis. Panels were cut into both sides of the tested doors, which resulted in areas of the door that were thin, much like the hollow-core doors. These thin areas were where the door burned-through on the same timeline as the hollow-core door.

Papers II, III, and IV utilized the same house geometries even though they were built at two different times. In hindsight, a number of additional measurements and experiments would have been beneficial to understanding occupant tenability and firefighter safety. Although the experiments were designed to examine the effects of ventilation, there was the opportunity to learn much more about suppression tactics. This could have been achieved by locating thermocouples in locations that would have been protected from the flow of the hose streams. We could have also utilized heat flux measurements at locations outside of fire rooms to gain better insight into the heat energy flowing into the remainder of the structure prior to and during suppression. This modification would have provided a more complete FED analysis for occupant tenability and understanding of firefighter safety during suppression.

Several other decisions were made for budget and laboratory availability reasons. We utilized surplus hotel furniture for these experiments so that we would have close to identical furnishings for every experiment. Although we characterized the furniture under a oxygen consumption calorimeter, it would have been nice to have new residential furnishings. While this compromise was made due to cost, we were still able to produce repeatable ventilation-controlled fire conditions. We also did not include all the additional items that would be in a home, such as clutter, clothes in the drawers and closets, decorations, etc. Although this would not have impacted the final conclusions, it could have revealed additional research questions or fire service tactical considerations.

Additionally, it would have been very useful to include more gas measurement locations during the experiments. Additional gas measurement locations and more measurement heights at these locations would have allowed for better understanding of gas flows and ventilation-controlled fire dynamics. Occupant tenability could have been better quantified once firefighter tactics were deployed, flow paths were created, and/or when a two-layer fire environment was no longer present in different rooms of the house.

The simulated fire response timeline was fixed in these experiments, but there is much more to learn based on different simulated fire service arrival times. We chose an average intervention time, but the time from ignition to notification of the fire service is rarely known, so it could vary widely. Intervention time impacts the conditions the fire service operates with. Finally, all of the initial horizontal ventilation experiments (Paper II) were conducted with the fire in the living room. The vertical ventilation experiments (Paper III and IV) added bedroom fires, but it would have assisted with the comparison and insights gained if additional fire rooms were studied during the horizontal ventilation fire experiments.

Papers V, VI, and VII report on different aspects of the same series of experiments, and therefore, the reflections can be combined. It became apparent during this series of experiments that there was a wide variance of time-to-task completion for the firefighters. Even though the firefighters were walked through the scenario and structure ahead of the experiment, as required by experimental protocol approved by the Institutional Review Board (IRB), large variations were found in the times to complete tasks as well as how the tasks were completed. The purpose of an IRB review is to assure, both in advance and by periodic review, that appropriate steps are taken to protect the rights and welfare of humans participating as subjects in the research. The wide variance resulted in two experiments that were outliers in the analysis. In one scenario the crew performed the suppression different than what was asked, and in a second scenario the suppression crew went into the wrong room and could not find their way to the fire room without assistance. The firefighters were necessary for measurements reported in Papers VI and VII, however they added limitations to the analysis of Paper V. This is also positive as it allows the first time we have been able to report human based variability in such controlled environments that would never be possible in actual structure fire responses.

The weather introduced another set of uncontrolled variables to this series of experiments. We did not have an indoor facility to use and we did not have human subjects who were all local and universally available, so based on the fixed time window for experiments, we had to incorporate the different ambient wind, temperature and humidity conditions into our analysis. Finally, we were able to utilize portable temperature and gas measurement equipment on the firefighters and simulated occupants (mannequins), but the portable gas measurement devices had lower ranges that were exceeded in several of these experiments. Fixed gas measurement locations were utilized for the analysis, but this was a limitation as it would be better to know the simulated occupant exposure as they were removed/rescued from the structure.

Although there were many limitations and missed opportunities, it may be concluded that despite the complexity of the full-scale experiments, we were able to control the key variables very well. There will always be another measurement we wish we had made or an experiment we wish we had conducted.

7.2 Reflecting on Validity

Validity relates to the accuracy of the research or if the study measured what was intended. Conducting fire experiments at full-scale limits the total number of observations that can be made. Therefore, to maximize the impact of a finite set of experiments, careful consideration is given to parameters such as building materials, the fuel load, and the ignition source during each experiment so the impact of specific firefighting operations (e.g., ventilation operations or fire suppression tactics) on tenability conditions in structures can be examined.

The houses used in these studies were constructed with wood framing (common in the U.S.), and the interior was lined with two layers of gypsum board. The interior linings lessened the potential for a structure fire, essentially ensuring that fire would be a contents fire. While structure fires were possible, if the experiments routinely became structure fires, this would have limited the applicability to non-wood frame structures that can be found around the world. The use of gypsum board also provided a balance of being reflective of real houses, while being easily replaced if damaged. This allowed for the continued reuse of the experimental structures by only replacing the damaged gypsum board without having to replace structural elements.

To repeatably control ventilation (i.e., size and timing of opening), the exterior vent enclosures (windows) were purpose-built as side-hinged shutters. Each shutter was wood-framed and finished with a layer of insulation on the inside with a layer of plywood on the outside. The shutters were affixed to the exterior of the framed window openings. These shutters allowed for the windows to be manipulated open and closed as many times as needed during the experimental series. Paper I examined the wide variability of window failure times and mechanisms. Removing this variability allowed for more accurate conclusions. However, in practice, the window venting process is neither as precise or as rapid as conducted here.

The layout or floor plan of the structures allowed for the comparison between traditional spaces and two-story connected volumes. While there are a multitude of possible floor plans, the layouts used for these experiments allowed for fires in different sized and purposed rooms (e.g. bedrooms, living rooms, and kitchens) that were connected to instrumented spaces through hallways, doorways, or open foyers/two-story family rooms. Instrumented spaces could also be isolated behind closed doors. In all cases, the structures were built or rehabilitated to typical residential standards to minimize the natural leakage. This ensured that the ventilation-controlled fire conditions that the fire service responds to could be repeatability achieved. The fire dynamics knowledge gained in these papers can be extrapolated to additional floor plan features such as different room sizes, different room configurations and different door and window openings. Particularly floor plan features bound by the two structures utilized in this study.

The fuel loads were selected to be representative of what could be found in homes. Each series of experiments had near identical furnishings. This was achieved by sourcing the furnishings from hotel surplus retailers. The furnishings were purchased in bulk to supply an entire experimental series. While the furnishings were not identical across experimental series, they were burned under an oxygen consumption calorimeter to confirm that their heat release rates would be sufficient to flashover their respective fire rooms (provided sufficient oxygen). All of the experiments were ignited with an electric match (thin wire wrapped around a match book to create a repeatable small flaming fire) placed on or adjacent to a sofa, chair or mattress. All fire service interventions were implemented after ventilation-controlled conditions were achieved, which allowed for a comparison that was based on conditions, not simply time. Variances in the source fuel load may have delayed the time to intervention but had minimal impact on the conditions at interventions. This is also why FED rate was examined because it allowed for an assessment of the impact of occupant tenability after fire service intervention, independent of an occupant's FED prior to intervention, something the fire service has little control over.

Experiments also require expertise in measurement science, specifically knowledge of measurement limits and uncertainty, to accurately quantify the fire environment. Measurements of gas temperature, gas velocity, gas concentration, pressure, and heat flux were made using common fire science instruments. Each of these instruments has sensor uncertainties as well as expanded uncertainties based on how it was utilized in the experiments.

Gas temperatures were measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.5 mm nominal diameter due to their large range and fast measurement response time. The standard uncertainty in the temperature of the thermocouple wire itself is ± 2.2 °C at 277 °C and ± 9.5 °C at 871 °C In addition to the uncertainty of the sensor itself, radiative effects to the thermocouple should be considered. Several studies have attempted to quantify these effects on thermocouple measurement uncertainty in compartment fires [114, 115]. These studies indicated that when the thermocouple is located in the upper gas layer, the actual temperature of the surrounding gas is typically higher than the measured temperature, although this difference is not as pronounced as when the thermocouple is in the lower layer. When the thermocouple is in the lower layer, particularly during a fully involved compartment fire, the percent error in measured temperature can be much larger. Because of these radiative contributions, the expanded total uncertainty is estimated as ± 15%. Results from an international study on total heat flux gauge calibration and response demonstrated that the uncertainty of a Schmidt-Boelter gauge is typically ± 8% [116].

The gas sampling instruments used throughout these studies have demonstrated a relative expanded uncertainty of ± 1% when compared to span gas volume fractions [117]. Given the non-uniformities and movement of the fire gas environment and the limited set of sampling points in these experiments, an estimated uncertainty of ± 12% is applied to the analyses [118].

For these FED analyses, it is important to consider the large uncertainty associated with the measurements. Additionally, the FED equations presented in Equations 4.2, 4.3 and 4.5 are exponential in nature, small measurement variations will result in larger variations in the FED calculation. Further, ISO 13571 lists the uncertainty for the FED calculations as high as 35% [70]. This large uncertainty was included in each appended paper that included a FED analysis.

Measurement uncertainty plays an integral role with respect to the conclusions made following experiments. For example, consider two experiments being assessed with respect to the influence of ventilation on temperature. If the temperature differences in the comparison are within the uncertainty of measurement, the scientific conclusion drawn from the comparison is that a difference cannot be identified even if there might be a qualitative trend of slightly lower temperatures for one of the experiments. The identification of what conclusions can be made versus what conclusions cannot be made based on the data is a key component of the scientific methodology that the fire service relies on as output from the research.

7.3 Reflecting on Reliability

Reliability relates to the reproducibility of the results. Even though these experiments were full-scale, care was taken to control the reliability and the repeatability. In Paper I, three series of comparative room fires were conducted to draw conclusions. Window failure experiments were also conducted to determine the repeatability of window failure. Since the timing of window failure was not repeatable, it could not be considered to reliably occur during testing and shutters were used in the house fire experiments to improve repeatability.

The house fire experiments in Paper II-VII addressed repeatability by comparing the fire growth conditions throughout the house prior to fire department intervention. Temperature and gas concentration values were used to initiate the fire service intervention to compare the impact of the tactics examined in each series of experiments. Additionally, some experiments were replicated to examine repeatability of measurements.

In Papers V-VII, all of the fire experiments were similar replicates up to the time of fire service intervention, after which differences in conditions could be attributed to interior or transitional attack. This was done to study the thermal and chemical exposure to the human subjects. To participate in these experiments, the subjects needed to meet important inclusion criteria related to health, history and employment as a firefighter. Following standardized firefighter training practices, participants were provided with the opportunity to conduct a walk-through of the structure prior to ignition. Although firefighters may have completed the tasks more rapidly than if they had not been familiar with the layout or been in worse physical shape, it lead to more consistent results. At the same time, these inclusion criteria and standardization for human subjects testing may have lead to some of the conclusions in Papers V-VII being conservative.

This knowledge has continued to be incorporated into experiments conducted after the experiments documented in this thesis, and expanded upon for future experiments. UL FSRI has conducted additional full-scale experiments on fire service topics of attic fires [57], positive pressure ventilation in homes [119], and fire attack [59]. This series of studies has led to research results that are first of their kind and have led to fire service tactical considerations and fire dynamics knowledge that will have a lasting impact on the fire service.

Chapter 8

Conclusions

This thesis provides a compilation of investigations into the fire service workplace through the lens of full-scale experimentation to provide evidence-based information that can be combined with firefighter experience to improve firefighter knowledge of fire dynamics. Such knowledge provides a basis for understanding the cause and effect impact of firefighter tactics on life safety, property conservation, and incident stabilization. The research in these papers is combined with a discussion of the fire service improvement model to address this objective. This thesis contains several contributions that are valuable to fire safety researchers and firefighters who protect all of us every day. The key conclusions are listed below:

- The conditions to which the fire service arrive to today can be markedly different than several generations ago due to changed construction practices and increased use of synthetic materials. Fire conditions can change rapidly due to under-ventilated fire conditions, and floor systems can collapse quickly and with little warning. Ultimately, if the fire environment has changed then tactics need to be reevaluated to give firefighters the greatest opportunity to be most effective on today's fires.
- If air is added to a ventilation-controlled fire and water is not applied in the appropriate time frame, the fire gets larger and safety decreases. Examining the times to untenability and the speed at which fires increased in size gives the best-case scenario of the necessary pace of fireground coordination. Based on these experiments, the average time from the moment of ventilation to the the onset of firefighter untenability conditions is 100 s for the one-story house and 200 s for the two-story house. In many

of the experiments, from the onset of firefighter untenability until flashover was less than 10 s.

- The fire service should prioritize the following at a ventilation-controlled fire in a house to reduce occupant exposure to heat and toxic gases: 1) effective suppression will make the ventilation-controlled fire a fuel-controlled fire and reduce the FED rate for any trapped occupants; 2) once a fuel-controlled fire, ventilation will begin to let out more products of combustion than are being created, which will continue to lower the FED rate for any trapped occupants and improve visibility for the fire service; and 3) occupants need to be located and removed from the house to stop the FED accumulation to give the occupant the best chance of survival.
- An occupant with a closed door between them and the fire has a much better chance of being rescued and surviving versus an occupant in a room with the door open to the fire area due to significantly lower thermal and gas concentration exposures over time.

In addition, in this thesis the fire service improvement model is analyzed and changes are offered. The two main changes include; an emphasis on a foundation of fire dynamics knowledge, and utilizing research to fill the gaps that exist in the current model. The fire dynamics knowledge is imperative to making sure that as the fire service applies their SOGs at emergency incidents, what they experience makes scientific sense. Fire dynamics is the fire service's common language. The gaps that research can assist with in the fire service improvement model are:

- Understanding and preparing for a changing work environment
- Gaining a better understanding of fire dynamics
- Getting answers to tactical what-ifs
- Understanding a diverse work environment
- Resolving conflicting experience
- Understanding chronic health hazards, implications, and solutions
- Incorporating new technology and tools
- Understanding combinations of tactics and timing

This integration of science-based knowledge and experience enables the fire service to better evaluate its strategies, tactics, and tasks, ensuring they remain as effective and efficient as possible.

Chapter 9

Future Research

The fire service's workplace will continue to evolve and research must keep up or stay ahead of that evolution to ensure the fire service is as prepared as possible to overcome the hazards they will face. Many fire service tactics and tasks still lack the theoretical and empirical support that should be provided by research. Emerging areas such as new technologies (e.g., energy storage systems, tall wood buildings, etc.), chronic health hazards (e.g., heart disease, cancer, mental health, etc.), and economic impact (e.g., staffing, return on investment, etc.) will need large investments in research to produce evidence-based results.

Research on global fire service best practices should be conducted by a global research team. Best practices on conducting the research can be combined with analyzing the similarities and differences of the firefighter's workplace. What do differences in equipment, construction practices, response models, training models, standard operating guidelines, etc., mean to life safety and property conservation outcomes? How is this different for developing countries versus developed countries, and how can developing countries implement what has already been learned even though they may have different resources available?

Additional research is needed in the areas of dissemination to make the best use of the limited research conducted with the global fire service. Future research on preparing firefighters for their career, including initial training and continuing education, should be prioritized. Questions such as,

- How do we support fire dynamics knowledge, the foundation of the fire service?
- How do we advance continuing education within the fire service and what

material needs to be included?

- How do we deliver training and education to the fire service with time constraints, particularly for volunteer firefighters?
- How do we teach the fire service abstract concepts?; how do you teach tactile minded firefighters when they cannot touch or see the answer?
- How do we produce firefighters that are able to think dynamically and still utilize SOGs as a framework?

Although it was not a primary component of the research for this thesis, computational fire modeling is a powerful research tool. It should be continually improved. Research should continue to improve the validity and reliability into the submodels needed for fire service applications. Two examples are continued research into models that can predict the complex physics of pyrolysis and the subsequent development of validation data sets for the response to water application from a fire service hose stream. The data from the full-scale experiments conducted as part of this thesis will be made available to the computation modeling community to further these research needs.

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Appendix: Appended Papers

A.1 Paper I: Analysis of Changing Residential Fire Dynamics and its Implications on Firefighter Operational Timeframes

Fire Technology, 48, 865–891, 2012

DOI: 10.1007/s10694-011-0249-2

Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes

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Received: 22 August 2011/**Accepted:** 29 November 2011

Abstract. There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, different home geometries, increased synthetic fuel loads, and changing construction materials. Several experiments were conducted to compare the impact of changing fuel loads in residential houses. These experiments show living room fires have flashover times of less than 5 min when they used to be on the order of 30 min. Other experiments demonstrate the failure time of wall linings, windows and interior doors have decreased over time which also impact fire growth and firefighter tactics. Each of these changes alone may not be significant but the all-encompassing effect of these components on residential fire behavior has changed the incidents that the fire service is responding to. This analysis examines this change in fire dynamics and the impact on firefighter response times and operational timeframes.

Keywords: Fire dynamics, Firefighting, Tactics, Residential fires

1. Introduction

There is a continued tragic loss of firefighters' and civilian lives, as shown by fire statistics [1, 2]. One significant contributing factor 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 the changes in home size, geometry, contents, and construction materials over the past 50 years add complexity to the fire behavior (Figure 1).

NFPA estimates [3] that from 2003 to 2006, US fire departments responded to an average of 378,600 residential fires annually. These fires caused an estimated annual average of 2,850 civilian deaths and 13,090 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 2001–2004 period, there were an estimated annual average 38,500 firefighter fire ground injuries in the US [4]. The rate for traumatic firefighter deaths when occurring outside structures or from cardiac arrest has declined, while at the same time, firefighter deaths' occurring inside structures has

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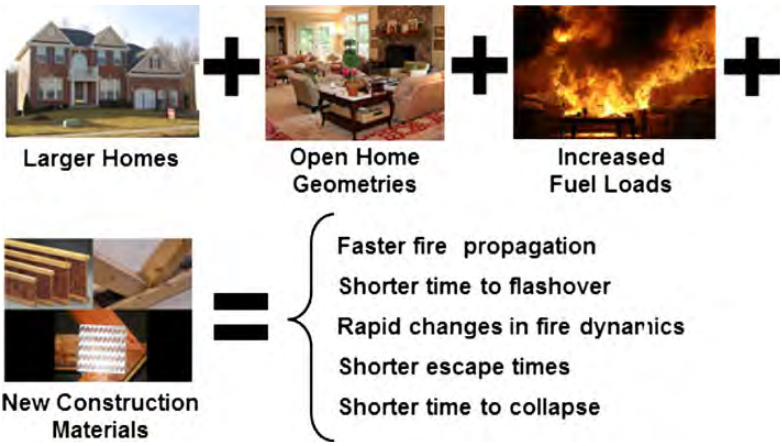

Figure 1. Modern fire formula.

continued to climb over the past 30 years [5]. Additionally, on average firefighters in the United States receive less than 1% of their training on the subject of fire behavior [6]. 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 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.

2. Background

While the physics of fire development has not changed over time, the fire environment or more specifically the single family home has evolved. Several factors including home size, geometry, contents and construction materials have changed significantly over the past 50 or more years. Each of these factors will be examined in detail as they pertain to the safety of occupants and the responding fire service.

2.1. Home Size

Many contemporary homes are larger than older homes built before 1980. Based on United States Census data [7] homes have increased in average area from approximately 144 m^2 in 1973 to over 232.3 m^2 in 2008. Twenty-six percent of homes constructed in 2008 were larger than 278.7 m^2 (Figure 2). In addition to increased area more homes are being built with two stories. In 1973 23% of homes were two-story and that has increased to 56% by 2008. The percentage of single story homes has decreased from 67% to 44% in the same time period (Figure 3).

The larger the home is the more air available to sustain and grow a fire in that home. Additionally, the larger the home the greater the potential to have a larger fire, and the greater the potential hazard to the responding fire service resources if the proper tactics aren't utilized. While the average home size has increased 56%,

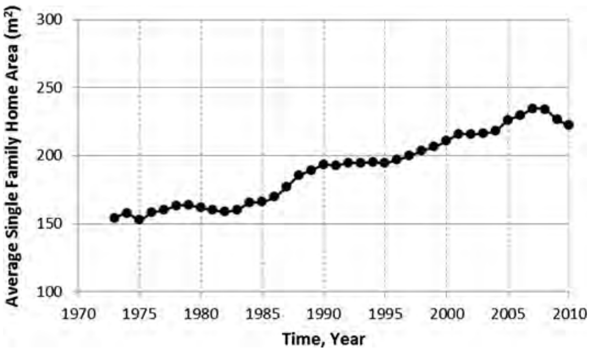

Figure 2. Average area of new single-family homes from 1973 to 2008 [7].

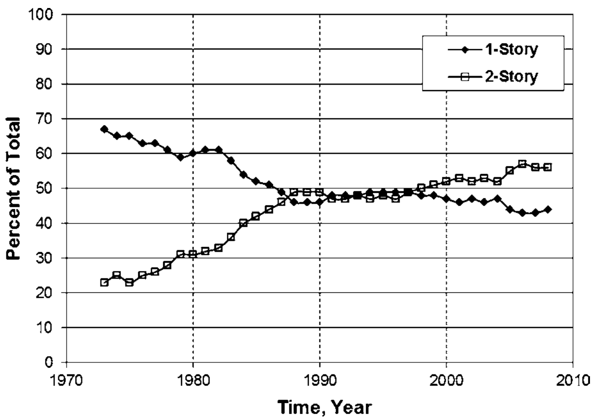

Figure 3. Percentage of number of stories of single family homes [7].

the fire service resources available to respond have not increased proportionally in many areas of the United States. This is emphasized in suburban areas where larger homes are being built but fewer fire service resources are available [8].

The increase in the number of homes with a second story means a potential for more volume above the fire which allows the smoke layer to remain above the fire and allows a longer time for the fire to grow. It also means more above ground areas for the fire service to access for civilian rescue and egress, potentially increasing the chance of injury.

2.2. Home Geometry

Newer homes tend to incorporate features such as taller ceilings, open floor plans, two-story foyers and great rooms [9]. All of these features remove compartmentation, add volume and can contribute to rapid smoke and fire spread. Commercial building codes require fire and smoke separations to limit the impact of the fire on occupants, there are minimal codes requiring compartmentation in single family homes [10].

A trend in new homes is to incorporate taller ceilings and two-story spaces or great rooms [11]. Much like the impact of having a two-story home, taller ceilings create a longer smoke filling time that allow for more oxygen to be available to the fire for it to grow before being surrounded by smoke filled, oxygen deficient air. The heat release rate of a fire slows down significantly once the oxygen content of the air decreases. Newer homes are being constructed with ceilings taller than the traditional 2.4 m, upwards of 4.3 m to 6.1 m [9]. It is also common for great rooms and open foyers to directly connect the living spaces to the sleeping spaces allowing for smoke generated in the living spaces to rapidly trap potential sleeping occupants.

Another trend in homes is to remove walls to open up the floor plan of the home [12]. As these walls are removed the compartmentation is lessened allowing for easier smoke and fire communication to much of the home. In the living spaces doors are often replaced with open archways creating large open spaces where there were traditionally individual rooms.

Combining of rooms and taller ceiling heights creates large volume spaces which when involved in a fire require more water and resources to extinguish. These fires are more difficult to contain because of the lack of compartmentation. Water from a hose stream becomes increasingly more effective when steam conversion assists in extinguishment, without compartmentation this effect is reduced. The simple tactic of closing a door to confine a fire is no longer possible in newer home geometries.

2.3. Home Contents

The challenge of rapid fire spread is exacerbated by the use of building contents that have changed significantly in recent years, contributing to the decrease in time to untenable (life threatening) conditions. Changes include: (a) the increased use of more flammable synthetic materials such as plastics and textiles, (b) the increased quantity of combustible materials and (c) the use of goods with unknown composition and uncertain flammability behavior.

Over time home contents have transitioned from being compromised of natural materials to dominated by synthetic materials [13, 14]. Synthetic materials such as polyurethane foam have replaced cotton as the padding found in upholstered furniture. Today more than 95 million kilograms of flexible polyurethane foam are produced in the US, enough to make 140 million sofas [15]. This difference was examined in the early 1980s when oxygen consumption calorimetry was utilized to measure the heat release rate of furniture. A study led by Babrauskas [16] compared different constructions of upholstered chairs. The cotton padded chair covered in cotton fabric produced a peak heat release rate of 370 kW at 910 s after ignition. The foam padded chair covered in polyolefin fabric produced a peak heat release of 1,990 kW at 260 s after ignition. Both chairs had a very similar total heat released 425 MJ for the natural chair and 419 MJ for the synthetic chair.

2.4. Home Construction Materials

Another change that has taken place over the last several decades is the continual introduction of new construction materials into homes [17]. The construction industry is continually introducing new engineered products that provide better structural stability, allow for faster construction time and are more cost effective. Additionally, the market for green or environmentally sustainable building materials experienced a growth rate of 23% through 2006 and is expected to continue growing at a rate of 17% through 2011 according to Green Building Materials in the US [18]. The increased market demand for environmentally sustainable products is driving engineered lumber products to further reduce material mass that could potentially result in even further concern for fire safety in building construction today and in the future. Environmentally sustainable products take into account resource efficiency, indoor air quality, energy efficiency, water conservation and affordability [19]. Life and fire safety are not part of the material selection criteria, while using less material and being more affordable are.

Many home construction materials have changed significantly for numerous reasons such as lack of supply, ease of manufacturing, cost, improved structural or energy efficiency performance, and many other reasons [20]. Home wall linings, structural components, windows and doors are some of the construction materials that have evolved. Table 1 shows some iterations of the evolution.

Table 1
Construction Material Evolutions

Construction material	Legacy $\rightarrow$ Modern			
Wall linings	Plaster and lath		Gypsum Board	
Structural components	Old growth lumber	New growth lumber	Wood trusses	Engineered I-joists
Windows	Single Glazed (Wood framed)		Double glazed (Vinyl Framed)	
Interior doors	Solid core	Hollow core	Composite hollow core	

Evolutions in building materials create changes in the fire environment. How all of these changes compound to impact fire behavior and firefighting tactics is not well understood.

3. Experimental Series

Experiments were conducted to examine the changes in contents and construction materials. Six room fire experiments examined the difference between modern and legacy living room furnishings. Furnace experiments were conducted to quantify changes in wall linings, structural components, windows and interior doors.

3.1. Comparison of Modern and Legacy Room Furnishings Experiments

Six fire experiments were conducted to examine the changes in fire development in a room with modern contents versus a room with contents that may have been found in a mid-twentieth century house. The modern rooms utilized synthetic contents that were readily available new at various retail outlets, and the legacy rooms utilized contents that were purchased used from a number of second hand outlets.

3.1.1. Experimental Description. The experiments were conducted in three pairs of living room fires (Table 2). The purpose was to develop comparative data on modern and legacy furnishings. The first four rooms measured 3.7 m by 3.7 m, with a 2.4 m ceiling and had a 2.4 m wide by 2.1 m tall opening on the front wall. The last two rooms measured 4.0 m by 5.5 m, with an 2.4 m ceiling and had a 3.0 m wide by 2.1 m tall opening on the front wall. All sets of rooms contained similar types and amounts of like furnishings. Weight measurements were not taken for the first set of experiments. However, in the second and third set of rooms, all furnishings were weighed before being placed in the rooms. In the second set of rooms the modern room had a fuel loading of 19.0 kg/m^2 while the legacy room had a fuel loading of 22.9 kg/m^2. The difference was due to the legacy sofa and chair weighing 47% and 31% more than the modern furniture. In the third set of rooms, both the modern room and legacy room had a fuel loading of approximately 11.2 kg/m^2. A similar amount of fuel was in both sets of room

Table 2
Experimental Overview

Experiment	Description	Room dimensions (m)	Front opening dimensions (m)	Fuel loading (kg/m^2)
1	Modern	3.7 × 3.7 × 2.4	2.4 × 2.1	NA
2	Legacy	3.7 × 3.7 × 2.4	2.4 × 2.1	NA
3	Modern	3.7 × 3.7 × 2.4	2.4 × 2.1	19.0
4	Legacy	3.7 × 3.7 × 2.4	2.4 × 2.1	22.9
5	Modern	4.0 × 5.5 × 2.4	3.0 × 2.1	11.2
6	Legacy	4.0 × 5.5 × 2.4	3.0 × 2.1	11.2

Figure 4. Experiment 1 setup.

experiments however the third set of rooms was 8.4 m^2 larger. Each experiment was ignited using a candle placed onto the sofa. An array of 0.8 mm gage Inconel thermocouples was located in each room with measurement locations of every 0.3 m from floor to ceiling. Temperatures were sampled and recorded every 1 s.

The first set of rooms was 3.7 m by 3.7 m. The modern room (Experiment 1) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with carpet and padding (Figure 4). The furnishings included a polyester microfiber covered polyurethane foam filled sectional sofa, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its right side. The end table had a lamp with polyester shade on top of it and a wicker basket on its lower shelf. The coffee table had six color magazines, a television remote and a synthetic plant on it. The television stand had a color magazine and a 37 inch flat panel television. The book case had two small plastic bins, two picture frames and two glass vases on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 5).

The legacy room (Experiment 2) was lined with a layer of 12.7 mm painted cement board and the floor was covered with unfinished hardwood flooring (Figure 6). The furnishings included a cotton covered, cotton batting filled sectional sofa, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its right side. Both end tables had a lamp with polyester shade on top of them. The one on the left side of the sofa had two paperback books on it. A wicker basket was located on the floor in front of the right side of the sofa at the floor level. The coffee table had three hard-covered books, a television remote and a synthetic plant on it. The television stand had a 27 inch tube television. The right front corner of the room had a wood toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 7).

The second set of rooms was also 3.7 m by 3.7 m with a 2.4 m ceiling and a 2.4 m wide by 2.1 m tall opening on the front wall. Both rooms contained identical furnishings with the exception of the sofa and the chair. The first room (Experiment 3) had a polyurethane foam filled sofa and chair with microfiber

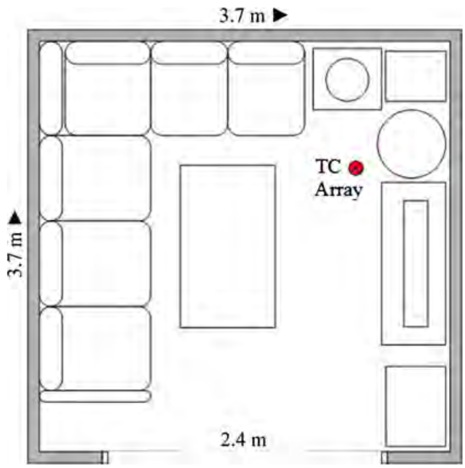

Figure 5. Experiment 1 furniture layout.

Figure 6. Experiment 2 setup.

fabric covering (Figures 8, 10). The second room (Experiment 4) had a cotton padded, innerspring sofa and chair with cotton cover fabric (Figures 9, 11). The contents were similar to those used in the first modern room. The floors were covered in polyester carpet over polyurethane foam padding. The contents included an engineered wood coffee table, two end tables, television stand and book case. The sofa had a polyester throw placed on its left side. The left end table had a lamp with polyester shade on top of it and the right end table had a television remote, candle and vase filled with synthetic rose pedals. The coffee table had four color magazines and a synthetic plant on it. The television stand had a 37 inch flat panel television. The book case had two baskets and a picture frame on it. The left side of the room had a plastic toy bin, a plastic toy tub and four stuffed

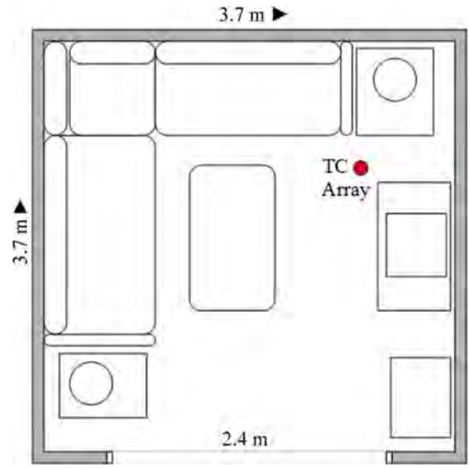

Figure 7. Experiment 2 furniture layout.

Figure 8. Experiment 3 setup.

toys. The rear wall had polyester curtains hanging from a metal rod and the left side walls had a wood framed picture hung on it.

The third set of rooms was larger and measured 4.0 m by 5.5 m. The modern room (Experiment 5) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with nylon carpet and polyurethane padding (Figure 12). The furnishings included a polyester microfiber covered polyurethane foam filled sofa, two matching chairs, engineered wood coffee table, end table, television stand and book case. The sofa had a polyester throw placed on its left side and two polyfill pillows, one on each side. The end table had a lamp with polyester shade on top of it. The coffee table had three color magazines, a wicker basket and a synthetic plant on it. The television stand had two picture frames

Figure 9. Experiment 4 setup.

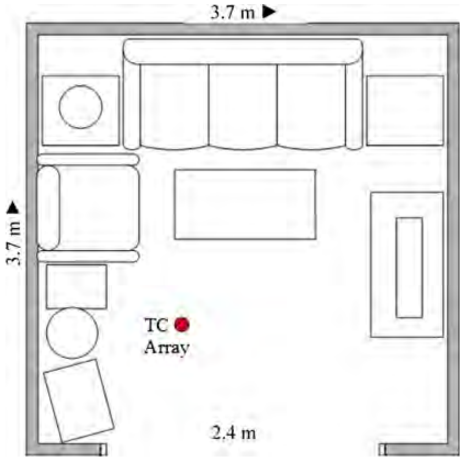

Figure 10. Experiment 3 furniture layout.

and a 32 inch flat panel television. The book case had a plastic basket on it. The right rear corner of the room had a plastic toy bin, a plastic toy tub and four stuffed toys. The rear wall had polyester curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 13).

The legacy room (Experiment 6) was lined with a layer of 12.7 mm painted gypsum board and the floor was covered with finished hardwood flooring (Figure 14). The furnishings included a cotton covered, cotton batting filled sofa, two matching chairs, solid wood coffee table, two end tables, and television stand. The sofa had a cotton throw placed on its left side. Both end tables had a lamp with glass shade on top of them and a wicker basket. The coffee table had a wicker basket filled with five books and two glass vases. The television stand had a 13 in

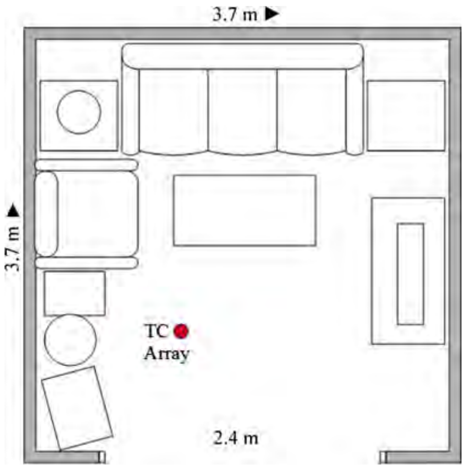

Figure 11. Experiment 4 furniture layout.

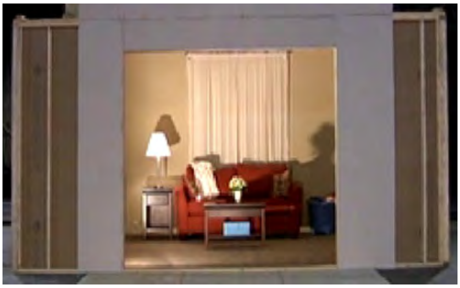

Figure 12. Experiment 5 setup.

tube television with a plant on top of it. The right rear corner of the room had a wood/wicker toy bin, and multiple wood toys. The rear wall had cotton curtains hanging from a metal rod and the side walls had wood framed pictures hung on them (Figure 15).

3.1.2. Results. The fire in Experiment 1 grew slowly for the first minute as the candle flame extended to the polyester throw blanket and sofa cushion. At 2 min the fire had spread to the back cushion of the sofa and a black smoke layer developed in the top two to three feet of the room. At 3 min approximately one half of the sofa was involved in the fire, the carpet had begun to burn and the hot gas layer was thickening and flowed out of the top third of the room opening. The modern room transitioned to flashover in 3 min and 40 s (Figure 16). Time to

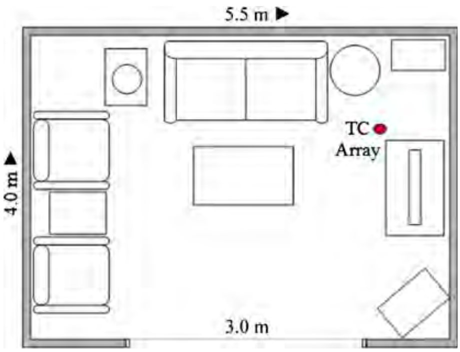

Figure 13. Experiment 5 furniture layout.

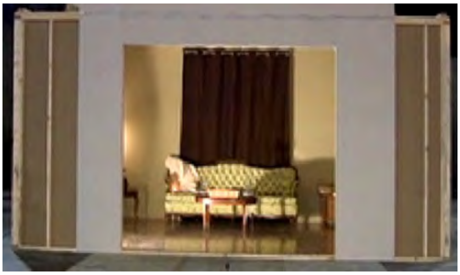

Figure 14. Experiment 6 setup.

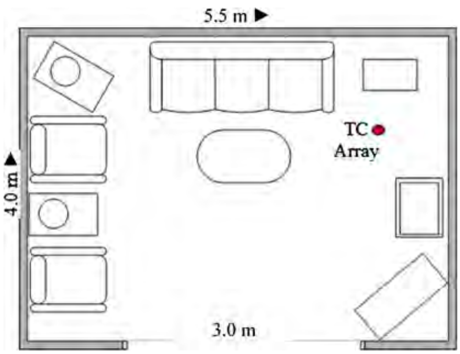

Figure 15. Experiment 6 furniture layout.

flashover was indicated by ignition of the flooring just inside the opening of the room as a result of the heat flux from the flames coming out of the top of the opening.

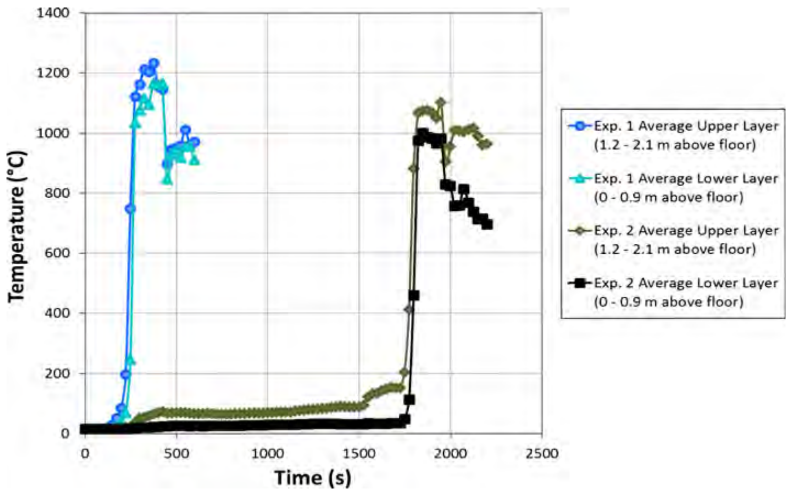

Figure 16. Experiment 1 and 2 room temperatures.

The fire in Experiment 2 also grew slowly in the first minute as the candle flame spread to the cotton throw blanket and sofa cushion. At 5 min the fire involved the arm of the sofa and extended to the curtains behind the sofa. At 10 min the fire had spread to approximately one-third of the sofa. From 10 min to 20 min the fire continued to spread across the sofa and began to develop a hot gas layer in the room. The legacy room transitioned to flashover at 29 min and 30 s after ignition (Figure 16).

Experiment 3 was ignited on the right hand corner of the sofa where the arm, seat and back joined. The fire involved the right 1/3 of the sofa at 3 min and 45 s. The fire spread to the television stand at 4 min and the left arm of the sofa ignited from radiant energy from the gas layer at 4 min and 16 s. Flames began to come out of the top of the front opening at 4 min and 20 s and flashover occurred at 4 min and 45 s. Room temperature was measured with a thermocouple array placed 0.9 m inside the opening and 1.5 m from the left wall (Figure 17). Flashover was observed at 285 s after ignition.

Experiment 4 was also ignited on the right hand corner of the sofa. At 5 min after ignition the fire was still in the corner where it was ignited. By 10 min the fire involved 2/3 of the right arm of the sofa and back cushion and only ¼ of the right seat cushion. At 20 min the fire spread to the second back and seat cushions, and the flames were burning behind the seat cushion and extending 0.3 m above the back of the sofa. The end table and television stand became involved in the fire 30 min after ignition. The room transitioned to flashover at 34 min and 15 s after ignition (Figure 17).

Heat release rate was also measured during Experiments 3 and 4 utilizing an oxygen consumption calorimeter. Figure 18 shows Experiment 3 peaked at approximately

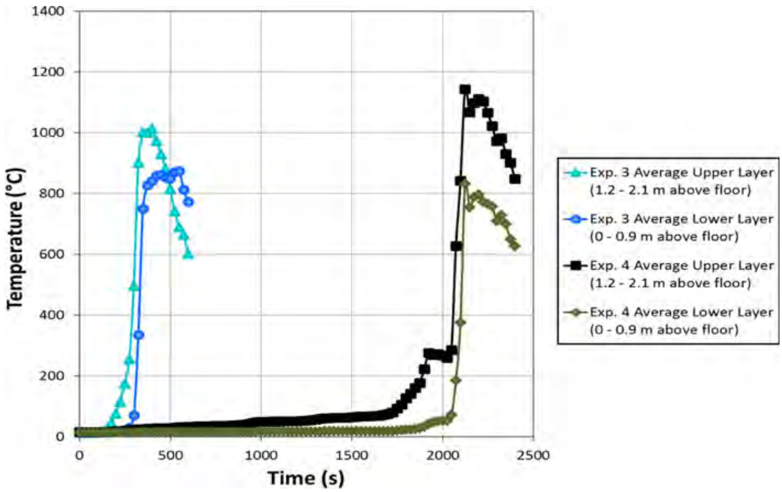

Figure 17. Experiment 3 and 4 room temperatures.

7.5 MW at 450 s after ignition, while Experiment 4 peaked at approximately 6 MW at 2,200 s after ignition. Both experiments released approximately the same amount of energy over the duration of the experiments. Experiment 3 released 3.2 MJ and Experiment 4 released 3.5 MJ.

Experiment 5 was ignited and the fire spread to the sofa cushion and pillow by the 1 min mark. By 2 min the fire involved approximately one-third of the top of the sofa and spread to the lamp shade. At 3 min the top of the entire sofa was on fire and the carpet began to burn adjacent to the sofa. The modern room transitioned to flashover in 3 min and 20 s (Figure 19).

Experiment 6 was also ignited on the left side and it spread to the throw blanket and sofa cushion by 1 min. By 5 min the fire involved the left side of the sofa and spread to the curtains burning the left panel away. At 10 min the entire surface of the sofa was burning and by 15 min the fire involved the entire sofa including the underside. The flames reached the ceiling but did not extend to the adjacent furnishings. The fire burned down and never transitioned to flashover so it was extinguished at 30 min after ignition (Figure 19).

3.2. New Construction Materials

3.2.1. Wall Linings. UL conducted a series of floor furnace experiments to examine modern and legacy construction practices [21]. Two of the experiments compared a dimensional lumber floor system with different protective linings. The first was lined with 12.7 mm unrated gypsum board that is used in most homes. The second was lined with a plaster and lath lining. Both assemblies were identical with the exception of the lining and had the same loading and bearing conditions.

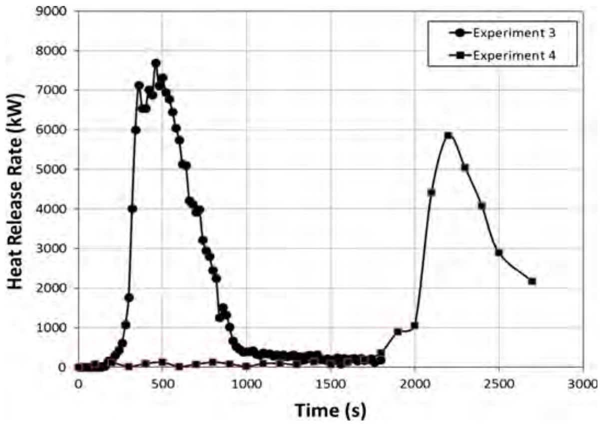

Figure 18. Experiment 3 and 4 heat release rate comparison.

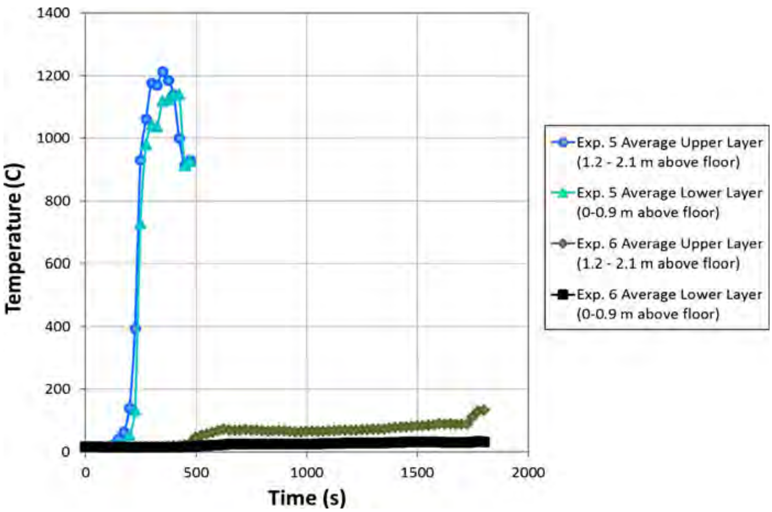

Figure 19. Experiment 5 and 6 room temperatures.

The gypsum board protected assembly exceeded the deflection criteria of L/240 at 35 min and 30 s after ignition and the plaster and lath protected assembly exceeded the same criteria at 75 min and 45 s. The gypsum board protective membrane was breached at 23 min and 30 s while the plaster and lath was breached at approximately 74 min.

In many other experiments conducted at UL that utilize gypsum wallboard to line walls for room fire experiments like those described in Section 4 it is observed that the gypsum wallboard fails at the seams. As drywall compound is heated it dries and falls out exposing a gap for heat to enter the wall space and ignite the paper on the back of the wallboard and the wood studs used to construct the walls. Gypsum wallboard also shrinks when heated to allow gaps around the edges of the wallboard. Plaster and lath does not have the seams that wallboard has and therefore does not allow for heat penetration as early in the fire. This change in lining material allows for easier transition from content fire to structure fire as the fire has a path into void spaces.

3.2.2. Structural Components. Engineered floor products provide financial and structural benefits to building construction; however, adequate fire performance needs to be addressed as well. Statistics from 2005 [22] highlight the amount of lightweight construction materials that are on the market. According to the National Association of Home Builders, 46% of single family home floor systems are being built with engineered I joists, 15% with wood trusses and 39% with lumber joists. Adequate fire performance provides a necessary level of safety for building occupants and emergency responders responsible for mitigating fire incidents. Previous research by various organizations, including UL, NIST [23, 24], NFPA [25] and National Research Council Canada [26], provided evidence of the greater risk in structural failure of engineered floor systems in fire events.

In 2008, UL conducted a series of experiments on a standard floor furnace [21], exposing unprotected wood floor systems to the standard time temperature curve (Table 3). Loading consisted of 195.3 kg/m^2 along two edges of the floor to simulate the load from furniture and two 136 kg mannequins that simulated firefighters in the center of the floor. Two unprotected floor systems compared a modern/lightweight floor system compromised of 0.3 m deep engineered wood I joists to a legacy/dimensional lumber 2 by 10 floor system. The engineered I joist floor collapsed in 6 min while the dimensional lumber collapsed in 18 min and 35 s. In the same study two truss floors were tested with a protective layer of 12.7 mm gypsum wallboard, one test had metal gusset plated trusses and the other had

Table 3
UL Study Experiment Description and Collapse Times [21]

Structural element	Type	Ceiling	Allowable deflection L/240 (min:sec)	Fire fighter breach (min:sec)
2 × 10 joist Floor	Legacy	None	3:30	18:35
Wood I joist Floor	Modern	None	3:15	6:00
2 × 10 joist Floor	Legacy	Lath and plaster	75:45	79
2 × 10 joist Floor	Legacy	Gypsum wallboard	35:30	44:40
Wood I joist floor	Modern	Gypsum wallboard	3:30	26:43
Metal gusset truss floor	Modern	Gypsum wallboard	20:45	29
Finger joint truss floor	Modern	Gypsum wallboard	24:00	26:30

finger jointed trusses. They both failed in less than 30 min as compared to the dimensional lumber test with the same protection of 12.7 mm gypsum wallboard, which failed in approximately 45 min.

This study clearly highlights the inferior structural performance of lightweight structural components under fire conditions. Engineered wood floor assemblies have the potential to collapse very quickly under well ventilated fire conditions. When it comes to lightweight construction there is no margin of safety. There is less wood to burn and therefore potentially less time to collapse. The results of tests comparing the fire performance of conventional and modern construction will improve the understanding of the hazards of lightweight construction and assist incident commanders, company officers and fire fighters in evaluating the fire hazards present during a given incident, and allow a more informed risk–benefit analysis when assessing life safety risks to building occupants and fire fighters.

3.2.3. Windows. With increased fuel loads in houses the amount of air available to allow a fire to grow has become the limiting factor and therefore very important. How long it takes for a residential window to fail has not been extensively examined. Most of the previous research has dealt with commercial windows or windows impacted by wildland fires [27]. The object of this series of experiments [28] was to evaluate the reaction to fire of six different window assemblies, by means of fire endurance experiments with the furnace temperatures controlled in accordance with the time–temperature curve presented in the Standard, ‘‘Fire Tests of Window Assemblies,’’ UL 9, 8th Edition dated July 2, 2009 [29].

Fire performance experiments were conducted to identify and quantify the self-ventilation performance of windows, comparing legacy to modern, in a fire event prior to fire service arrival (Figure 20). Different window construction parameters assessed include: (1) wood frame and vinyl frame construction; (2) single and multi-pane designs and (3) single and multi-glazed designs. Modern windows are defined as windows that are able to be easily purchased new and that are typically

Figure 20. Window experimental setup.

Table 4
Window Experiment Sample Descriptions

Designation	Description	Type	Size width (m) × height (m)/ glass thickness (mm)
A	Wooden frame, two pane, single glazed, storm	Legacy	0.8 × 1.2/2.4
B	Vinyl clad wood frame, two pane, double glazed	Modern	0.8 × 1.4/2.2
C	Wood/metal frame/nine pane over one pane, single glazed	Legacy	0.7 × 1.5/2.9
D	Premium plastic frame, two pane, double glazed	Modern	0.7 × 1.4/2.2
E	Plastic frame, two pane, double glazed	Modern	0.7 × 1.4/2.2
F	Premium wooden frame, two pane, double glazed	Modern	0.7 × 1.4/2.3

found in houses constructed after the year 2000. The legacy windows used in these experiments were purchased used and are meant to be representative of windows that would be found on houses built between the years 1950 and 1970 (Table 4).

There were a number of different window failure mechanisms and degrees of failure observed during the experiments. In order to have an impact on the fire growth there has to be a passage for air to enter the structure, therefore the failure of interest was the breaking out of the glass as opposed to the cracking of the glass. Failure is defined as a passage through the window of 25% or more of the total glass area. In most cases this was the failure of the top or bottom pane(s) of the window but in some cases the top window sash moved downward, opening the window 25% or more. The two legacy windows with single glazing failed later than the four modern windows with double glazing (Figure 21). The two legacy windows failed at 577 s and 846 s respectively while the modern windows failed at 259 s, 254 s, 312 s, and 270 s respectively (Table 5).

Figure 21. Windows after the experiment (middle window was modern).

Table 5
Window Failure Times

	Window [mm:ss (sec)]					
Experiment	A (L)	B (M)	C (L)	D (M)	E (M)	F (M)
1	6:34 (394)	4:24 (264)	11:49 (709)	3:58 (238)	5:16 (316)	3:39 (219)
2	10:06 (606)	4:38 (278)	14:30 (870)	3:39 (219)	4:26 (266)	5:49 (349)
3	12:11 (731)	3:56 (236)	16:00 (960)	5:05 (305)	5:55 (355)	4:02 (242)
Average	9:37 (577)	4:19 (259)	14:06 (846)	4:14 (254)	5:12 (312)	4:30 (270)

These experiments demonstrated a significant difference in legacy and modern windows exposed to fire conditions. In this series of experiments the legacy single glazed windows outperformed the modern double glazed windows in terms of longer failure times. It is proposed that this occurred for two reasons. First the legacy windows had thicker glazing than the modern windows. The legacy windows had glass thicknesses of 2.4 mm and 2.8 mm, while the modern window thicknesses were 2.2 mm. Second, the method the glass was fixed into the frame differed greatly between the two eras. The legacy window glass was held in place with putty like substance and there was room in the frame for expansion of the glass. The modern glass was fixed very tightly into the frame with an air tight gasket and metal band, to provide better thermal insulation. This configuration did not allow for much expansion and therefore stressed the glass as it heated and expanded.

3.2.4. Interior Doors. Much like structural components, doors have been changed from a solid slab of wood to an engineered approach where doors are made hollow to use less material. To examine the impact of this change on fire resiliency three different interior door designs were exposed to the panel furnace following the temperature curve specified in "Positive Pressure Fire Tests of Door Assemblies," UL 10C, 2nd Edition dated January 26, 2009 [30]. Different door construction parameters assessed include: (1) Hollow and solid core construction; and (2) different wood types (Figure 22).

There was only one door failure experiment conducted and the failure times are shown in Table 6. Failure was defined to have occurred when the unexposed surface of the door sustained burning. All of the doors failed at approximately 300 s (Table 6). There was very little difference between the two hollow core doors (1 and 2). The fire ignited the unexposed side and quickly consumed what was left of the door. The solid core door (3) had a similar failure time but the mechanism was different. Door 3 burned through at the panels because of their reduced thickness. The thicker portions of the door remained intact at the termination of the experiment (Figure 23). This experiment shows the fire containment ability of interior doors during a well-ventilated compartment fire is approximately 5 min. For the doors evaluated in this experiment it can also be concluded that the type of wood had no noticeable impact on failure time.

Figure 22. Door samples prior to testing.

Table 6
Door Failure Times

	Door		
Experiment	Hollow Oak	Hollow Composite	Solid 6-panel
7	5:12 (312)	5:15 (315)	5:02 (302)

Figure 23. Door samples after the test.

The doors evaluated in this experiment demonstrated that the type of wood had no noticeable impact on failure time. The failure time was dictated by the thickness of the door. The hollow core doors had the same overall wood thickness as the panels of the solid core door and therefore the fire breached them at very similar times. Without the panels cut into the solid core door it would have lasted substantially longer as indicated by the amount of wood remaining in the post test analysis of the door.

3.3. Impact on Firefighting Operational Timeframes

The most significant impact of the changing residential fire environment on firefighting tactics is the dramatic shift of the safe operational timeline for the fire service. The operational timeframe for the fire service begins with their arrival on scene and ends when the fire is placed under control (Figure 24). To compare the modern and legacy fire environment it is important to examine the time prior to fire department arrival.

The time t_1, depends upon a number of factors such as when the fire is detected after initiation, and the time to call for fire service assistance. This time can vary greatly depending on the source of ignition, item ignited, presence of occupants, presence of fire protection devices and many other factors.

The time t_2, is the time for the 911 operator to call the appropriate fire station to respond. The US national standard NFPA 1221 [31] define the maximum value for t_2 as 60 s.

The time t_3 is the time it takes for the firefighters to get onto the fire apparatus and respond. As per NFPA 1710 [32] this equals 60 s to begin the response.

The time t_4 is the time it takes for the firefighters to drive to the scene of the fire. Following NFPA 1710, the goal for fire emergency response is to arrive at the scene within 4 min after the 911 call is made. That is, $t_2 + t_3 + t_4 \leq 6$ min. Following NFPA 1720 [33], the goal for fire emergency response is to arrive at the scene within 9 min in an urban area (~384 people/km^2), 10 min in a suburban area (192 people/km^2 to 384 people/km^2), 14 min in a rural area (~192 people/km^2) and directly related to driving distance for remote areas greater than 8 miles from the closest fire station. Therefore $t_2 + t_3 + t_4 \leq 11$ min to 16 min.

Analyzing the National Fire Incident Reporting System (NFIRS) database yields a very consistent average fire department response time to one and two family detached homes (Occupancy Code 419 in NFIRS) in the United States. Table 7 shows an average response time ($t_2 + t_3 + t_4$) of approximately 6.4 min from 2006 to 2009.

Some international comparisons of fire department response times are available. In 2006, the average response time to dwelling fires in England was 6.5 min [34]. A report comparing residential fire safety in several countries states, "Response time goals in Sweden and Norway are more lenient than in the United States. The Scandinavian nations require the first responding unit to arrive in 10 min, versus a

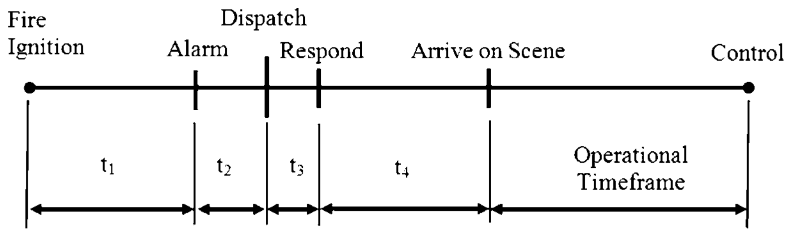

Figure 24. Fire service timeline.

Table 7
Average Fire Department Response Times

Year	Incident count	Average response time
2006	42,584	6.2
2007	49,664	6.5
2008	50,775	6.6
2009	49,386	6.4

Note: Fires in homes >$10,000 in value with >$1 in loss

goal of 6 min in the typical United States city. Scandinavia generally gives more weight to prevention and early extinguishment by homeowners, less to rapid response'' [35]. A report written by a German Fire Officer in 2004 examined response times in Europe by contacting country officials and asking them questions about their acceptable response times and conducting an internet search. Many countries such as Denmark, France, Greece, Ireland, Norway and Sweden had acceptable urban response times of 10 min and response times to suburban or rural areas of 15 min to 30 min [36].

Conservatively assuming the fire is noticed quickly and the fire department is called quickly t_1 could be 2 min. Using the average response time for the US fire service, the operational timeframe would begin at 10 min (Figure 25).

To compare modern and legacy fires as they pertain to the operation timeframe, times to flashover can be added to the respective times to collapse. Times to flashover were taken from the room fire experiments in Section 4. The modern room flashed over in 3:30 to 4:45 and the legacy room flashed over in 29:30 to 34:15. The unprotected modern floor system (Engineered Wood I joist) collapsed in 6:00 (Table 3), and adding a layer of gypsum board increased the collapse time to 26:43. The unprotected legacy floor system (Dimensional Lumber 2 by 10) collapsed in 18:35, and adding a layer of plaster and lath increased the collapse time to 79:00 (Figure 26).

4. Discussion

There has been a steady change in the residential fire environment over the past several decades. These changes include larger homes, more open floor plans and

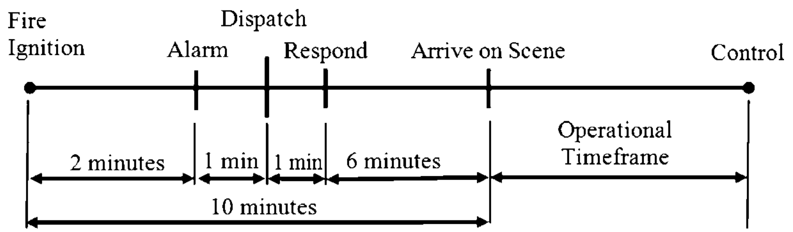

Figure 25. Fire service timeline example.

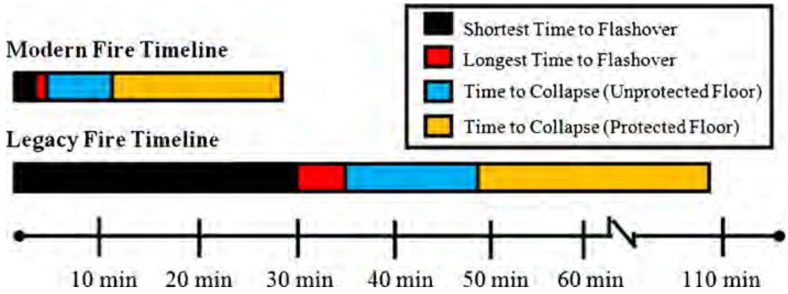

Figure 26. Modern versus legacy fire timelines.

volumes, increased synthetic fuel loads and new construction materials. The larger the home is the more air available to sustain and grow a fire in that home. Additionally, the larger the home the greater the potential to have a larger fire, and the greater the potential hazard to the responding fire service resources.

Combining of rooms and taller ceiling heights creates large volume spaces which when involved in a fire require more water and resources to extinguish. These fires are more difficult to contain. This also means shorter escape times for occupants as the egress routes may be compromised earlier due to lack of compartmentation.

Comparing the experiments, times to flashover are very similar between the three modern experiments and the three legacy experiments (Table 8). All of the modern rooms transitioned to flashover in less than 5 min while the fastest legacy room to achieve flashover did so at in over 29 min. In these three sets of experiments legacy furnished rooms took at least 700% longer to reach flashover.

Even though the third modern room was 8.4 m^2 larger and had a 1.3 m^2 larger front opening a similar fuel load was able to flash the room over in the same time. The 4.0 m by 5.5 m legacy experiment did not transition to flashover because it did not have enough fuel burning at the same time to create significant heat in the upper gas layer to ignite items that were not adjacent to the sofa. The chairs on the left side of the room and the television and bookcase of the right side of the room were never heated to their ignition temperatures.

The modern rooms and the legacy rooms demonstrated very different fire behavior. It was very clear that the natural materials in the legacy room released energy slower than the fast burning synthetic furnished modern room. The times

Table 8
Comparison of Flashover Times

Experiments	Modern	Legacy
1, 2	3:40	29:30
3, 4	4:45	34:15
5, 6	3:20	Not achieved

to flashover show that the a flaming fire in a room with modern furnishings leaves significantly less time for occupants to escape the fire. It also demonstrates to the fire service that in most cases the fire has either transitioned to flashover prior to their arrival or became ventilation limited and is waiting for a ventilation opening to increase in burning rate. This difference has a substantial impact on occupant and firefighter safety. This change leads to faster fire propagation, shorter time to flashover, rapid changes in fire dynamics, and shorter escape times.

Four examples of new construction materials were examined; wall linings, structural components, windows and interior doors. The change in wall linings now allows for more content fires to become structure fires by penetrating the wall lining and involving the void spaces. This change allows for faster fire propagation and shorter times to collapse. The changes in structural components have removed the mass of the components which allows them to collapse significantly earlier. In these experiments an engineered I joist floor system collapsed in less than 1/3 the time that the dimensional lumber floor system collapsed. Modern windows and interior doors fail faster than their legacy counterparts. The windows failed in half the time and the doors failed in approximately 5 min. If a fire in a closed room is able to get air to burn from a failed window, then it can burn through a door and extend to the rest of the house. This can lead to faster fire propagation, rapid changes in fire dynamics and shorter escape times for occupants as well as firefighters.

Using the conservative value of 10 min as the start of the operational timeframe and comparing it to the modern and legacy fire timelines shows the hazard that the modern fire environment poses to firefighters. It also highlights that the operational timeframe begins after potential flashover. In many cases this means that if sufficient ventilation is available the fire will spread significantly prior to fire service arrival. If sufficient ventilation is not available the fire will become ventilation limited and be very sensitive to initial fire service operations. The potential for fast fire propagation, and rapidly changing fire conditions should be expected in the modern fire environment while arriving at 8 min to a legacy fire, it would still be in the growth stage and less volatile.

Looking beyond fire development and to collapse further hazards are highlighted. In the modern fire environment, after arriving at 8 min, collapse is possible as soon as 1:30 later. Firefighters may not be in the house yet or may be just entering to search for occupants. The legacy fire collapse hazard begins 40 min after arrival of firefighters. This allows for a significant amount of fire operations to take place all while reading the safety of the structure. Figure 27 shows the standard response times for different types of fire departments and the location on the fire development timeline that they arrive in both the modern and legacy fires.

The conditions that firefighters are going to be faced with today and into the future have been significantly impacted by the ever changing fire environment. As society continues to make changes to building materials as a result of the desire to be environmentally conscience and to increase profit the fire environment is going to continue to change and if the current trends continue it will not be in favor of firefighter safety. Therefore it is important that firefighters study this new fire environment and its impact on their safety and tactics. The first component of this is

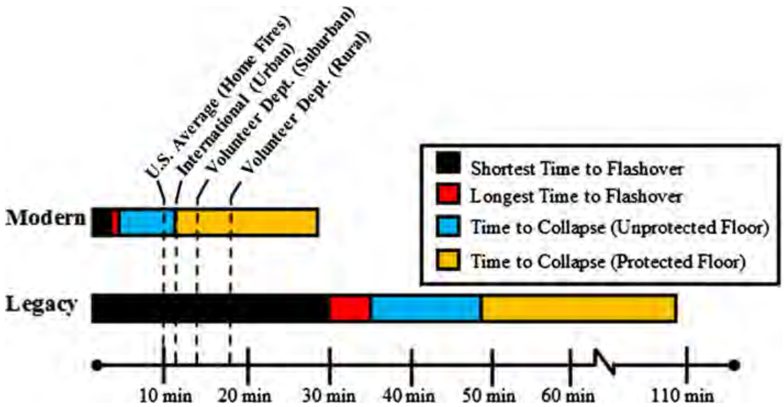

Figure 27. Fire service arrival times versus fire development.

understanding the conditions they are arriving to are very different than several generations ago. Fire conditions can change rapidly due to the under ventilated fire conditions and floor systems can collapse quickly and with little warning. While operating conditions need to be constantly monitored to understand the impact of the tactics used and the potential need to change them. Ultimately, if the fire environment has changed tactics need to change or be reevaluated to have the greatest opportunity to be most effective on today's fires.

5. Suggestions for Future Research

Research should be conducted to examine the impact of changing fuel loads in full-scale structures especially how it pertains to fire service operations. The impact of ventilation is key to this fire development as well. Experiments need to focus on fire department tactics to make sure that they are still relevant with this evolving fire environment.

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A.2 Paper II: Analysis of One and Two-Story Single Family Home Fire Dynamics and the Impact of Firefighter Horizontal Ventilation

Fire Technology

DOI: 10.1007/s10694-012-0294-5

Analysis of One and Two-Story Single Family Home Fire Dynamics and the Impact of Firefighter Horizontal Ventilation

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Received: 25 March 2012/**Accepted:** 16 August 2012

Abstract. This paper describes experimental investigations on fire service ventilation practices in modern house geometries. Two houses were constructed inside a large fire facility. The first of two houses constructed was a one-story, 111.5 m^2, 3 bedroom, 1 bathroom house with 8 total rooms. The second house was a two-story 297.3 m^2, 4 bedroom, 2.5 bathroom house with 12 total rooms. The second house featured a modern open floor plan, two-story great room and open foyer. Fifteen experiments were conducted varying the ventilation locations and the number of ventilation openings. Ventilation scenarios included ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only and ventilating a higher opening in the two-story house. One scenario in each house was conducted in triplicate to examine repeatability. The results of these experiments examine potential occupant tenability and provide knowledge for the fire service for them to examine their horizontal ventilation standard operating procedures and training content. The fire dynamics resulting from ventilation practices such as ventilation near or remote from the seat of the fire and high versus low in relation to the fire are examined. Several other tactical considerations were developed utilizing the data from these experiments to provide specific examples of changes that can be adopted based on a departments current strategies and tactics. Such tactical considerations and a systems approach to fire service tactics should be investigated further.

Keywords: Fire behavior, Ventilation, Firefighting, Tenability, Tactics

1. Introduction

Ventilation is frequently used as a firefighting tactic to control and fight fires. In firefighting, ventilation refers to the process of creating an opening so that heat and smoke will be released, permitting the firefighters to locate and attack the fire. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. However, poorly placed or timed ventilation may increase the air supply to the fire, causing it to rapidly grow and spread [1].

When ventilation is increased, either through tactical action of firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window)

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Published online: 29 August 2012

or human action (e.g., door opened), heat release will increase, potentially resulting in flashover conditions. These changing fire conditions are sometimes unexpectedly swift, providing little time for firefighters to react and respond. The changing dynamics of residential fires as a result of the changes in construction materials, building contents, and building size and geometry over the past 50 years add complexity to the influence of ventilation on fire behavior [2].

Traditional fire service training does not effectively replicate the impact of ventilation. A large number of fire training buildings are made of concrete or standard shipping containers and utilize small fuel loads to increase the safety of the training exercises. As a result, any ventilation practices utilized in these buildings leads to improved conditions. If instructors do not explain how these training exercises differ from ventilation under real world conditions, firefighters may gain a false sense of reality and potentially use incorrect tactics during actual incidents.

The rate for traumatic firefighter deaths occurring outside structures or from cardiac arrest has declined while, at the same time, the rate of firefighter deaths occurring inside structures has continued to climb over the past 30 years [3]. It is believed that one significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from both natural ventilation and the use of ventilation as a firefighter practice. Three recent ventilation related incidents have resulted in firefighter fatalities and were investigated by the National Institute for Occupational Safety and Health (NIOSH). In 2010, a fire in a one-story house claimed the life of a firefighter and the investigation report suggests, "Fire departments should ensure that fire fighters and officers have a sound understanding of fire behavior and the ability to recognize indicators of fire development and the potential for extreme fire behavior [4]." The second incident occurred in 2000 and resulted in NIOSH suggesting, "Ventilation timing is extremely important and must be carefully coordinated between both fire attack and ventilation crews. [5]." A third incident in 2008 claimed the life of one firefighter and one civilian. The NIOSH report conclusion states "This contributory factor (tactical ventilation) points to the need for training on the influence of tactical operations (particularly ventilation) on fire behavior [6]." There has been little research conducted to provide the fire service with data they need to update their ventilation tactics especially with changes to the fire environment over the last several decades.

Traditionally, the fire service has adapted their tactics based on knowledge or experience gained while fighting fires and passing that information on through the generations. This approach can be very slow to adapt to changes and can be incorrect because rarely are two fires identical so the variables encountered are never well understood. The research in this study examines these variables to provide the scientific knowledge currently lacking in the fire service needed to supplement their training system.

2. Full-Scale House Experiments

To examine ventilation practices as well as the impact of changes in modern house geometries, two houses were constructed inside a large fire experimental facility. Fifteen experiments were conducted varying the ventilation locations and the number of ventilation openings (Table 1). Ventilation scenarios were designed to examine common fire service practices and included the following: ventilating the front door only, opening the front door and a window near and remote from the seat of the fire, opening a window only, and ventilating a higher opening in the two-story house. One scenario in each structure was conducted in triplicate to examine repeatability. Experiments in each house were conducted 3 days apart to allow for ambient conditions inside the houses between 15 and 22°C and below 50% relative humidity prior to ignition.

2.1. One-Story Structure

Seven of the experiments took place in the one-story house. The house was designed to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings. The one-story house had an area of 111.5 m^2; with three bedrooms, one bathroom and eight total rooms (Figure 1). The home was wood framed, lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm) to protect the structure and allow for multiple experiments. All of the windows were filled with plugs so that window opening could be controlled by removing the plugs at the time specified for each experiment.

2.2. Two-Story Structure

The two-story house had an area of 297.3 m^2; with four bedrooms, 2.5 bathrooms house and 12 total rooms (Figures 2, 3). The house incorporated modern features such as an open floor plan, two-story great room, and open foyer. The home was also a wood framed structure lined with two layers of gypsum board (Base layer

Table 1
Experimental Series

Exp. #	Structure	Location of ignition	Ventilation parameters
1	1-Story	Living room	Front door
2	2-Story	Family room	Front door
3	1-Story	Living room	Front door + LR window
4	2-Story	Family room	Front door + FR1 window
5	1-Story	Living room	LR window only
6	2-Story	Family room	FR1 window only
7	1-Story	Living room	Front door + BR2 window
8	2-Story	Family room	Front door + BR3 window
9	1-Story	Living room	Front door + LR window (Repeat Exp. 3)
10	2-Story	Family room	Front door + FR1 window (Repeat Exp. 4)
11	2-Story	Family room	Front door + FR1 window (Repeat Exp. 4)
12	1-Story	Living room	Front door + LR window (Repeat Exp. 3)
13	2-Story	Family room	Front door + FR3 Window
14	1-Story	Living room	Front door + 4 windows (LR, BR1, BR2, BR3)
15	2-Story	Family room	Front door + 4 windows (LR, Den, FR1, FR2)

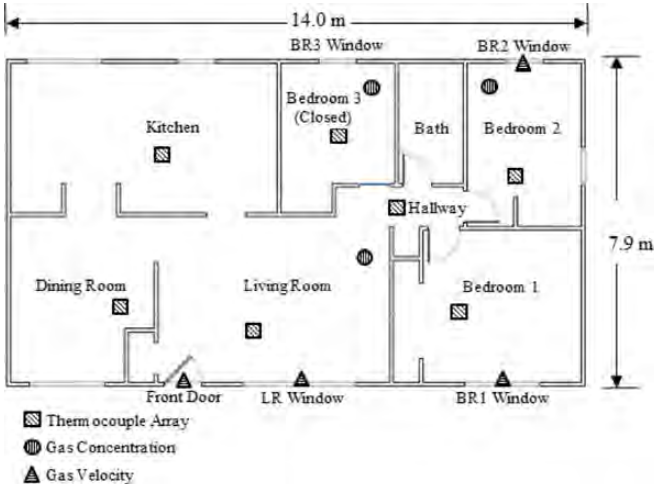

Figure 1. One-story house floor plan.

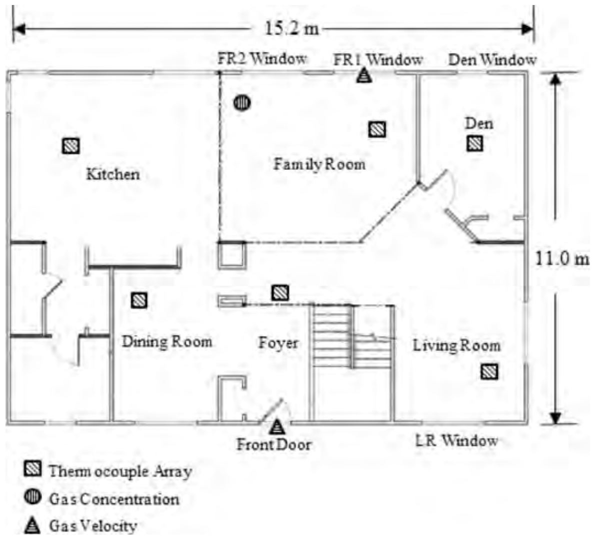

Figure 2. Two-story house first floor plan.

16 mm, Surface layer 13 mm). All of the windows were filled with plugs so that window opening could be controlled by removing the plugs at the time specified for each experiment.

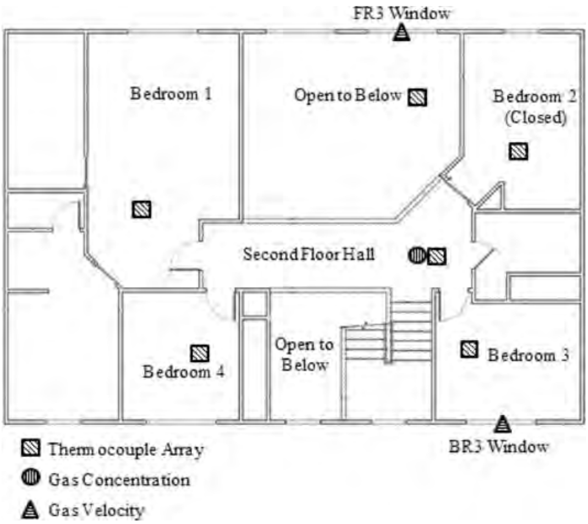

Figure 3. Two-story house second floor plan.

2.3. Fuel Load

Both houses were furnished with like furnishings. Figures 4, 5 6 show three dimensional renderings of both houses with furniture locations. The living room (LR) in the one-story house, along with the family room and the LR in the two-story house, were furnished similarly with two sofas, armoire, television, end table, coffee table, chair, two pictures, lamp with shade and two curtains. The floor was covered with polyurethane foam padding and polyester carpet. The fuel loading was approximately 29 kg/m^2.

In order to characterize the living/family room fuel load it was placed in a 5.5 m wide by 4.0 m deep room with a 2.4 m high ceiling. The room had a 3.7 m wide by 2.1 m tall opening on the front wall. The room was placed under an oxygen consumption calorimeter and a peak heat release rate of 11.3 MW was measured.

Bedroom 1 in both houses was furnished with a queen bed comprised of a mattress, box spring, wood frame, two pillows and comforter. The room also contained a dresser, armoire and television. The floor was covered with polyurethane foam padding and polyester carpet. The remainder of the bedrooms (2–4) in both houses was furnished with the same bed, armoire, television and flooring compliment as well as a smaller dresser, headboard, and a framed mirror.

The dining room of both houses was furnished with a solid wood table and four upholstered chairs. The kitchens were furnished with the same table and chairs as the dining room, as well as a dishwasher, stove, refrigerator and oriented strand board base cabinets with cement board counters. The floors of both rooms

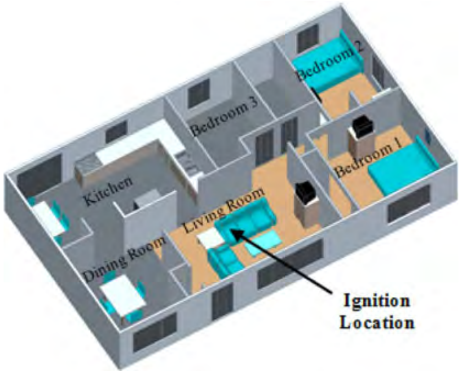

Figure 4. 3D rendering of the one-story house.

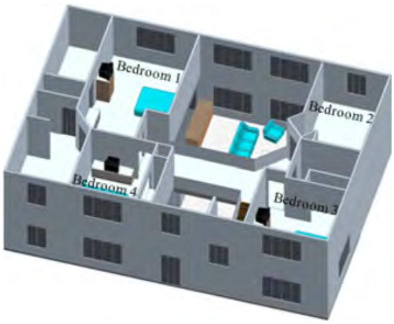

Figure 5. 3D rendering of the 2-story house.

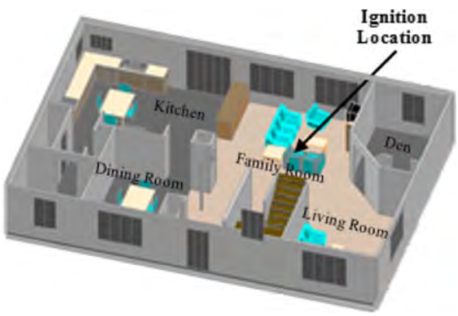

Figure 6. 3D rendering of the first floor of the 2-story house.

were also cement board to simulate a tile floor. The two-story house also had a den on the first floor in which a stuffed chair was placed as a target fuel.

2.4. Instrumentation

The measurements taken during the experiments included gas temperature, gas velocity, gas concentrations, and video recording. Gas temperature was measured with bare-bead, Chromel–Alumel (type K) thermocouples, with a 0.5 mm nominal diameter. Thermocouple arrays locations are shown in Figures 1, 2 and 3. The thermocouples were located in the LR and hallway in the one-story house and foyer and second floor hallway in the two-story house. Each location had an array of thermocouples with measurement locations of 0.03 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m and 2.1 m below the ceiling. The thermocouple arrays located in the dining room, kitchen, den and bedrooms had measurement locations of 0.3 m, 0.9 m, 1.5 m, and 2.1 m below the ceiling. The family room had thermocouple locations every 0.3 m below the ceiling down to the floor.

Gas velocity was measured utilizing differential pressure transducers connected to bidirectional velocity probes. These probes were located in the front doorway and the window used for ventilation (Figures 1, 2, 3). There were five probes on the vertical centerline of each doorway located at 0.3 m from the top of the doorway, the center of the doorway, and 0.3 m from the bottom of the doorway. Thermocouples were co-located with the bidirectional probes to complete the gas velocity measurement.

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured in four locations in the structure. Concentrations were measured at 0.3 m and 1.5 m from the floor in the LR and at 1.5 m from the floor in bedrooms 2 and 3 of the one-story house (Figure 1). Concentrations were measured at 0.3 m and 1.5 m from the floor in the family room and second floor hallway of the two-story house (Figures 2, 3). Gas concentration measurements after water flow into the structure may not be accurate due to the impact of moisture on the gas measurement equipment.

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

2.5. Experimental Methodology

All of the experiments began with all of the exterior doors and windows closed and all of the interior doors in the same locations, either open or closed. The interior doors to Bedroom 3 in the one-story house and Bedroom 2 in the two-story house were closed for every experiment. The fire was ignited on a sofa in the LR of the one-story house (Figure 4) and on a sofa in the family room for the two-story house (Figure 6) using a remote ignition device comprised of three stick matches.

The flaming fire was allowed to grow until ventilation operations were simulated. The one-story house was ventilated at 8 min after ignition. This was determined based on three factors; time to achieve ventilation limited conditions in the house, potential response and intervention times of the fire service, and window failure times from previous window failure experiments [7]. The two-story house was ventilated 10 min after ignition. The additional 2 min enabled ventilation limited conditions, as the larger volume needed more time to consume the available oxygen.

When more than one ventilation opening was created in an experiment, such as opening the door and a window, the subsequent openings were made in 15 s intervals. This time was arrived at by assuming well timed and efficient ventilation by the fire service independent of the ventilation scenario.

After ventilation, the fire was allowed to grow until flashover or perceived maximum burning rate based on the temperatures, observation of exterior conditions, and monitoring of the internal video. Once the fire maintained a peak for a period of time, with respect given to wall lining integrity, a firefighting hose stream was flowed in through an external opening. The experiment was terminated approximately 1 min after the hose stream, and suppression was completed by a deluge sprinkler system and the firefighting crew.

2.6. One-Story Experimental Results

Seven experiments were conducted in the one-story structure (Table 1). Data graphs are provided for temperatures throughout the structure at 2.1 m and 0.9 m from the floor for each experiment. Each graph has the events labeled across the top with a vertical line indicating when they occurred. Additional data for each experiment including temperatures at additional elevations, gas concentrations, and gas velocities is documented in the full project report [7].

2.6.1. Experiment 1. Experiment 1 was designed to simulate a fire fighting crew making entry by opening the front door. The fire grew without intervention until 8 min after ignition, at which time the front door was opened. The fire again was allowed to grow until 12:30, post-flashover condition, when 10 s of water were flowed into the front door with a 379 lpm firefighting fog nozzle positioned in a straight stream (SS) pattern. At 13:30 another 10 s of water was flowed out of the same nozzle in a 30 degree fog pattern (Fog). At 14:15 the left half of the LR window was opened, allowing more air into the LR. The experiment was terminated at 15:30 and was extinguished by the firefighting crew (Figures 7, 8).

2.6.2. Experiment 3. Experiment 3 was designed to simulate a fire fighting crew making entry through the front door and having a ventilation opening made shortly after near the seat of the fire. The fire grew without intervention until 8 min after ignition, at which time the front door was opened. Fifteen seconds later, the LR window was opened. The fire again was allowed to grow until 10:22 when 10 s of water were flowed into the LR window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 11:30 and was extinguished by the firefighting crew (Figures 9, 10).

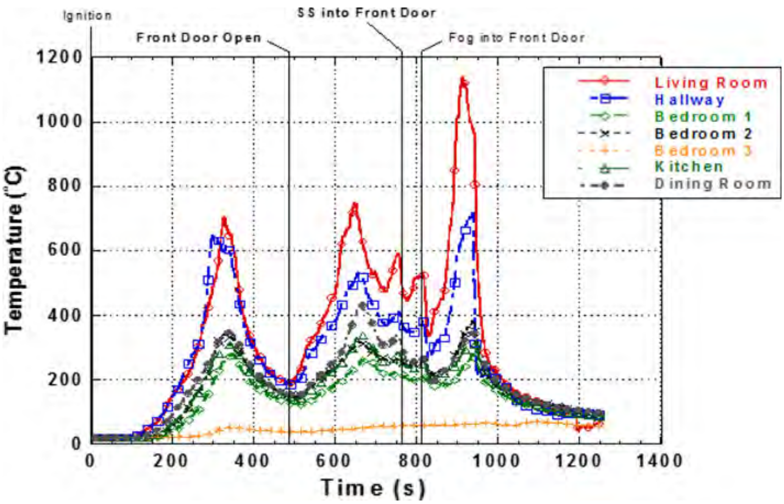

Figure 7. Experiment 1—2.1 m temperatures.

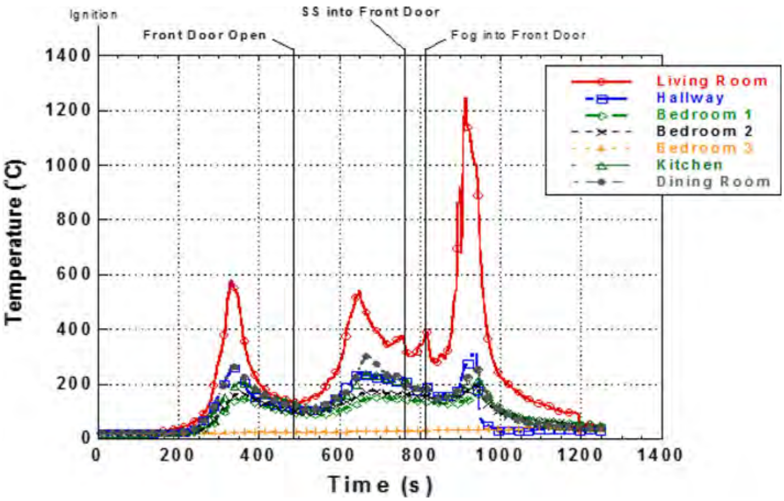

Figure 8. Experiment 1—0.9 m temperatures.

2.6.3. Experiment 5. Experiment 5 was designed to simulate a fire fighting crew making a ventilation opening near the seat of the fire prior to entry. The fire grew without intervention until 8 min after ignition, at which time the LR window was

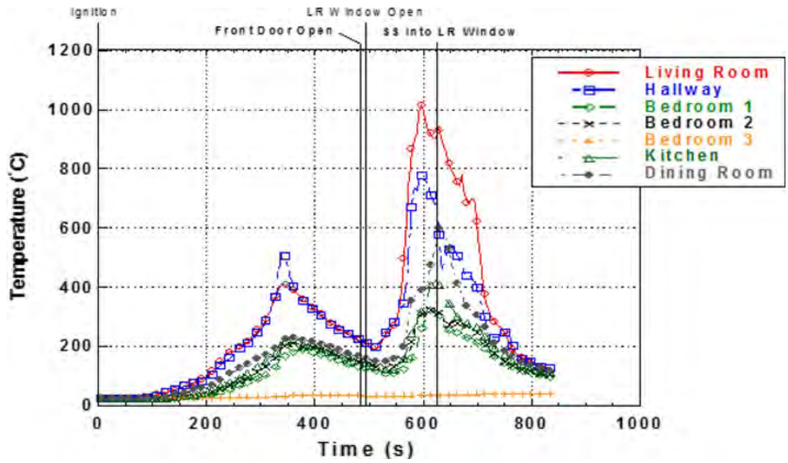

Figure 9. Experiment 3—2.1 m temperatures.

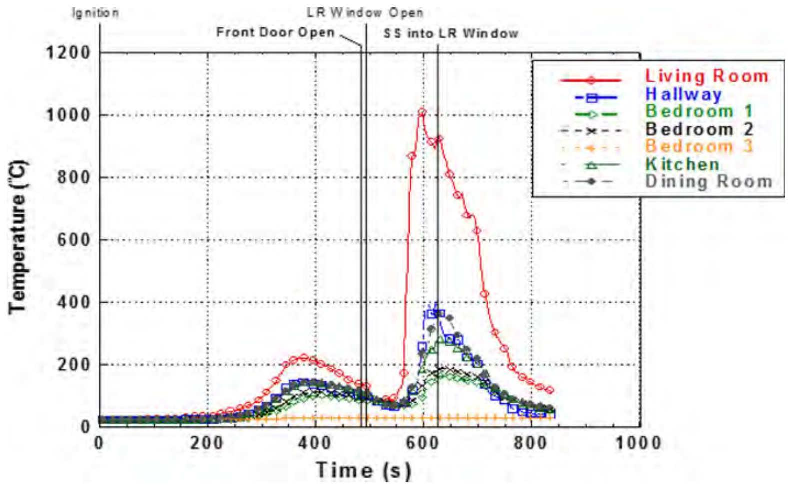

Figure 10. Experiment 3—0.9 m temperatures.

opened. The fire again was allowed to grow until 11:32 when 10 s of water were flowed into the LR window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 12:45 and was extinguished by the firefighting crew (Figures 11, 12).

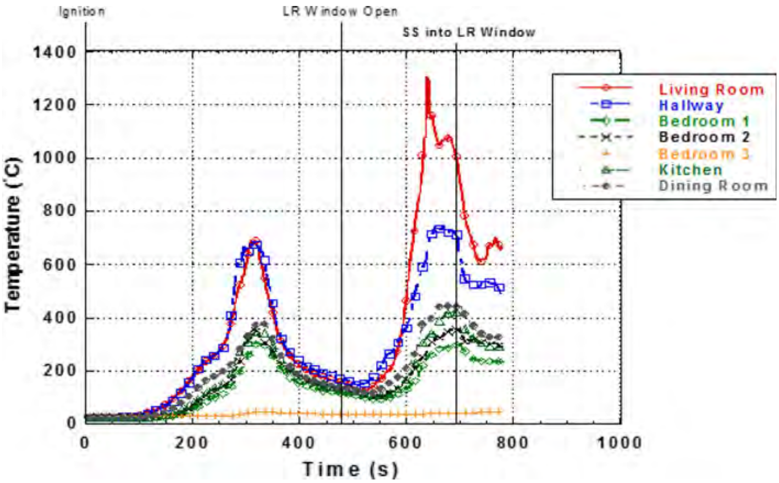

Figure 11. Experiment 5—2.1 m temperatures.

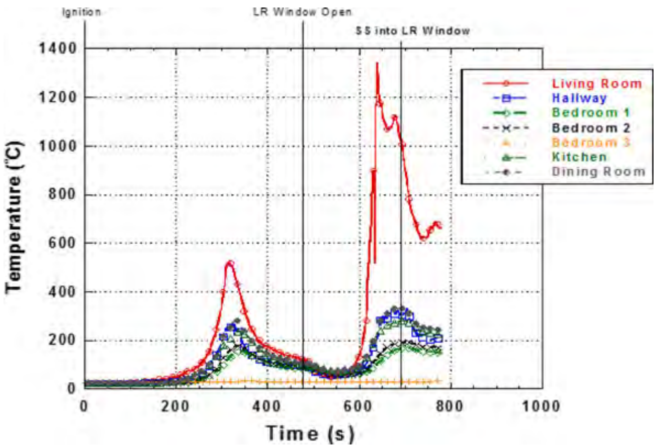

Figure 12. Experiment 5—0.9 m temperatures.

2.6.4. *Experiment 7*. Experiment 7 was designed to simulate a fire fighting crew making entry through the front door and having a ventilation opening made shortly after, remote from the seat of the fire. The fire grew without intervention until 8 min after ignition, at which time the front door was opened, followed 15 s later by the opening of the Bedroom 2 (BR2) window. The fire again was allowed to grow until 15:46 when 10 s of water were flowed into the front door with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 16:40 and was extinguished by the firefighting crew (Figures 13, 14).

2.6.5. Experiment 9. Experiment 9 replicated Experiment 3 and was the second of three replicate experiments to examine repeatability. The fire grew without intervention until 8 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the LR window was opened. The fire again was allowed to grow until 11:12 when 10 s of water were flowed into the LR window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 12:20 and was extinguished by the firefighting crew (Figures 15, 16).

2.6.6. Experiment 12. Experiment 12 was the third of three replicate experiments to examine repeatability. The fire grew without intervention until 8 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the LR window was opened. The fire again was allowed to grow until 11:09 when 10 s of water were flowed into the LR window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 12:20 and was extinguished by the firefighting crew (Figures 17, 18).

2.6.7. Experiment 14. Experiment 14 was designed to examine the impact of ventilating with several openings. The fire grew without intervention until 8 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the LR window was opened. In fifteen second intervals, the Bedroom 1 (BR1) window, Bedroom 2 (BR2) window, and Bedroom 3 (BR3) window were opened. The fire again was allowed to grow until 13:02 when 10 s of

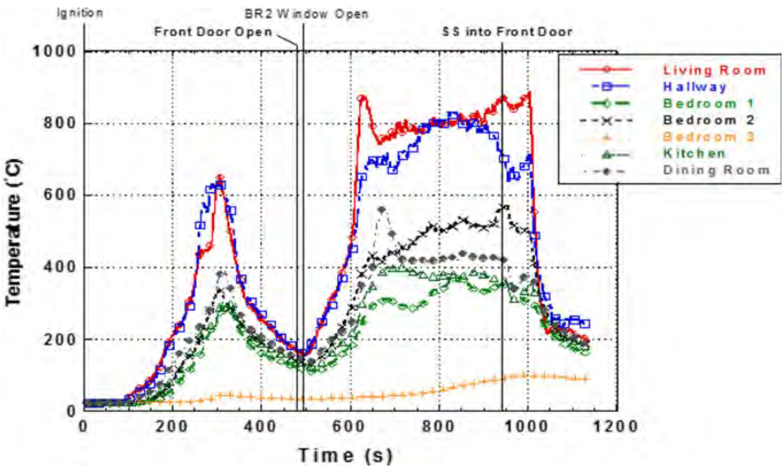

Figure 13. Experiment 7—2.1 m temperatures.

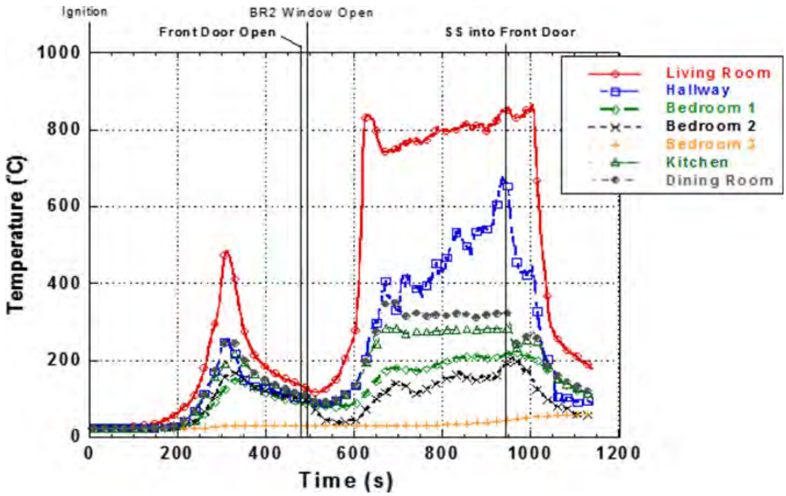

Figure 14. Experiment 7—0.9 m temperatures.

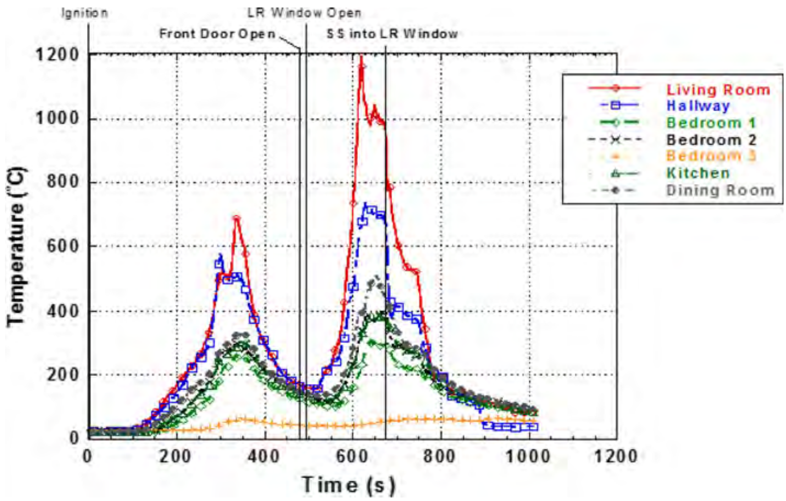

Figure 15. Experiment 9—2.1 m temperatures.

water were flowed into the LR window with a firefighting fog nozzle positioned in a fog stream pattern. The experiment was terminated at 14:10 and was extinguished by the firefighting crew (Figures 19, 20).

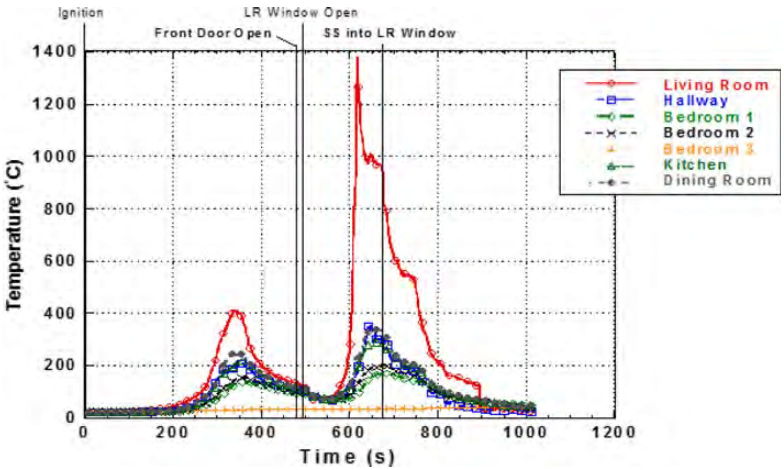

Figure 16. Experiment 9—0.9 m temperatures.

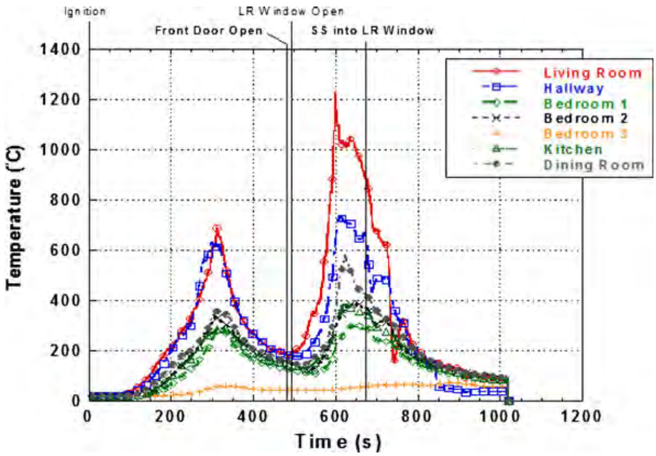

Figure 17. Experiment 12—2.1 m temperatures.

2.7. Two-Story Experimental Results

Eight experiments were conducted in the two-story structure (Table 1). Each experiment's purpose will be described and a figure will show the fire and ventilation locations. The experimental timeline will show the time of ventilation and

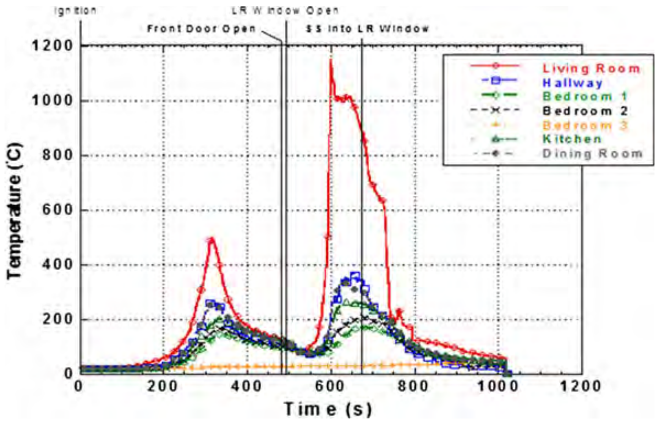

Figure 18. Experiment 12—0.9 m temperatures.

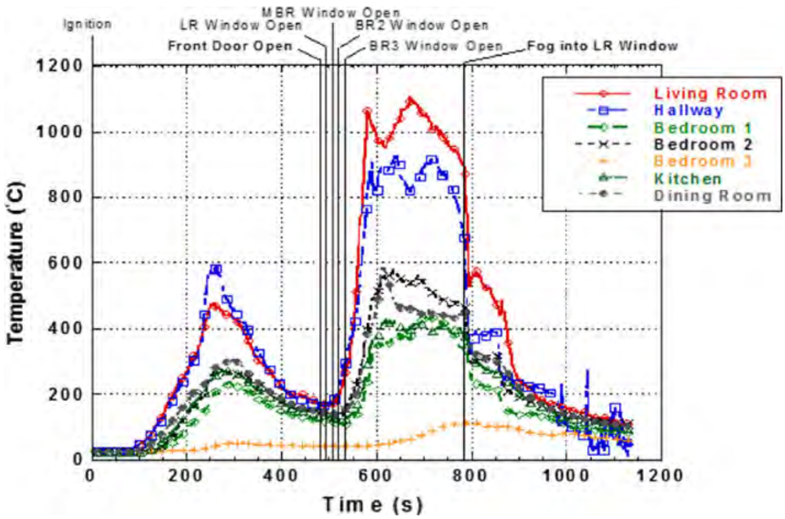

Figure 19. Experiment 14—2.1 m temperatures.

suppression changes. Data graphs are provided for temperatures throughout the structure at 2.1 m and 0.9 m from the floor for each experiment. Each graph has the events labeled across the top with a vertical line indicating when they occurred (Figures 21, 22).

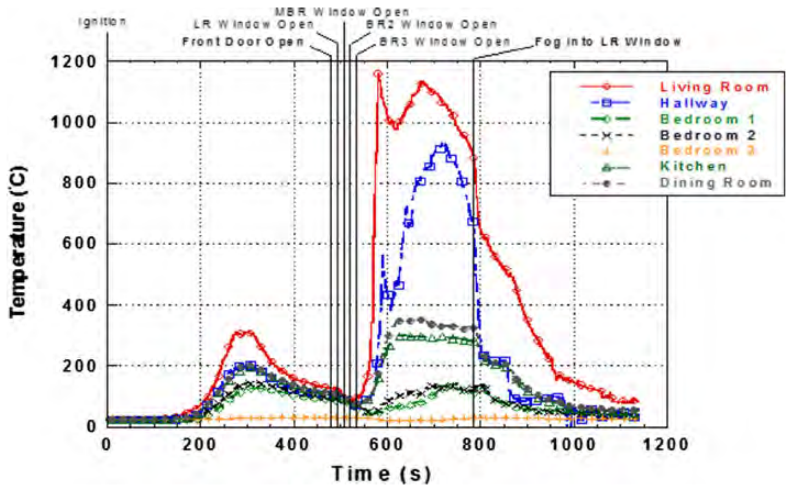

Figure 20. Experiment 14—0.9 m temperatures.

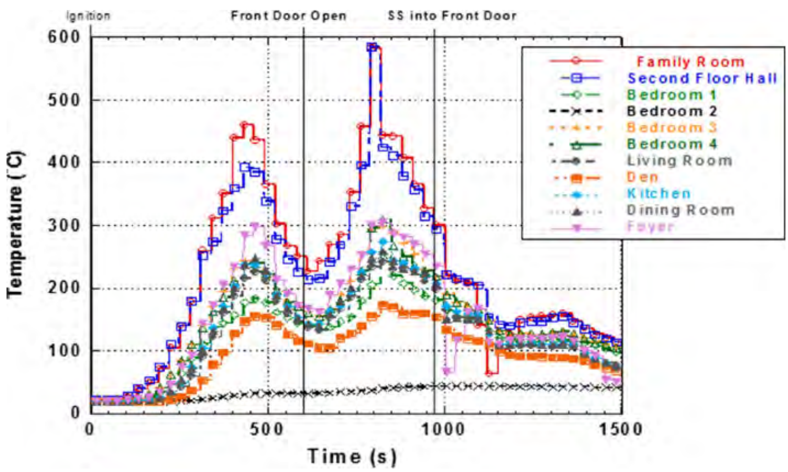

Figure 21. Experiment 2—2.1 m temperatures.

2.7.1. Experiment 2. Experiment 2 was designed to simulate a fire fighting crew making entry by opening the front door. Ignition took place in the family room on the sofa with a remote device igniting matches. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. The fire again was allowed to grow until 16:05 when 10 s of water were flowed into the

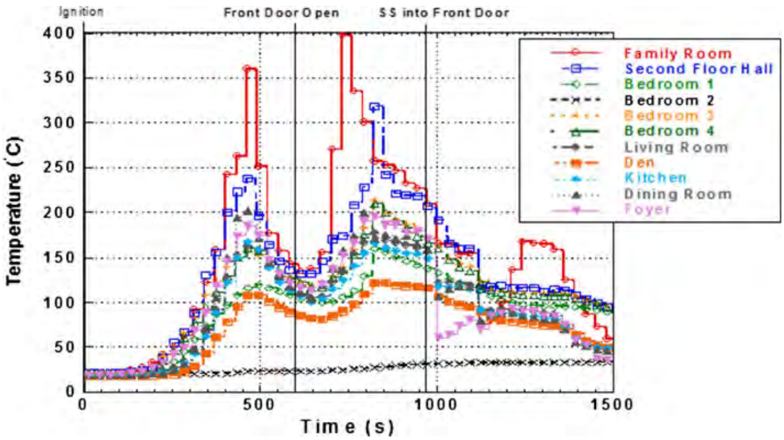

Figure 22. Experiment 2—0.9 m temperatures.

front door with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 18:00 and was extinguished by the firefighting crew.

2.7.2. Experiment 4. Experiment 4 was designed to simulate a fire fighting crew making entry through the front door and having a ventilation opening made shortly after, near the seat of the fire. Ignition took place in the LR on the sofa with a remote device igniting matches. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. Fifteen seconds later, the first floor family room (FR1) window was opened. The fire again was allowed to grow until 17:31 when 10 s of water were flowed into the family room window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 18:30 and was extinguished by the firefighting crew (Figures 23, 24).

2.7.3. Experiment 6. Experiment 6 was designed to simulate a fire fighting crew making a ventilation opening near the seat of the fire prior to entry. Ignition took place in the family room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the first floor family room (FR1) window was opened. The fire again was allowed to grow until 16:32 when 10 s of water were flowed into the family room (FR1) window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 17:30 and was extinguished by the firefighting crew (Figures 25, 26).

2.7.4. Experiment 8. Experiment 8 was designed to simulate a fire fighting crew making entry through the front door and having a ventilation opening made shortly after remote from the seat of the fire. Ignition took place in the family

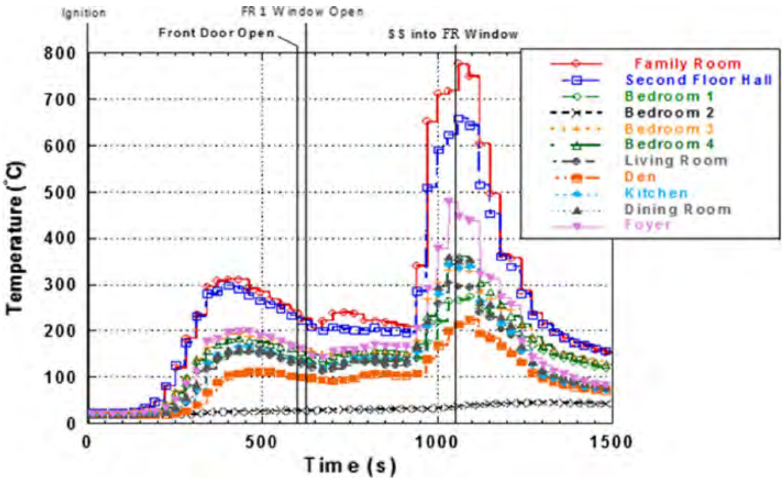

Figure 23. Experiment 4—2.1 m temperatures.

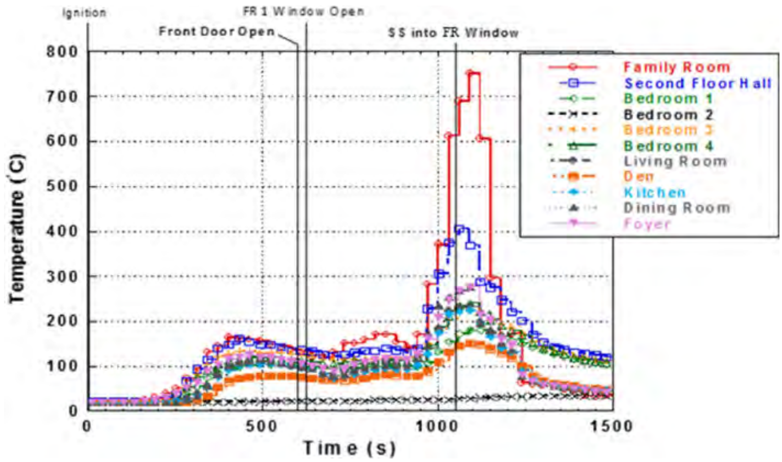

Figure 24. Experiment 4—0.9 m temperatures.

room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the front door was opened followed 15 s later by the opening of the Bedroom 3 (BR3) window. The fire again was allowed to grow until 17:32 when 10 s of water were flowed into the BR3 window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 18:30 and was extinguished by the firefighting crew (Figures 27, 28).

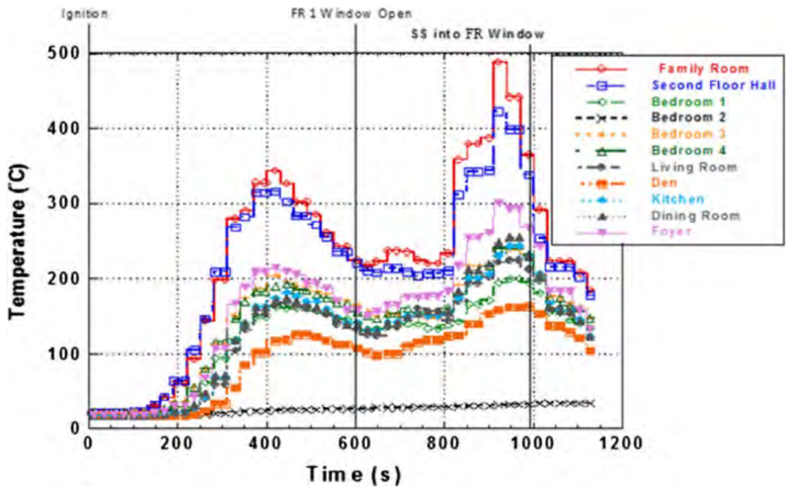

Figure 25. Experiment 6—2.1 m temperatures.

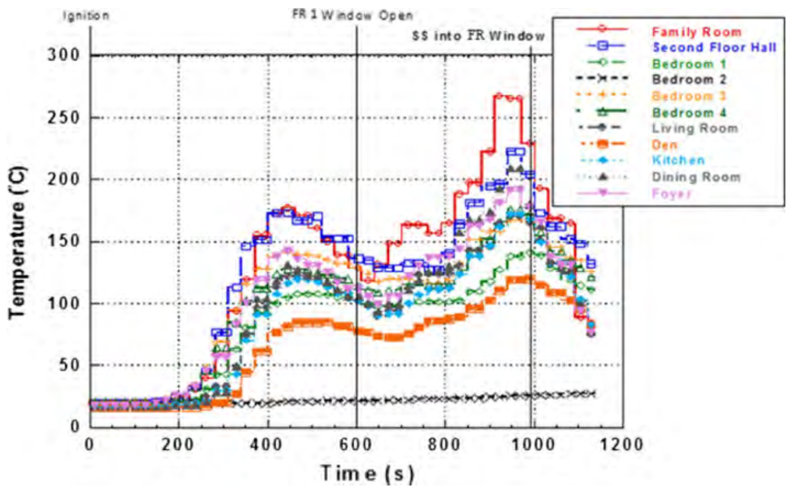

Figure 26. Experiment 6—0.9 m temperatures.

2.7.5. Experiment 10. Experiment 10 was the second of three replicate experiments to examine repeatability. Ignition took place in the family room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened the

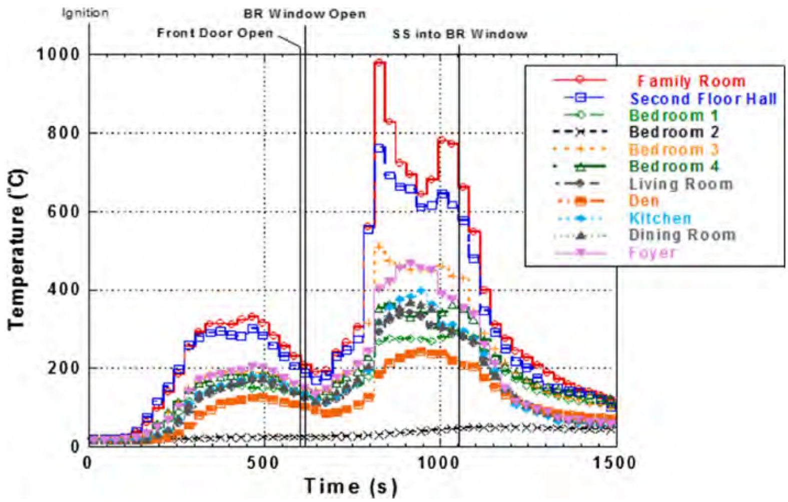

Figure 27. Experiment 8—2.1 m temperatures.

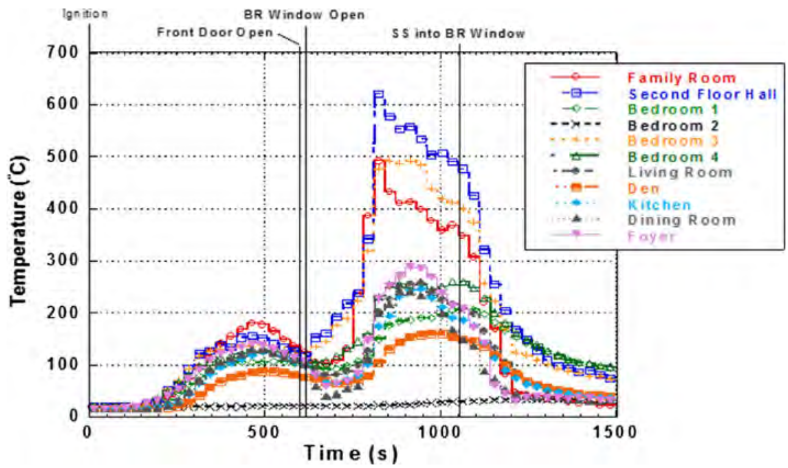

Figure 28. Experiment 8—0.9 m temperatures.

family room (FR1) window was opened. The fire again was allowed to grow until 24:16 when 10 s of water were flowed into the family room window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 25:30 and was extinguished by the firefighting crew (Figures 29, 30).

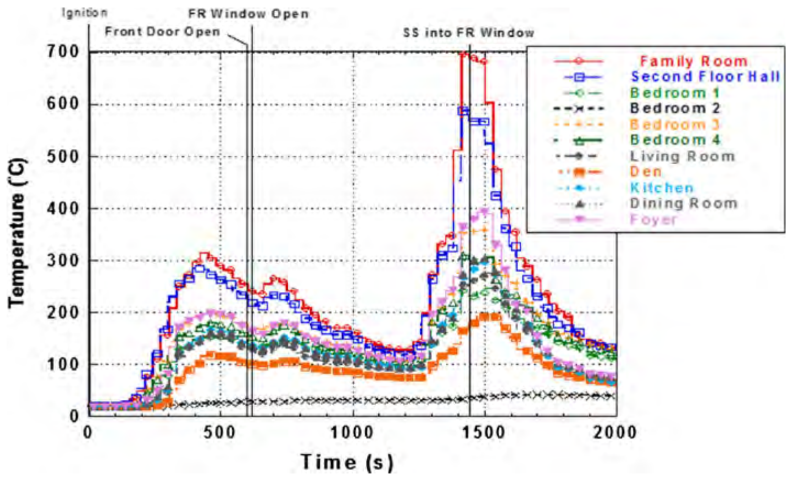

Figure 29. Experiment 10—2.1 m temperatures.

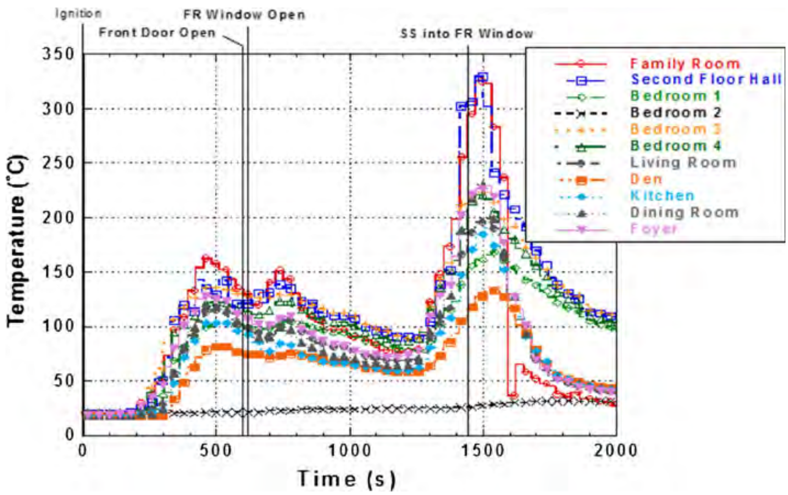

Figure 30. Experiment 10—0.9 m temperatures.

2.7.6. *Experiment 11.* Experiment 11 was the third of three replicate experiments to examine repeatability. Ignition took place in the family room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the family room (FR1) window was opened. The fire again was allowed to grow until 15:17 when 10 s of water were flowed into the family room window with a firefighting fog nozzle positioned in a straight stream pattern. The experiment was terminated at 16:30 and was extinguished by the firefighting crew (Figures 31, 32).

2.7.7. Experiment 13. Experiment 13 was designed to examine the impact of ventilation horizontally as high as possible near the seat of the fire. Ignition took place in the family room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the second floor family room (FR3) window was opened. The fire again was allowed to grow until 12:28 when 10 s of water were flowed into the FR3 window with a firefighting fog nozzle positioned in a straight stream pattern. A second 10 s burst of water was directed into the same window at 14:28 with the same nozzle positioned in a fog pattern. The experiment was terminated at 15:30 and was extinguished by the firefighting crew (Figures 33, 34).

2.7.8. Experiment 15. Experiment 15 was designed to examine the impact of ventilating with several openings. Ignition took place in the family room on the sofa. The fire grew without intervention until 10 min after ignition, at which time the front door was opened. Fifteen seconds after the front door was opened, the LR (LR) window was opened. In fifteen second intervals, the den window, FR1 window, and FR2 window were opened. The fire again was allowed to grow until 14:33 when 10 s of water were flowed into the FR1 window with a firefighting fog nozzle positioned in a fog stream pattern. The experiment was terminated at 16:00 and was extinguished by the firefighting crew (Figures 35, 36).

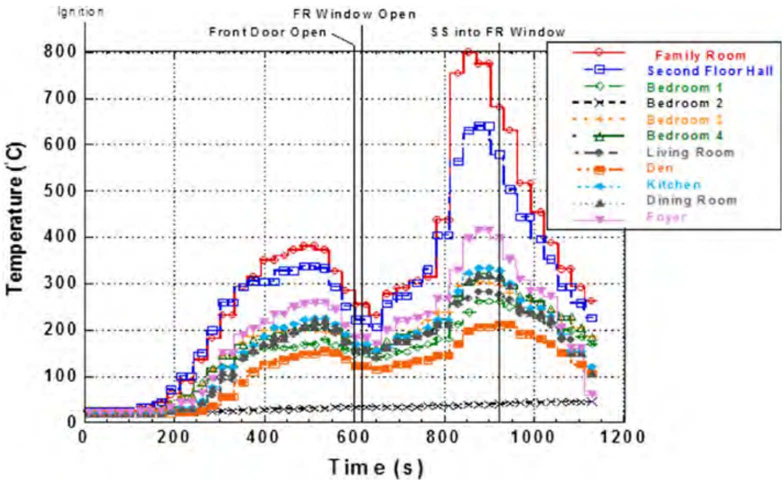

Figure 31. Experiment 11—2.1 m temperatures.

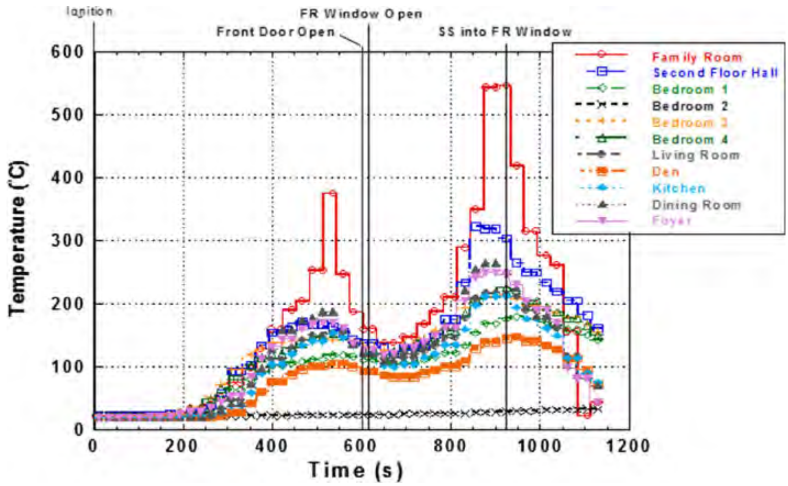

Figure 32. Experiment 11—0.9 m temperatures.

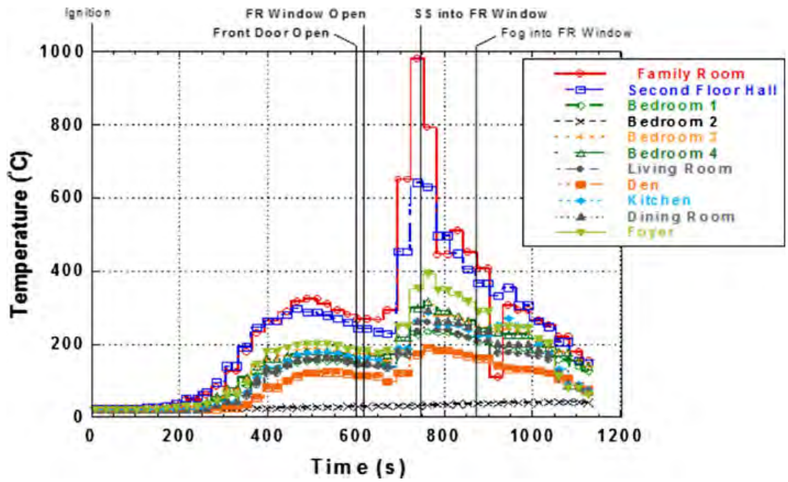

Figure 33. Experiment 13—2.1 m temperatures.

3. Discussion

The repeatability of these experiments was examined by comparing the first 8 min of the one-story experiments and the first 10 min of the two-story experiments. Another important factor in these experiments is tenability of potential occupants

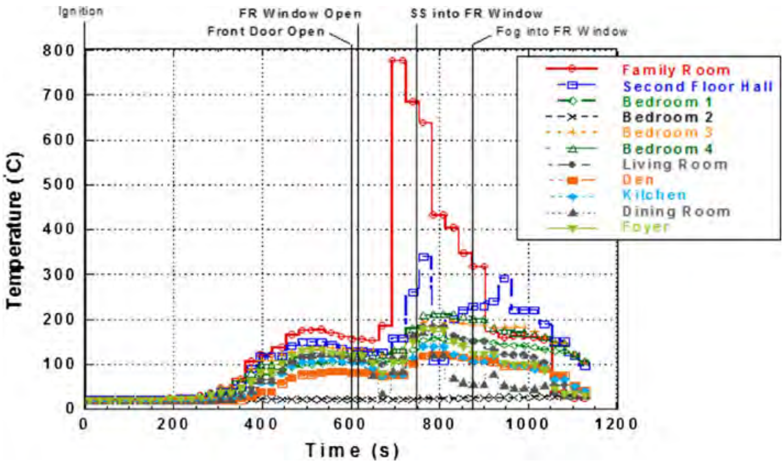

Figure 34. Experiment 13—0.9 m temperatures.

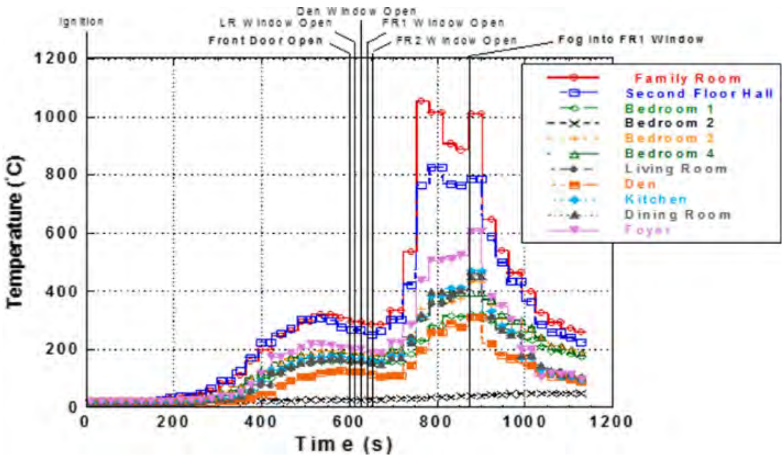

Figure 35. Experiment 15—2.1 m. temperatures.

in the structures prior to fire department intervention, as well as after fire department intervention. Firefighter ventilation practices will also be discussed. The temperature data will be compared to examine the conditions in the houses dependent upon which ventilation openings are made. Firefighters are taught to ventilate based on the location of the fire and in coordination with the operation that is being implemented. These comparisons provide a way to examine why they are

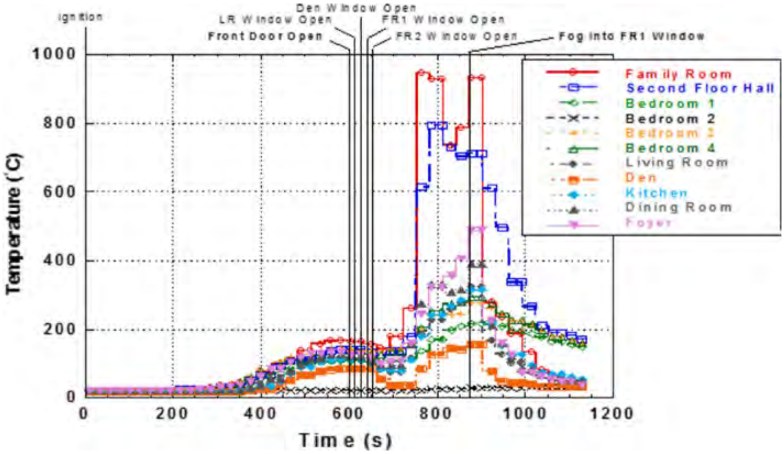

Figure 36. Experiment 15—0.9 m. temperatures.

taught those strategies and what those concepts mean for the tenability and fire dynamics within the houses.

3.1. One-Story Repeatability

In order to compare the ventilation practices, great emphasis was placed on ensuring pre-ignition conditions were as identical as possible. Multiple pieces of the same furniture were purchased and the positioning of the furniture was the same between experiments. Ignition was initiated in the same location and the amount of air leakage area was controlled by filling cracks around the doors and windows with fiberglass insulation.

Of the seven experiments, Experiment 3 had a slower growing fire and Experiment 14 had a faster growing fire. The other five experiments grew similarly for the first 8 min before ventilation. Temperatures near the ceiling in the LR of the five similar experiments reached approximately 700°C at around 320 s and quickly decreased to 175°C at 480 s as the oxygen was consumed in the house. The temperatures at the same elevation in Bedroom 2 (most remote from the LR) reached 350°C before decreasing to an average of 150°C as the fire became ventilation limited.

As a whole, the set of experiments in the one-story structure showed repeatability prior to ventilation. The two experiments which showed different growth rates from the others, 3 and 14, still had similar temperatures at the time of ventilation. Every experiment was within 50°C at the time of ventilation at the two measurement locations chosen, which were remote from each other.

Experiments 3, 9 and 12 followed the same timeline to examine repeatability during the entire experiment. In all three experiments, the front door was opened at 8 min and the LR window was opened 15 s later. The fire was allowed to burn until a post flashover condition was reached. Figure 37 shows the temperature versus time at 2.1 m above the floor in the LR and bedroom 2 (BR2). Experiments 9 and 12 were similar throughout the entire timeline. Experiment 3 develops slower prior to ventilation but responds faster to the window being ventilated. After ventilation all of the experiments have similar temperature rates of change as well as peaks (Figures 37).

3.2. Two-Story Repeatability

The two-story house had the same furniture layout and ignition location as the one-story house. The only difference in the family room was the geometry of the room. To examine repeatability in all eight two-story house experiments the first 10 min of each experiment was compared. Ventilation took place at 10 min after ventilation in every experiment. Temperatures at 4.9 m in the family room peak between 325°C and 450°C between 450 s and 550 s. Just before ventilation, the temperatures at this elevation are all between 240°C and 310°C. Experiments 13 and 15 grew slower than the other six experiments, but every experiment peaked and declined in temperature prior to ventilation which is consistent with a ventilation limited fire.

Temperatures in Bedroom 3 were also compared between the eight experiments. Bedroom 3 was remote from the family room and is a good indication of heat flow to the second floor of the house. At 2.1 m above the floor in Bedroom 3, all of the temperatures peaked around 200°C and leveled off or slightly decreased up to the time of ventilation.

Experiments 4, 10 and 11 followed the same timeline to examine repeatability during the entire experiment. In all three experiments, the front door was opened at 10 min and the FR1 window was opened 15 s later. The fire was allowed to burn until a post flashover condition was reached. Figure 38 shows the temperature

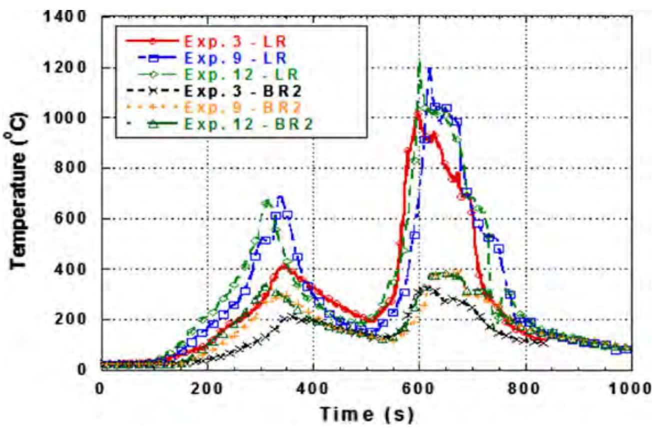

Figure 37. Exp. 3, 9, 12 repeatability—2.1 m temperatures.

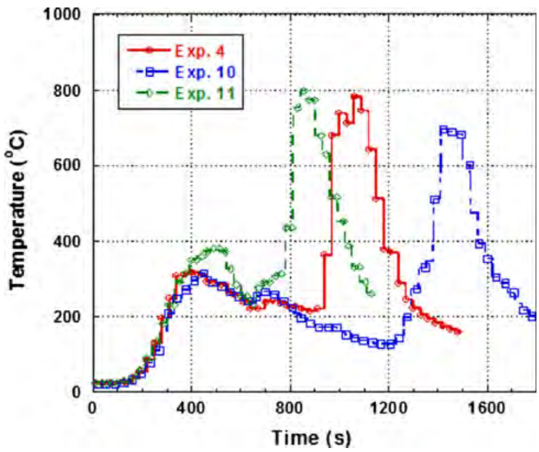

Figure 38. Exp. 4, 10, 11 repeatability—4.9 m family room temperatures.

versus time at 4.9 m above the floor in the Family Room and Bedroom 2. Each of these experiments followed similar trends, however had very different times to peak after ventilation. In experiments 4 and 11 the fire spread to both sofas in the family room before becoming ventilation limited. In Experiment 10 this did not occur, therefore, the fire grew more slowly after ventilation. Once the second sofa became involved in the fire, the temperatures near the ceiling of the family room increased at a similar rate as the other two replicate experiments (Figures 38).

3.3. Tenability

Two measures of tenability were used during these experiments; temperature and gas concentration. In order to estimate the time to untenability for potential occupants, the fractional effective dose (FED) methodology from ISO 13571 [8] was utilized. This methodology provides specified thresholds and allows for calculation of time to incapacitation based on an accumulated exposure to either heat or toxic gases. Two typical thresholds were chosen for this analysis; FED = 0.3 and FED = 1.0. FED = 0.3 is the criterion used to determine the time of incapacitation of susceptible people (11% of the population) and FED = 1.0 is used for healthy adults (50% of the population).

FED's were calculated for elevations of 0.3 m and 1.5 m from the floor for both houses. The 1.5 m elevation is representative of a person's head height while walking and the 0.3 m elevation is representative of the worst case scenario of a person lying on the floor. The time to exceed the thresholds for all of the experiments in each house for both heat and carbon monoxide were averaged and shown in Tables 2 and 3.

Table 2
FED Results for the One-Story House

	Temperature				Carbon monoxide			
	0.3 m		1.5 m		0.3 m		1.5 m	
	0.3	1	0.3	1	0.3	1	0.3	1
Living room	5:31	6:08	4:05	4:27	7:30	9:15	6:12	7:09
Bedroom 1	11:30	NA	5:19	6:26	–	–	–	–
Bedroom 2	11:46	NA	5:02	5:36	–	–	6:19	7:20
Bedroom 3	NA	NA	NA	NA	–	–	NA	NA

NA, not achieved; –, not a measurement location
Note: Temperature results standard deviation = 1:33, carbon monoxide results standard deviation = 1:54

Table 3
FED Results for the Two-Story House

	Temperature				Carbon monoxide			
	0.3 m		1.5 m		0.3 m		1.5 m	
	0.3	1	0.3	1	0.3	1	0.3	1
Family room	6:30	7:38	5:45	6:22	15:46	16:00	14:56	18:34
Bedroom 1	12:25	17:27	7:10	9:27	–	–	–	–
Bedroom 2	NA	NA	NA	NA	–	–	–	–
Bedroom 3	8:10	12:58	6:17	7:35	–	–	–	–
Bedroom 4	10:53	16:11	6:28	7:53	–	–	–	–
Kitchen	15:19	17:28	6:52	8:08	–	–	–	–
Second floor hall	–	–	–	–	16:00	18:47	12:52	16:54

NA, not achieved; – not a measurement location
Note: Temperature results standard deviation = 3:50, carbon monoxide results standard deviation = 5:31

$$FED_{in,heat} = \sum_{t_0}^{t} \frac{T^{3.4}}{5 \times 10^7} \Delta t, \qquad FED_{in,\mathrm{CO}} = \sum_{t_0}^{t} \frac{[\mathrm{CO}] \cdot \Delta t}{35000} \exp\left(\frac{\%\mathrm{CO}_2}{5}\right)$$

Examining the average FED's, it is clear that heat causes incapacitation prior to the toxic gases in these experiments. If the occupant was in the living/family room or standing (1.5 m) in the open bedrooms, the average times to incapacitation in the one and two-story houses occur prior to the simulated fire department arrival at 8 min or 10 min after ignition. Incapacitation of victims lying on the floor (0.3 m) in the bedrooms occurred after fire department ventilation, or did not occur in the bedroom with the closed door. This demonstrates two important concepts; (1) it is evident that there are places in these homes where people could be in need of rescue, and (2) firefighter ventilation practices need to be done properly because they can have a significant impact on the occupants inside the structure.

3.4. Ventilate Near and Remote to the Fire

The main guidance firefighters are given in their basic ventilation training is to ventilate as close to the seat of the fire as possible. This is meant to release the heat and smoke from the fire and to localize the growth of the fire to the area of origin. Ventilating remote from the seat of the fire creates the potential to spread the fire to uninvolved parts of the house by creating a flow path and source of oxygen from that uninvolved area.

Experiment 12 and Experiment 7 in the one-story house are compared in Figure 39. The RED lines represent the temperatures 1.5 m above the floor during the experiment when the front door was opened, followed by opening the LR window. The BLUE lines are measurements in the same locations but from the experiment where the front door was opened followed by the opening of the window in Bedroom 2, remote from the fire. The graph shows a slightly faster growing fire when ventilated near the seat of the fire. This can be expected because the source of oxygen is in the fire room and the fire can react to this and increase its heat release rate. The bedrooms also increase in temperature but Bedroom 2 only peaks at approximately 250°C and Bedroom 1 peaks at 210°C. Then they begin to decrease in temperature because of the lack of oxygen available to burn at that side of the house.

When ventilated remote from the seat of the fire, the LR temperature does not peak as high because it has less oxygen supplied to it. The difference is in the bedrooms. An area that was previously limited in temperature because it was out of the flow path has now become part of the flow path. This increases the temperatures to close to 500°C in Bedroom 2 and up to 300°C in Bedroom 1. If the fire had not been suppressed in order to save the structure for subsequent experiments, both bedrooms would have become involved in fire, creating an undesired situation from a ventilation choice. Bedroom 3 was unaffected by either ventilation scenario because the door was closed (Figures 39).

Experiment 4 and Experiment 8 in the two-story house are compared in Figure 40. The RED lines represent the temperatures 1.5 m above the floor during the experiment where the front door was opened, followed by opening the family room window (FR1). The BLUE lines are measurements in the same locations but from the experiment where the front door was opened followed by the opening of the window in Bedroom 3. Ventilating near the seat of the fire localizes the combustion. This also creates the highest peak temperature (775°C) in the family room because all of the available oxygen is coming right into the family room.

Unlike the ranch house, ventilating near the seat of the fire peaked later than ventilating remote from the seat of the fire because the remote vent location was on the second floor which allowed more air to enter from the front door and grow the fire. This air was limited, which did not allow for temperatures to peak as high as the experiment with two ventilation points near the seat of the fire. Comparing the bedroom temperatures highlights the impact of creating a flow

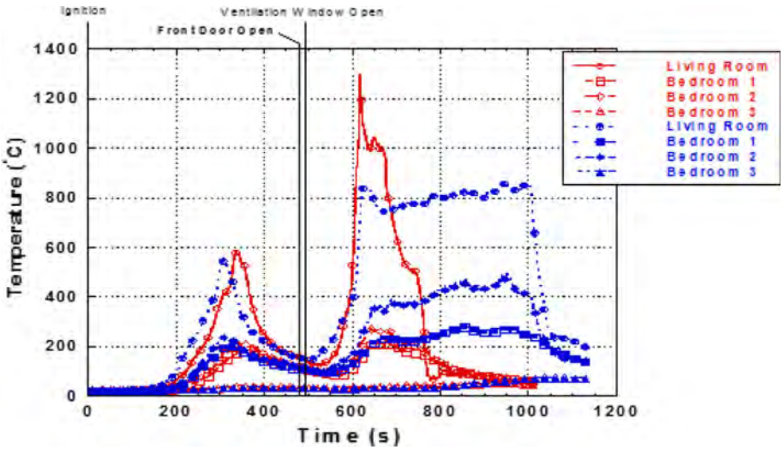

Figure 39. Comparison of living room and bedroom temperatures at 1.5 m above the floor when ventilated near and remote from the fire.

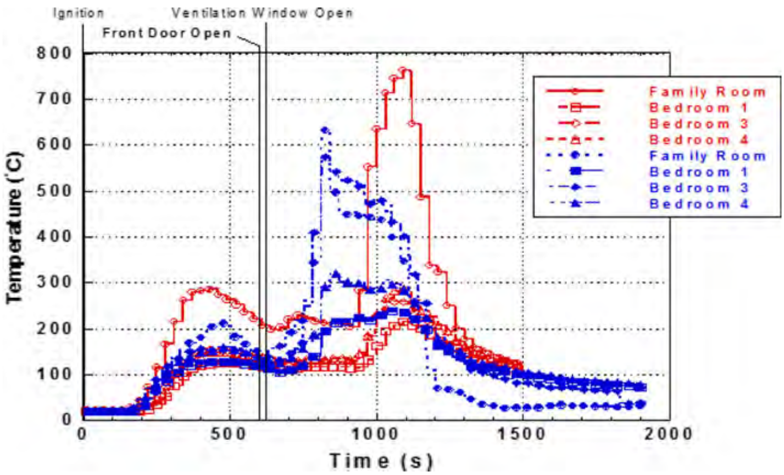

Figure 40. Comparison of family room and bedroom temperatures at 1.5 m above the floor.

path through the bedroom. When Bedroom 3 was not in the flow path, its peak temperature was 250°C. However, when it was in the flow path, temperatures increased to 575°C.

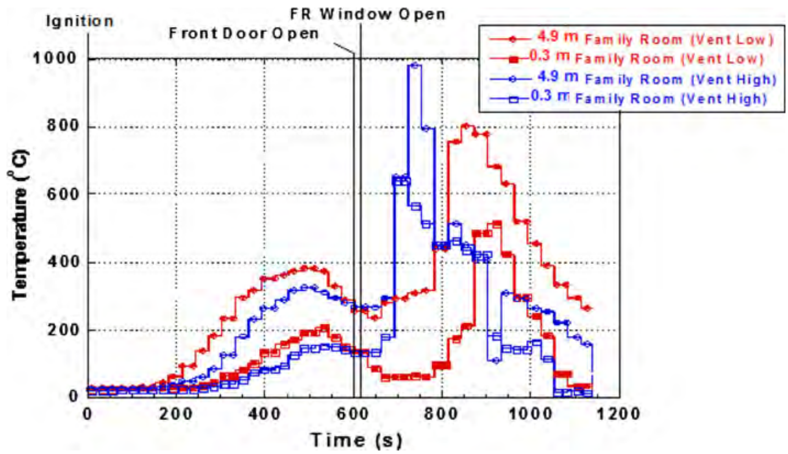

Figure 41. Comparison of ventilating high and low.

3.5. Ventilating High Versus Ventilating Low

When determining how to most effectively ventilate a room, it would be intuitive to ventilate near the top of the room since that is where the hot gases from a fire develop a layer. One must also consider how the cool air enters the room as the hot gases are leaving the room. If the fire is ventilation limited, than the additional air can generate more energy than can be exhausted out of the ventilation openings. In this scenario, ventilating the top of the room did not provide the temperature relief that was intended.

The temperatures at 0.3 m above the floor and 4.9 m above the floor are plotted in Figure 41. In Experiments 11 and 13, the fire grew, became ventilation limited and then the temperatures decreased. Once the door and window were opened, the high ventilation window caused temperatures to increase much faster than the low ventilation window. The high window experiment reached 950°C at the ceiling and 650°C at the floor at approximately 720 s. The low window experiment reached 800°C at the ceiling and 500°C at the floor at approximately 870 s.

This is a dramatic difference in fire growth. Allowing air into a ventilation limited fire low and letting the hot gases out high can create prime conditions for a flashover, even in a large volume like the two-story family room. Another point illustrated by this graph is that the family room did not cool much, if at all, when the high window was ventilated. The temperature 0.3 m above the floor did not decrease from 125°C before it increased exponentially to 650°C. This is counterintuitive to the reason the fire service would create a ventilation opening in the first place, which is to reduce the temperature low in the room where they would be operating. In this case, the ventilation limited fire responded so quickly to the additional air that it did not cool the family room.

4. Conclusions

This study consisted of a series of 15 full-scale residential structure fires to examine fire behavior and the impact of firefighter ventilation tactics. This fire research project developed the empirical data needed to quantify the fire behavior associated with these scenarios, and to develop the necessary firefighting ventilation practices to reduce firefighter death and injury.

The fires in both houses repeated ventilation limited conditions, which was necessary to assess the different ventilation practices of the fire service. Tenability in these two homes was limited for occupants. But the possibility of savable lives, especially behind closed doors, should be considered by the fire service in their risk analysis. The results of this series of experiments were similar to other studies; when a flaming furniture fire occurs in a home, occupants have a short time to evacuate safely. This furthers the need for smoke alarms and residential sprinkler systems to increase occupant safety.

This research study developed empirical fire experiment data to demonstrate fire behavior resulting from one and two-story home fires and the impact of ventilation opening locations during fire service operations. This data has been used to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic that will result in mitigation of the firefighter injury and death risk associated with improper use of ventilation [9].

5. Future Research Needs

There are several variable changes that could be done to further validate and expand the conclusions from this series of experiments. The first variable that could be altered is the fire location. These experiments focused on LR or family room fires. Additional experiments with fires in the kitchen or bedrooms would allow for analysis of fire spread from these locations.

Future experiments should also consider creating a ventilation opening after one already exists (from the fire creating one of its own by failing a window, or a door being left open by an escaping occupant, or a window left open on a warm day). There are also two more types of ventilation in addition to horizontal ventilation that are frequently used by the fire service: vertical ventilation and positive pressure ventilation. They did not fit into the scope of this project but should be analyzed in a similar manner. Very little research has been conducted on these common fire service tactics used in a house.

Acknowledgments

The author would like to thank the Grant Program Directorate in the Federal Emergency Management Agency for funding this research through the Fire Prevention and Safety Grants (FP&S) as part of the Assistance to Firefighters Grants Program.

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A.3 Paper III: Occupant Tenability in Single Family Homes: Part I - Impact of Structure Type, Fire Location and Interior Doors Prior to Fire Department Arrival

Fire Technology, 53, 1589–1610, 2017

Manufactured in The United States
DOI: 10.1007/s10694-017-0651-5

Occupant Tenability in Single Family Homes: Part I—Impact of Structure Type, Fire Location and Interior Doors Prior to Fire Department Arrival

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Received: 1 August 2016/**Accepted:** 15 February 2017

Abstract. This paper describes an experimental investigation of the impact of structure geometry, fire location, and closed interior doors on occupant tenability in typical single family house geometries using common fuels from twenty-first century fires. Two houses were constructed inside a large fire facility; a one-story, 112 m^2, 3-bedroom, 1-bathroom house with 8 total rooms, and a two-story 297 m^2, 4-bedroom, 2.5-bathroom house with 12 total rooms. Seventeen experiments were conducted with varying fire locations. In all scenarios, two bedrooms had doors remaining open while the door remained closed in a third bedroom immediately adjacent to the open door bedrooms. Temperature and gas measurement at the approximate location of a crawling or crouching trapped occupant (0.9 m from the floor) were utilized with the ISO 13571 fractional effective dose (FED) methodology to characterize occupant tenability up to the point of firefighter intervention. The FED values for the fire room were higher for heat exposure than for toxic gases, while target rooms reached highest FED due to CO/CO_2 exposure. The closed interior door decreased FED significantly, with the worst case scenario resulting in a 2% probability of receiving an incapacitating dose compared to the worst case scenario for an open bedroom of 93% probability of receiving an incapacitating dose. In fact, in 7 of the 17 experiments, the closed interior door resulted in a less than 0.1% chance of an occupant receiving an incapacitating dose prior to firefighter 'intervention.'

Keywords: Fire, Residential fires, Tenability, Heat Exposure, Toxic Gases, Fractional Effective Dose, Firefighting

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1. Introduction

NFPA estimates that from 2009 to 2013 [1], U.S. fire departments responded to an average of 357,000 residential fires annually. These fires caused an estimated annual average of 2470 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.

Many contemporary homes are larger than older homes built before 1980. Based on United States Census data [2] homes have increased in average area from approximately 144 m^2 in 1973 to over 247 m^2 in 2014. While the average home size has increased by 71%, newer homes tend to incorporate features such as open floor plans and great rooms [3]. All of these features remove compartmentation and can contribute to rapid smoke and fire spread. While commercial building codes require fire and smoke separations to limit the impact of the fire on occupants, there are minimal requirements for compartmentation in single family homes [4].

The design of installed features in residential structures is a critically important component to ensure a fire-safe home. Great progress has been made in the effectiveness and utility of active detection and suppression systems in the residential market. Recently, significant attention has also been paid to the effectiveness of passive fire compartmentation particularly on the capabilities of interior residential doors as an effective fire safety system within modern homes. Based on both anecdotal evidence and a study by Kerber (2012) [5], public education materials have been produced to encourage families to ensure door closure when sleeping in or exiting a burning structure to help keep the fire and products of combustion compartmentalized [6]. While concerns remain about the impact of door closure on risks for detection (if detector is outside of the compartment of origin) or notification of occupants (if detector is outside of the compartments where occupants are sleeping), additional, quantifiable data on the effectiveness of closed doors can help the general public understand the relative risk and benefits of door closure.

While interior residential doors are not designed specifically as a fire protection system, the ability for such doors to provide temporary protection is important to quantify. Kerber showed that, with a typical living room fire in a one-story house, a fractional effective dose (FED) of 0.3 could be reached at a height of 1.5 m in an adjoining bedroom in approximately 5 min [7]. This FED value corresponds to a probability that the conditions are not tenable for 11% of the population (likely to include young children, elderly, and/or unhealthy occupants). Another bedroom immediately adjacent to this one, with its door closed never reached FED = 0.3. Furthermore, while that study allowed a comparison between times to achieve a typical benchmark FED (0.3 or 1.0), the data did not provide a means of ***quantitatively characterizing improvement*** in tenability for victims who may be in those rooms.

Assessing the risk created by different fire scenarios is paramount to further improving fire safety for building occupants. A recent study looked to analyze the fire risk of residential buildings in China by analyzing the large-scale probabilities of fire frequency, and the effectiveness of automatic suppression systems and fire-fighting, etc. [8]. Another study analyzed the effectiveness of smoke alarm presence and found that death rates are halved when smoke alarms are present [9]. While these studies supply useful information at the macro-scale of fire risk analysis to help inform and improve fire safety, they do not analyze individual fire risk and the timelines for occupant tenability that can inform firefighters in their risk/benefit analysis when determining best approaches to rescue occupants from structures.

Previous research has been performed to analyze occupant tenability in model fires with typical household furnishings. In 1978, animal models were used to study tenability in room corner tests and found that furniture posed a greater threat than wall insulation materials [10]. Other studies have been performed that have focused on the threat of toxic gases, such as carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen cyanide (HCN), in compartment fires, and found both to have significant impacts on occupant tenability [11–13]. In 2000, Purser [14] used the fractional effective dose methodology to analyze tenability in constructed rigs designed to simulate compartment fires. In particular, the study examined the differences in ventilation on the fire growth and tenability in the different compartments. One of the major findings of the study was that toxic gases contributed more to incapacitation of occupants than heat exposure did.

Many other studies have also implemented the FED methodology used in [14], and later outlined in ISO 13571 [15], to assess the impact of different fires on occupant tenability. These studies include assessing the tenability risk to occupants in numerical simulations of compartment fires [16], one-bedroom apartment fires [17], 1950s legacy residential housing [18], and basement fires [19].

This study will extend the previous work using the FED methodology by studying fires in full-scale modern one- and two-story structures using ISO 13571. This manuscript will focus on the impact of different structure type and different fire location and how that impacts tenability throughout the entire structure. The threat posed by actual residential fires and the typical times to untenability for occupants trapped in such fires will be quantified. Additionally, this data set will provide the ability to quantify the improvement in survivability achieved when an occupant is behind a closed door as compared to an open bedroom in a typical residential structure.

2. Experimental Setup

To examine the impact of common US single family house geometries, two full-size residential structures were constructed inside a large experimental fire facility. Seventeen experiments were conducted varying fire location between living room, bed room and kitchen in one- and two-story structures (Table 1). Experiments in each house were conducted three days apart to allow for ambient conditions inside the houses to be maintained between 15°C and 22°C and below 50% relative humidity prior to ignition.

2.1. One-Story Structure

Nine of the experiments took place in a one-story structure, designed to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings throughout. The one-story structure had a floor area of 112 m^2; with three bedrooms, one bathroom and eight total rooms (Fig. 1). The house was wood framed and lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm) to protect the structure and allow for multiple experiments. All of the windows were filled with removable inserts so that window failure did not occur in any scenario. The leakage area determined from a blower door test was found to be approximately 0.1 m^2.

2.2. Two-Story Structure

The two-story structure had an area of 297 m^2; with four bedrooms, 2.5 bathrooms and twelve total rooms (Figs. 2, 3). The structure incorporated features common in twenty-first century construction such as an open floor plan, two-story great room, and open foyer. The house was a wood framed structure and lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm). All of the windows in this structure were filled with removable inserts so that window failure did not occur in any scenario prior to fire department intervention (see Part B). The leakage area determined from a blower door test was found to be approximately 0.2 m^2.

2.3. Fuel Load

Figures 1, 2 and 3 include 3-dimensional renderings of the floorplan in each house with ignition and furniture locations (Table 1). The living room in the one-story house as well as the family room and living room in the two-story house were furnished similarly; with television stand, television, end table, lamp with shade, cof-

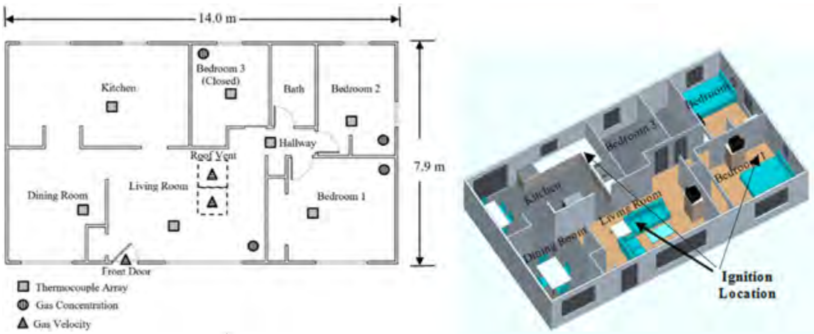

Figure 1. One-story house floor plan and 3D rendering showing furniture and ignition location.

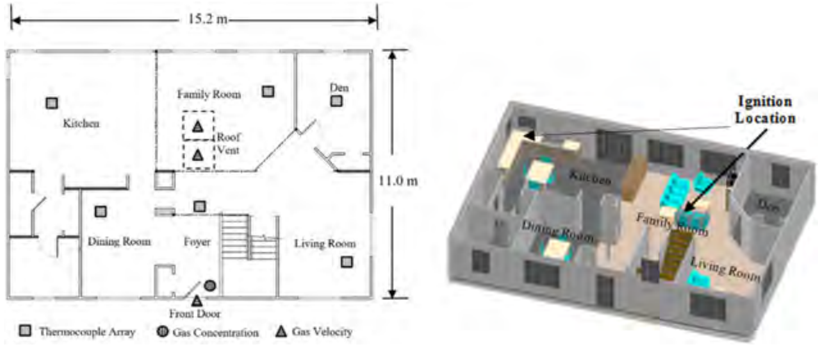

Figure 2. Two-story house first floor plan and 3D rendering showing furniture and ignition location.

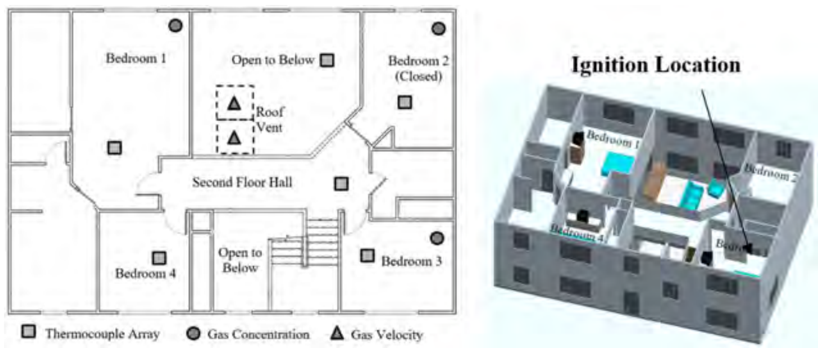

Figure 3. Two-story house second floor plan and 3D rendering showing furniture and ignition location.

fee table, chair, ottoman, two sofas, two pictures, and two curtains. The floor was covered with polyurethane foam padding and polyester carpet. The fuel loading was approximately 29 kg/m^2. To describe the potential energy of the fuel package, a test with the living room furnishings was performed in a compartment with a large opening (6.5 m^2 of ventilation area) under a cone calorimeter resulting in a maximum heat release rate of 8.8 MW and a total of 4060 MJ of heat released [3]. The scenarios reported in Part I of this series are conducted with all windows and door closed, resulting in underventilated conditions and lower heat release rates. This manuscript focuses on occupant exposures from the fire prior to ventilation and flashover did not occur in this timeframe (though flashover did occur after ventilation). Part II will analyze conditions after fire service ventilation [20].

Table 1
Ignition Locations for Each Experiment

Location of ignition	Experiment number
1 Story structure	
Living room	1,3,5,7, 15, 17†
Bedroom 1	9, 11
Kitchen	13
2 Story structure	
Family room	2,4,6,8,12
Bedroom 3	10, 14
Kitchen	6

Experiment number is provided to allow the reader to relate to UL Internal Report [3]
† Denotes legacy furnishings

Bedroom 1 in both houses was furnished with a queen bed comprised of a mattress, box spring, wood frame, two pillows and comforter. The room also contained a dresser, television stand and television. The floor was covered with polyurethane foam padding and polyester carpet. The remainder of the bedrooms (2 to 4) in both houses were furnished with the same bed, armoire, television and flooring compliment as well as a smaller dresser, headboard, and a framed mirror. A heat release rate experiment was conducted with the bedroom furnishings in a compartment with a large opening (6.5 m^2 of ventilation area) under the cone calorimeter. The maximum heat release rate was 9.4 MW and the total heat released was 3580 MJ [3].The dining room of both houses was furnished with a solid wood table and four upholstered chairs. The kitchens were furnished with the same type of table and chairs as the dining room, as well as a dishwasher, stove, refrigerator and wood upper and base cabinets with cement board counters. The floors of the dining rooms and kitchen were also cement board to simulate a tile floor.

The same make and model of all of these fuels (with the exception of Experiment 17) were purchased from the same supplier and stored in an environmentally controlled warehouse before they were used in an identical layout in the structure for each experiment. Experiment 17 was conducted using a different fuel package than the remaining experiments. While the room layout was the same, the natural fiber furnishings are intended to provide a relative risk from a common structure fire of 50+ years ago.

2.4. Instrumentation

While significant amounts of instrumentation were included in each of these structures (Figs. 1, 2, 3), this manuscript will focus on gas temperature and concentration data collected in the fire rooms and bedrooms at a height of 0.9 m from the floor. Gas temperature was measured with bare-bead, type K thermocouples, with a 0.5 mm nominal diameter in locations shown in Figs. 1, 2 and 3. The uncertainty in type K thermocouple measurements is less than 1% to 2% of the measured value for temperatures up to 1250 K [21].

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured using Ultramat 23 NDIR from Siemens at 0.9 m from the floor adjacent to the front door and in bedrooms 1, 2 and 3 for both houses. The uncertainty of the measured concentration is 1% of the maximum concentration measurement. The maximum concentration measurements were 1% by volume for CO and 10% by volume for CO_2. The gases were extracted from the corners of rooms to minimize transport length from sample location to the sensor and reduce the risk of damage during firefighting operations. All data was collected at a frequency of 1 Hz.

For this study, tenability was calculated based on the measurements of air temperature and CO/CO_2. Other factors could contribute to increased FED values and lower times to untenability, including the effect of radiant heat (particularly in the fire room) and the presence of HCN and other gases in the structure. However, due to experimental limitations, these factors are not considered here. The FED values from HCN should scale with CO/CO_2. So although are values may be conservative, there is consistency in the comparisons.

2.5. *Experimental Methodology*

All of the experiments started with the exterior doors and windows closed, the roof vents closed, and all of the interior doors open except for Bedroom 3 in the one-story and Bedroom 2 in the two-story structure. The fire was ignited on a sofa in the living room (one-story) or family room (two-story), in a trash can next to the bed, or in a coffee maker on the kitchen countertop (Figs. 1, 2, 3). The ignition of each experiment was performed with a set of matches that were spark ignited on a fuel source (couch in the living/family room, trash can next to the bed in the bedrooms, and towels under a cabinet in the kitchen) in the room of interest [3].

A flaming fire was allowed to grow until ventilation operations were simulated. Fire service ventilation for each scenario was determined based on three factors; time to achieve ventilation limited conditions in the house, potential response and intervention times of the fire service, and window failure times from previous window failure experiments [5]. Times to arrival on-scene vary greatly based on fire department capabilities and response distance. NFA 1710 suggests that departments should provide for the first arriving engine company to be on-scene within approximately five minutes (80 s for turnout, 240 s for travel time) after alarm handling (which includes 15 s for alarm handling [95% of the time], and 64 s for processing [90% of the time]) [22]. According to NFPA 1720, the goal for fire emergency response for volunteer departments is to arrive at the scene **at a maximum** of 9 min in an urban area (~384 people/km^2), 10 min in a suburban area (192 people/km^2 to 384 people/km^2), 14 min in a rural area (~192 people/km^2) and directly related to driving distance for remote areas greater than 8 miles from the closest fire station [22]. Of course, these times do not include the time to detection and notification, which can also vary greatly (60 s to 310 s [23]). To account for this variation, while still achieving objectives for other components of this study, firefighter intervention was largely determined on achieving ventilation limited conditions for each scenario, within the realistic timeframes provided by NFPA standards. In all cases, temperatures were relatively stable (see Fig. 4) such that accumulation of additional exposure and increased FED is estimated to be constant. Therefore, to allow estimation of changes in FED if ventilation were delayed beyond the intervention time used here, the instantaneous rate of FED per second will be reported at the time when initial ventilation was provided.

For living room fires in the one-story structure, ventilation began at 8 min after ignition for most experiments (to simulate quick fire department arrival and due to the fire stabilizing under ventilation-limited conditions). The two exceptions were Experiment 15 at 6 min (ventilated to study the impact of flow path and fire spread) and Experiment 17 at 24 min (to allow for the legacy fire to become ventilation-limited), while the two-story house was ventilated 10 min after ignition for the family room fires. The additional time in the two-story structure enabled ventilation limited conditions, as more time is needed for oxygen to be consumed in a larger volume. In all bedroom scenarios, ventilation occurred at 6 min after ignition due to the smaller fire room compartment and simulated window failure, while kitchen fires were ventilated 10 min after ignition (to allow for ventilation-limited conditions). As an example, Fig. 4 shows a typical evolution of temperature with time in the one-story structure from Experiment 3, collected at a height of 0.9 m. This experiment began with ignition on the couch in the living room, which grew until the fire became ventilation-limited. The temperatures then began to decrease until 8 min into the experiment when an initial ventilation opening was created, in this case, by opening the front door. The data analyzed here focuses on tenability prior to Fire Service intervention, and will largely consider temperature and gas concentrations up to the times listed above. However, for

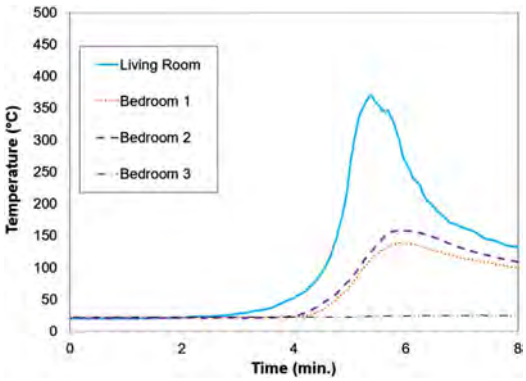

Figure 4. Temperature 0.9 m above the floor in experiment 3. Ignition was located in the living room. This study will focus on the time prior to fire department intervention (in this case, prior to 8 min).

reference and to contextualize this data, some of the following tables do include exposures after fire department intervention (Tables 2, 3).

2.6. Occupant Tenability

Occupant tenability, which is the survivability of occupants in the fire environment, is a primary concern for any firefighting operation. Two standard measures of occupant tenability were used during these experiments—temperature and gas concentration-based upon the fractional effective dose methodology (FED) from ISO 13571 [15]. This methodology provides a method to calculate the time to incapacitation based on an accumulated exposure to either toxic gases:

$$\upsilon_{CO_2} = exp\left(\frac{\varphi_{CO_2}}{5}\right) \tag{1}$$

$$FED_{CO} = \sum\left[\frac{\varphi_{CO}}{3.5} \cdot \upsilon_{CO_2} \cdot \Delta t\right] \tag{2}$$

or local ambient air temperature

$$FED_{temp} = \sum\left[\left(\frac{T^{3.61}}{4.1 \cdot 10^8}\right) \cdot \Delta t\right] \tag{3}$$

where υ_{CO_2} is a frequency factor to account for the increased rate of breathing due to carbon dioxide, φ_{CO_2} and φ_{CO} are the mole fractions (%) of carbon dioxide and carbon monoxide, T is the temperature near the occupant (°C), and Δt is the time increment of the measurements made in the experiments in minutes (1/60 in these experiments). According to ISO 13571, the uncertainty in Eq. 1 is ±20% and the uncertainty in Eq. 2 is ±35%. Equation 3 only applies for temperatures greater than 120°C, which is taken as the lower limit to this method. Gas concentration measurements did become saturated for some of the experiments (1% by volume for CO and 10% by volume for CO_2), so the FED values that we report are conservative estimates. Tables 2, 3, 4 and 5 will indicate which specific samples were saturated.

FED relates to the probability of the conditions being non-tenable for a certain percent of the population through a lognormal distribution. For reference, FED = 0.3 is the criterion used to determine the time of incapacitation for susceptible individuals (young children, elderly, and/or unhealthy occupants) and corresponds to untenability for 11% of the population, and FED = 1.0 is the value at which 50% of the population would experience untenable conditions.

FED's were calculated at an elevation of 0.9 m above the floor for both houses, representative of exposures that would be experienced by a person crawling on the floor. The time to exceed the thresholds for all of the experiments in each house for both heat (only convection considered as no radiant heat flux measurements were made) and carbon monoxide/carbon dioxide are calculated for both houses in living rooms and bedrooms, both with doors open and closed. It should be noted that the values assume the occupant was in that location for the duration of the experiment up to ventilation. These estimates may be considered lower bound scenarios as additional thermal risks may be present from exposure to large radiant heat exposures or from the additive effects of exposure to a variety of different hazardous gases.

While these measurements estimate exposures for the most likely case of an occupant crawling in smoky conditions, it is acknowledged that both heat exposure and toxic gas exposure will be larger with increasing elevation in the structure. If an occupant is standing or attempting to walk out of the structure, higher FED values and lower times to untenability will likely result.

3. Results

Calculations for FED = 0.3 and total FED at firefighter intervention are provided in Tables 2 and 3 for the one-story structure and in Tables 4 and 5 for the two story structure.

Table 2
Time to Untenability in One-Story Experiments for FED = 0.3 at 0.9 m Above the Floor

Location of the fire, experiment #			Living room (mm:ss)	Bedroom 1 (mm:ss)	Bedroom 2 (mm:ss)	Bedroom 3 (closed door) (mm:ss)
Living room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**05:29**[a]	06:14[a]	05:32[a]	–
		Temp	**05:08**	(11:29)	07:00	–
	3	CO	**05:30**[a]	06:44[a]	05:29[a]	–
		Temp	**05:06**	(14:27)	07:17	–
	5	CO	**04:40**[a]	06:02[a]	EM	–
		Temp	**04:18**	(11:12)	05:57	–
	7	CO	**05:06**[a]	06:24[a]	05:57[a]	–
		Temp	**04:46**	(10:55)	06:18	–
	15	CO	**05:39**[a]	05:32[a]	05:24[a]	***(13:41)***
		Temp	**04:29**	–	05:19	–
	17[†]	CO	**(27:10)**	(23:14)	(23:06)	–
		Temp	**(27:43)**	(33:17)	(29:13)	–
Bedroom 1 (FD intervention at 6:00)	9	CO	05:37[a]	**04:01**[a]	04:40[a]	***(11:16)***
		Temp	–	**03:10**	(16:16)	–
	11	CO	06:06[a]	**EM**	05:09[a]	–
		Temp	–	**03:13**	07:29	–
Kitchen (FD intervention at 10:00)	13	CO	(12:38)[a]	(10:37)[a]	(09:48)[a]	***(19:06)***
		Temp	(13:08)	–	–	–

Bold values indicate fire room, while the bold italicised value highlights the bedroom behind closed doors. For reference, times when FED = 0.3 after fire department intervention are included in parentheses

– not achieved, *EM* equipment malfunction

[†] Denotes legacy (>50 years ago) furnishings

[a] The calculated time to attain untenable conditions in the one-story structure are longer than the actual times (conservative) because the CO and CO_2 gas concentration exceeded the measurement limits (1% and 10% respectively) of the instruments used

Table 3
FED Values at Initial Firefighter Intervention in One-Story Structure

Location of the fire, experiment #			Living room (%)	Bedroom 1(%)	Bedroom 2	Bedroom 3 (closed door) (%)
Living Room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**3.27 (88)**	2.21 (79)	4.41 (93%)	***0.01 (< 0.1)***
		Temp	**4.21 (92)**	0.18 (4)	0.33 (13%)	*<0.01 (< 0.1)*
	3	CO	**3.17 (88)**	0.80 (41)	4.51 (93%)	***0.11 (1)***
		Temp	**4.01 (92)**	0.14 (2)	0.31 (12%)	*<0.01 (< 0.1)*
	5	CO	**3.72 (91)**	1.85 (73)	EM	***0.05 (0.1)***
		Temp	**4.45 (93)**	0.21 (6)	0.41 (19%)	*<0.01 (< 0.1)*
	7	CO	**4.53 (93)**	1.84 (73)	1.79 (72%)	*<0.01 (< 0.1)*
		Temp	**6.82 (97)**	0.22 (6)	0.44 (21%)	*<0.01 (< 0.1)*
	15	CO	**1.02 (50)**	1.17 (56)	1.17 (56%)	***0.01 (< 0.1)***
		Temp	**16.3 (>99)**	0.16 (3)	0.50 (24%)	*<0.01 (<0.1)*
	17†	CO	**0.23 (7)**	0.36 (15)	0.37 (16%)	***0.01 (<0.1)***
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1%)*	*<0.01 (<0.1)*
Bedroom 1 (FD intervention at 6:00)	9	CO	3.57 (90)	**9.81 (99)**	6.06 (96%)	***0.08 (0.5)***
		Temp	*<0.01 (<0.1)*	**37.1 (>99)**	0.21 (6%)	*<0.01 (<0.1)*
	11	CO	0.18 (4)	**0.24 (8)**	0.46 (22%)	***0.01 (<0.1)***
		Temp	*<0.01 (<0.1)*	**31.1 (100)**	0.11 (1%)	*<0.01 (<0.1)*
Kitchen (FD intervention at 10:00)	13	CO	0.16 (3)	0.18 (4)	0.51 (25%)	***0.07 (0.4)***
		Temp	*<0.01 (0)*	*<0.01 (0)*	*<0.01 (0)*	*<0.01 (<0.1)*

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. Percent of the population that would experience untenable conditions is included in parentheses

Italic values indicate <0.01 (<0.1%)

† Denotes legacy furnishings

In the one-story structure, where ignition occurred in the bedroom or living room, untenable conditions for susceptible populations (FED = 0.3) were reached in every room (except for the closed door room) before Fire Service intervention (Table 2). The average time to FED = 0.3 in the living room, bedroom 1, and bedroom 2 was 5 min 32 s. Thus, depending on firefighter response times, susceptible occupants inside the structure (and outside of closed rooms or compartments) are likely to have experienced untenable conditions prior to fire department intervention.

In the two-story structure, experiments with initial ignition in the family room (2, 4, 6, 8, 12), resulted in average times to untenability of 9 min 36 s for a FED criterion of 0.3 in open bedrooms and at the front door (Table 4). Additionally, FED values at the time of firefighter intervention (Table 5) outside of the fire room typically remain below 1. The exception to this trend was for the scenarios where the fire was ignited on the second floor bedroom. In those cases, FED values in the open bedroom on the same level were remarkably high for CO exposure.

Table 4
Time to Untenability in Two-Story Experiments for FED = 0.3 at 0.9 m Above the Floor

Experiment #			Family Room (mm:ss)	Bedroom 1 (mm:ss)	Bedroom 2 (mm:ss)	Bedroom 3 (mm:ss)
Family room (FD intervention at 10:00)	2	CO	**07:55**	09:43	–	09:06
		Temp	**05:36**	(13:52)	–	07:34
	4	CO	**09:28**	(10:43)	–	(10:25)
		Temp	**07:12**	(17:21)	–	09:04
	6	CO	**08:49**	(10:08)	–	10:00
		Temp	**06:18**	(13:29)	–	08:23
	8	CO	**09:51**	(10:48)	–	(10:36)
		Temp	**07:10**	(11:55)	–	08:34
	12	CO	**09:29**	08:42	–	08:21
		Temp	**05:57**	(10:54)	–	07:31
Bedroom 3 (FD intervention at 6:00)	10	CO	–	05:07[a]	***(17:31)***	**03:56[a]**
		Temp	–	–	–	**03:03**
	14	CO	–	05:14[a]	***(12:37)***	**04:00[a]**
		Temp	–	–	–	**03:19**
Kitchen (FD intervention at 17:00)	16	CO	(17:08)	(15:39)	***(22:19)***	(16:02)
		Temp	(26:05)	(28:33)	–	(27:05)

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. For reference, times when FED = 0.3 after fire department intervention are included in parentheses. Family room CO measurements were made at the front door of the structure

– not achieved

[a] The calculated time to attain untenable conditions in the bedroom 3 fire scenarios in the two-story structure are longer than the actual times (conservative) because the CO and CO_2 gas concentration exceeded the measurement limits (1% and 10% respectively) of the instruments used

Table 5
FED Values at Initial Firefighter Intervention in Two-Story Structure

Experiment #			Family Room[a] (%)	Bedroom 1(%)	Bedroom 2 (closed door) (%)	Bedroom 3 (%)
Family Room (FD intervention at 10:00)	2	CO	**0.68 (35)**	0.29 (11)	*<0.01 (<0.1)*	0.44 (21)
		Temp	**2.39 (81)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.64 (33)
	4	CO	**0.34 (14)**	0.16 (3)	*<0.01 (<0.1)*	0.19 (5)
		Temp	**3.77 (91)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.46 (22)
	6	CO	**0.47 (23)**	0.23 (7)	***0.05 (0.1)***	0.26 (9)
		Temp	**5.84 (96)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.55 (28)
	8	CO	**0.49 (24)**	0.21 (6)	***0.04 (0.1)***	0.27 (10)
		Temp	**9.77 (99)**	0.14 (2)	*<0.01 (<0.1)*	0.70 (36)
	12	CO	**0.09 (1)**	0.13 (2)	***0.03 (0.1)***	0.17 (4)
		Temp	**3.74 (91)**	0.03 (0.1)	*<0.01 (<0.1)*	0.42 (19)
Bedroom 3 (FD intervention at 10:00 for #10 & 8:35 for #14)	10	CO	*<0.01 (<0.1)*	8.5 (98)	***0.05 (0.1)***	**10.5 (99)**
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	**137 (>99)**
	14	CO	*<0.01 (<0.1)*	5.5 (96)	***0.03 (0.1)***	**9.2 (99)**
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	**100 (>99)**
Kitchen (FD intervention at 17:00)	16	CO	0.27 (10)	0.54 (27)	***0.13 (2)***	0.47 (23)
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (0.1)*

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. Percent untenable is in parentheses

Italic values indicate <0.01 (<0.1%)

4. Discussion

The results from the 17 experiments show that both heat and toxic gases present a significant threat to trapped occupants in residential fires. And while heat is typically considered the more serious concern very near the fire, as distance from the seat of the fire increases, i.e. the adjacent non-fire rooms, CO production begins to become the more serious threat to trapped occupants. For the timelines investigated in this study, the total FED for CO and temperature were very similar in the single story structure, while temperature affects dominated the larger two-story structure. This affect is attributed to the fires more rapidly becoming ventilated limited in the smaller structure as well as the reduced volume for diluting the effluent gases.

The selected ventilation times represent, for the most part, best case scenarios of fire department arrival (based on rapid fire detection) given the recommended NFPA standard alarm processing and response times. However, if the time of initial ventilation were further delayed, additional FED accumulation (FED/s) can be estimated since the temperature and gas concentration conditions were relatively stable upon ventilation. These estimates are shown in Tables 6 and 7. For example, if ventilation were delayed in Experiment 1 from 8 min to 10 min the values in Table 3 (e.g. FED_{Temp} = 4.21) would be increased by approximately 0.96 (FED_{Temp}/s = 0.008×120 s). It is clear from these tables that at this point in the fire development, the additional threat from thermal exposure is typically less than the threat due to toxic gases, even in the fire rooms for the one-story structure.

Based on the results presented here and typical response times that may be expected by the fire service it is likely that susceptible individuals who remain stationary (sleeping or otherwise unable to self-evacuate) at these locations will have experienced untenability in all parts of the one-story structure that have direct connection to the fire room. The high FED levels achieved over relatively short duration (typically 6 min to 10 min) also raises a concern for those who may be attempting to evacuate from the structure, particularly if exiting through the main living room or family room areas. Tables 2 and 4 highlight the times to untenability for susceptible individuals, which can be compared to the required safe egress time (RSET). In 2006, the National Research Council Canada published a report reviewing the available information on egress times from single family from residential structures and found that the time for egress can range from 2 min to 16 min [23]. This fact points to the critical need for active detection to reduce the detection time and suppression systems installed in these structures to control the fires allowing egress. This data also suggests additional consideration for the importance of ‘‘design for tenability'' in residential structures, e.g. through compartmentalization.

The fire department interventions times utilized in these studies remained fairly constant for all of the living room and family room fires. While these intervention time are similar to the NFPA 1720 recommendations, variations in the response times are likely to have a relatively small impact on the outcomes for these ventilation limited fires. As seen in Fig. 4, the temperatures at the fire service interven-

Table 6
FED Instantaneous Exposure at the Time of Ventilation in the One-Story Experiments

Location of the fire, experiment #			Living room (FED/s)	Bedroom 1 (FED/s)	Bedroom 2 (FED/s)	Bedroom 3 (closed door) (FED/s)
Living Room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**0.0145**	0.0236	0.0288	***0.0001***
		Temp	**0.0018**	0.0006	0.0009	***0***
	3	CO	**0.0094**	0.0179	0.0290	***0.0001***
		Temp	**0.0018**	0.0007	0.0009	***0***
	5	CO	**0.0092**	0.0253	EM	***0.0003***
		Temp	**0.0014**	0.0005	0.0007	***0***
	7	CO	**0.0210**	0.0254	0.0264	***0***
		Temp	**0.0018**	0.0006	0.0009	***0***
	15	CO	**0.0348**	0.0273	0.0352	***0.0001***
		Temp	**0.0102**	0.0017	0.0031	***0***
	17†	CO	**0.0010**	0.0014	0.0014	***0***
		Temp	**0.0002**	0.0001	0.0001	***0***
Bedroom 1 (FD intervention at 6:00)	9	CO	0.0319	**0.0308**	0.0352	***0.0007***
		Temp	0.0007	**0.0260**	0.0012	***0***
	11	CO	0.0048	**0.0032**	0.0144	***0.0001***
		Temp	0.0007	**0.1623**	0.0020	***0***
Kitchen (FD intervention at 10:00)	13	CO	0.0010	0.0029	0.0031	***0.0001***
		Temp	0.0001	0	0.0001	***0***

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors

tion times were on a gradual decline and often even below the 120°C threshold for which heat is an imminent threat for the trapped victim. On the other hand, the accumulation of FED due to CO exposure was usually at the maximum measurable value (due to saturation of the CO and CO_2 measurement equipment) at 0.035 FED/s at both 6 and 8 min after ignition. Thus, the longer the victims remain within these ventilation-limited fire scenarios, the more important the gas exposures to the victims become. Were these fires conducted with a different ventilation profile, such as one that would be caused by an open door or after window failure, results may be different. Such scenarios will be the subject of future study.

The FED methodology predicts that susceptible victims in the fire room will reach a critical thermal exposure prior to reaching a similar critical gas exposure. In most cases, this difference is only 20 s to 30 s, even with utilizing the simple two gas (CO & CO2) model. It is possible that if temperature and concentration sampling were taken at a vertical location higher in the room, this discrepancy would be larger. Victims' proximity to the flaming fire would also have a significant impact on these values, increasing the thermal FED closer to the seat of the fire. Furthermore, including the effect of exposure to radiant heat would increase thermal FED in the fire room. For the sampling locations in non-fire (but connected) rooms, critical levels of exposure were reached for CO exposure, typically well before critical exposure to elevated temperatures.

Table 7
FED Instantaneous Exposure at the Time of Ventilation in the Two-Story Experiments

Experiment #			Family room[a] (FED/s)	Bedroom 1 (FED/s)	Bedroom 2 (closed door) (FED/s)	Bedroom 3 (FED/s)
Family Room (FD intervention at 10:00)	2	CO	**0.0035**	0.0034	***0***	0.0044
		Temp	**0.0009**	0.0008	***0***	0.0018
	4	CO	**0.0034**	0.0020	***0***	0.0026
		Temp	**0.0093**	0.0010	***0***	0.0026
	6	CO	**0.0038**	0.0028	***0.0001***	0.0031
		Temp	**0.0070**	0.0010	***0***	0.0024
	8	CO	**0.0053**	0.0041	***0.0002***	0.0052
		Temp	**0.0096**	0.0016	***0***	0.0034
	12	CO	**0.0014**	0.0023	***0.0001***	0.0188
		Temp	**0.0136**	0.0014	***0***	0.0036
Bedroom 3 (FD intervention at 10:00 for #10 & 8:35 for #14)	10	CO	0	0.0310	***0.0003***	**0.0032**
		Temp	0	0.0003	***0***	**0.0027**
	14	CO	0	0.0352	***0.0004***	**0.0313**
		Temp	0	0.0006	***0***	**0.0275**
Kitchen (FD intervention at 17:00)	16	CO	0.0027	0.0049	***0.0003***	0.0040
		Temp	0.0007	0.0004	***0***	0.0010

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors

As we conducted four experiments that were identical pre-ventilation in both the one-story (1, 3, 5, 7) and two-story (2, 4, 6, 8) structures, it is possible to quantify the repeatability in tenability for identical fuel loads and fires. Table 8 shows the average accumulated FED value at ventilation in each room as well as the sample standard deviation for both the heat and toxic gases exposure. The largest variability was seen in the fire room of the two-story structure. However, for the most part, the standard deviation was ±25% of the mean.

Table 8
Repeatability of FED Accumulation for Identical Experiments (Values in Table Written in Mean ± Standard Deviation)

Structure	Exposure type	Living room/family room	Master bedroom	Target bedroom with open door	Target bedroom with closed door
One-story	CO	3.67 ± 0.62	1.68 ± 0.61	3.57 ± 1.54	0.045 ± 0.047
	Temp	4.87 ± 1.31	0.19 ± 0.04	0.37 ± 0.06	0 ± 0
Two-story	CO	0.50 ± 0.14	0.22 ± 0.05	0.29 ± 0.11	0.022 ± 0.026
	Temp	5.44 ± 3.21	0.035 ± 0.07	0.59 ± 0.11	0 ± 0

4.1. One-Story versus Two Story Structure: Living Room Fires

Four experiments in the single story structure (Experiments 1, 3, 5, and 7) are all identical in terms of structure and fuel package layout and materials, ignition location (Living Room), and ventilation conditions up to the 8 min where firefighters intervened. Environmental conditions were held to a high level of repeatability in terms of temperature, moisture and air velocity (basically still). However, outside of the closed bedrooms, FED values ranged dramatically. For the fire room (living room), FED_{temp} ranged from 4.0 to 6.8, while FED_{CO} in Bedroom 2 ranged from 1.2 to 4.5. For the two-story structure, a similar series of experiments were run with the Family Room as the ignition location. Nearly identical fuel packages were ignited in experiments 2,4,6,8, and 12. For the fire room, FED_{temp} ranged from 2.4 to 9.8, while FED_{CO} in Bedroom 3 ranged from 0.2 to 0.5.

Time to untenability for these 'room and contents' fires with limited ventilation is much improved on the second floor of the two story structure compared to the one-story structure, largely due to the increased volume of the structure. If the same volume of CO is generated by these fires, the two-story structure will have a smaller CO concentration because of the increased dilution with air in the enclosed space. Additionally, carbon monoxide generation typically increases as the fire becomes oxygen-limited. Since the two-story structure has more oxygen available inside the enclosed space at the start of the fire, CO generation is likely to increase more slowly than in the one-story structure. Importantly, while the second floor bedrooms are more tenable than the first floor spaces, egress through the interior of the structure would likely require exposure to the highly untenable conditions on the first floor. Firefighters should consider this fact in the risk–benefit analysis when employing vent-enter-isolate-search techniques to rapidly access victims on the second floor from the exterior as opposed to attempting rescue through the high temperature environment on the interior of the first floor.

For the single story structure, the FED_{CO} values in the target bedrooms with open doors were consistently higher in Bedroom 2 compared to Bedroom 1. The trend for FED_{temp} was not as clear, though the values were higher in Bedroom 2 compared to Bedroom 1 for two experiments and similar in the remaining three living room fire experiments. This affect could possibly be attributed to the smaller volume of Bedroom 2, the orientation of the door at the end of the hallway, or the distance from the heat source which results in lower temperatures further from the heat source and thus less stratification of the gas layer. For the two-story structure, FED_{CO} was similar in Bedroom 1 and 3. However, FED_{temp} was significantly higher in Bedroom 3, exceeding 0.3 for all 5 scenarios while never exceeding 0.2 in Bedroom 1 for any scenarios. Interestingly, the largest FED in the second floor bedrooms was due to thermal effects for Bedroom 3, but due to CO in Bedroom 1. Again, this may be due to the distance from the heat source resulting in lower temperatures but also less stratification of the gas layer. Additional research would be required to fully understand and decouple these potentially interacting effects.

4.2. Impact of Fire Location and Fuel Source

The bedroom fire scenarios each transition to ventilation limited conditions more rapidly than the Living Room fires, and result in higher fire compartment temperatures. FED at the time of fire department intervention for the bedroom scenarios was well in excess of 30, suggesting that more than 99.9% of the population would be incapacitated. These fires are ignited in smaller compartments providing significant re-radiation and more rapid growth. For the single story structure, FED_{CO} values produced by the bedroom scenarios were similar to or larger than those produced by the Living Room fire despite fire department 'intervention' 2 min earlier than the Living Room scenarios. At the same time, the temperature increase in the non-fire rooms is relatively small, with the maximum FED-temp = 0.21 in the adjacent bedroom.

For the two story scenarios, where the fire was ignited in the second floor bedrooms, the FED_{temp} values are almost three times higher than similar fires in the single story structure, even with identical furnishings and similar room size. However, this is partially attributed to the longer times to firefighter 'intervention' in those experiments. Additionally, for open bedrooms on the second floor, the FED_{CO} values were 20× to 30× higher in the bedroom fires than those measured during the family room fires. As with the living room/family room scenarios, the largest risk for remote victims is again gas exposures, but the risk is relatively more elevated in the bedroom fire scenarios because the fires become locally ventilation-limited due to their confined nature. It is also likely that since these scenarios resulted in higher ambient fire room temperatures more rapidly, they were able to sustain the combustion process even at lower oxygen concentrations, producing relatively larger amounts of CO. On the first floor of the structure, there was little measureable impact on tenability, most likely due to the buoyant nature of the combustion products. Furthermore, without a ventilation location for combustion products to escape, air from the first floor is not as easily entrained into the oxygen-limited fire on the second floor.

The kitchen fuel package (Experiments 13 and 16) resulted in low FED compared to the living room and bedroom fuel packages in both structures. For the kitchen fire scenarios—and typical of common structures in the US—the majority of the fuel is wood cabinets and countertop appliances of hard plastic. Fewer soft and/or foamed polymers are typically found in the kitchen. At the time of fire department intervention (even delayed to 10 min), $FED_{temp} < 0.01$ in all target rooms. The worst case bedroom $FED_{CO} = 0.5$, which is equivalent to the lowest value measured for the living room fire. The fuel sources in the kitchen fires consisted mostly of wood cabinets and countertops that burn slower and take longer for the structure to reach ventilation-limited conditions. CO production increases significantly when the fire reaches ventilation-limited conditions [24], and thus there is more CO produced by the bedroom and living room fires. Kitchen fires are the most common source of residential fires (43%), but fortunately appear to be the most survivable based on results from this study.

Finally, experiment 17 was added to the test series to provide a comparison with furnishings constructed from mostly natural materials (sometimes referred to as legacy furniture [5]) as opposed to the largely polymer based furnishings that are currently common in US households. The average times to achieve untenable conditions for Experiment 17 were well beyond the timeframe of initial fire service intervention (24:30 for FEC criteria of 0.3). This is an increase of approximately 20 min compared to the experiments with living room furnishings common in the twenty-first century in the one-story structure. Compared to the NFPA 1710 and 1720 based response timeframes, it is apparent that firefighters of the past responding to fires with these fuels were likely to find survivable victims more readily than fires involving fuel loads typical of today's structures. At the same time, fire-related occupant fatalities have continued to decline over the past several decades in apparent contrast to the tenability data presented here. Thanks to progress in public education, fire safety initiatives, widespread use of smoke detectors, and increasing installation of active fire sprinkler system, fire protection engineers have been successful at not only keeping pace with this increasing tenability risk, but actually affecting an improvement in life safety.

4.3. Behind Closed Doors

While improved detection, suppression and public education have helped to drive down fire related injuries and fatalities, a complimentary initiative can be supported by the notable tenability levels in Bedroom 3 of the one-story structure and Bedroom 2 of the two-story structure. Both of these rooms had the interior doors closed for the duration of the experiments, physically separating these spaces from the fire room. Importantly, the times to untenability found in Tables 2 and 4 suggest that occupants in compartments with closed doors never receive an FED > 0.3, even though an immediately adjacent bedroom may reach FED $= 0.3$ in approximately 5 min or less. In every case, thermal FED in the bedroom behind closed doors remained less than 0.01. The maximum FED based on CO exposure in these rooms was measured for living room fires at 0.11, which would be considered untenable for 1.4% of the population. For this same scenario, the adjacent bedroom with open door resulted in a measured $FED_{CO} = 4.51$, which would be untenable for 93% of the population.

In order to quantitatively characterize the improvement in tenability behind closed doors, FED ratios at the time of firefighter intervention were calculated and they are reported in Tables 9 and 10. The FED ratio is calculated for the nearest bedroom of the same dimensions compared to the closed door bedroom (BR2/BR3 for one-story and BR3/BR2 for two-story). Two scenarios for the two-story structure utilized bedroom 3 as the fire room, so in this case, the bedroom 1 is the open bedroom control. This bedroom is farther away from the fire room than bedroom 2 and larger, so should provide a conservative FED estimate. In some scenarios, the FED behind closed doors is very small, so a lower limit of FED $= 0.01$ is utilized for these calculations to bound the calculation. In all cases, the maximum FED—based on either temperature or gas—is utilized for each room.

Due to the relatively small FED in the closed bedroom, the FED ratio varies widely even for the same ignition location. However, for the single story structure,

Table 9
Maximum FED Values and FED Ratios Comparing Open and Closed Bedroom FED in the Single Story House

Experiment #		Bedroom 2	Bedroom 3 (closed door)	FED Ratio
Living Room	1	4.41 CO	0.01 CO	441
	3	4.51 CO	0.11 CO	41
	5	1.85 (CO, BR1)	0.05 CO	37
	7	1.79 CO	0.01 CO	179
	15	0.50 Temp	0.01 CO	50
	17†	0.37 < CO	0.01 CO	37
Bedroom 1	9	6.06 CO	0.08 CO	179
	11	0.46 CO	0.01 CO	46
Kitchen	13	0.51 CO	0.07 CO	7.3

For closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide lower bound estimate

Table 10
Maximum FED Values and FED Ratios Comparing Open and Closed Bedroom FED in the Two Story House

Experiment #		Bedroom 2 (closed door)	Bedroom 3	FED Ratio
Family room	2	0.01 CO/Temp	0.64 Temp	64
	4	0.01 CO/Temp	0.46 Temp	46
	6	0.05 CO	0.55 Temp	11
	8	0.04 CO	0.70 Temp	17.5
	12	0.03 CO	0.42 Temp	14
Bedroom 3	10	0.05 CO	8.5 (BR1) CO	170
	14	0.03 CO	5.5 (BR1) CO	183
Kitchen	16	0.13 CO	0.47 CO	3.6

For closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide lower bound estimate the FED ratio ranged from 7.3 for the kitchen scenario (which resulted in FED <0.5 throughout the structure) to over 400 for a Living Room scenario. The median value (for all 17 experiments) was 46—a potential trapped victim behind a closed door would be exposed to a 46× lower FED than those in a bedroom with an open door.

In both cases, the lowest FED ratio behind closed doors was for the Kitchen scenarios, which were significantly longer and had relatively low temperatures compared to the other tests. For the two story structure, the largest FED ratio was found for the Bedroom fires, which occurred on the same level as the other bedrooms. For the one story structure, there was little difference in the FED ratio from the Bedroom to Living Room fires.

Once again, this data suggests the importance of teaching the public the value of a comprehensive fire safety plan in residential structures. As mentioned earlier, the rapid accumulation of an incapacitating FED in a timeframe that is well within the 2 min to 16 min RSET analysis of Proulx et al. [22] highlights the need for rapid fire detection and notification throughout a structure as well as active suppression systems that can control the fire. At the same time, certain individuals will not feasibly be able to respond rapidly enough to self-evacuate, in which case the critical message of sheltering behind a closed door should be shared. The tables included in this manuscript show the unequivocal improvement in tenability behind closed doors, particularly for those who may be susceptible to smoke exposure and also have a long RSET (young, elderly, mobility impaired). Furthermore, for those individuals whose means of egress may be cut off by the progression of a fire, the value of sheltering behind closed doors should be reinforced based on this data.

5. Conclusions

Using the ISO 13571 tenability criteria for occupant exposure to heat and toxic gases, tenability conditions were determined throughout a series of 17 experiments. It was observed that prior to firefighter intervention, fires in the one-story structure result in a larger threat to occupant tenability for similar fires due to the lower amounts of available oxygen and smaller volume for the toxic gases to fill. These two factors lead to increased carbon monoxide and carbon dioxide concentrations. In many of the one-story experiments, the FED values prior to firefighter intervention were larger than 1 even in the non-fire rooms. In the single story structure, gas exposure was the highest risk for target rooms, while thermal exposure was the largest risk in the same rooms in the larger two-story structure. However, it was also observed that for rooms where the door was closed during the development of the fire, the FED values remained below 0.1 in all cases prior to firefighter intervention. Importantly, the median FED value was 46× higher for occupants in open bedrooms than for occupants behind closed doors, significantly reducing the risk the occupant faces.

This study provides further understanding of the timelines for tenability for common residential structure fires. It is important to note that the effect of radiant heat in the fire room and the impact of other toxic gases, especially HCN, was not measured. As a result, the presented FED values may be lower and times to untenability higher than if the combined effects were included. Future research should expand upon this data by incorporating those additional measurements (heat flux and HCN concentration) as well as other types of construction common in different parts of the world.

Acknowledgements

Funding was provided by U.S. Department of Homeland Security (Grant No. EMW-2010-FP-00661).

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A.4 Paper IV: Occupant Tenability in Single Family Homes: Part II - Impact of Door Control, Vertical Ventilation and Water Application

Fire Technology, 53, 1611–1640, 2017

Manufactured in The United States
DOI: 10.1007/s10694-017-0652-4

Occupant Tenability in Single Family Homes: Part II: Impact of Door Control, Vertical Ventilation and Water Application

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Received: 4 August 2016/**Accepted:** 15 February 2017

Abstract. This paper describes experimental investigations of fire service ventilation and suppression practices in full-scale residential structures, including a one-story, 112 m^2, 3 bedroom, 1 bathroom house with 8 total rooms and a two-story 297 m^2, 4 bedroom, 2.5 bathroom house with 12 total rooms. The two-story house featured a modern open floor plan, two-story great room and open foyer. Seventeen experiments were conducted varying fire location, ventilation locations, the size of ventilation openings and suppression techniques. The experimental series was designed to examine the impact of several different tactics on tenability: door control, vertical ventilation size, and exterior suppression. The results of these experiments examine potential occupant and firefighter tenability and provide knowledge the fire service can use to examine their vertical ventilation and exterior suppression standard operating procedures and training content. It was observed that door control performed better at controlling the thermal exposure to occupants than did fully opening the door. Additionally, the impact of increased vertical ventilation area was minimal, and only slightly reduced the thermal exposure to occupants in a few non-fire rooms. In the two-story structure, the non-fire rooms on the second floor consistently had larger thermal fractional effective rate (FER) values (approximately 2.5× the thermal risk to oocupants) than did the non-fire rooms on the first floor. Water application was also shown to reduce the thermal risk to occupants 60 s after water application 1/3rd the original values on second floor rooms of the two-storry structure and by at least 1/5th of the original values on the first floor rooms of both structures. Data also showed that the impact of front door ventilation on the toxic gases exposure was minimal, as the toxic gases FER actually increased after front door ventilation for several experiments. However, after vertical ventilation there was a 30% reduction in the toxic gases exposure rate in two of the one-story structure experiments.

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Keywords: Fire, Fire behavior, Vertical ventilation, Firefighting tactics, Tenability, Water application, Residential homes

1. Introduction

There is a continued tragic loss of firefighter and civilian lives during residential fires. One significant contributing factor is the lack of understanding of fire behavior in residential structures resulting from the use of ventilation as a firefighter practice on the fire ground. The changing dynamics of residential fires as a result of evolutions in home construction materials, contents, size and geometry over the past 30 years compounds our lack of understanding of the effects of ventilation on fire behavior [1]. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. On the other hand, improper ventilation can have significant impacts on tenability for occupants and, as well as potentially impacting fire spread, can lead to flashover [2].

NFPA estimates that from 2009 to 2013 [3], U.S. fire departments responded to an average of 357,000 residential fires annually. These fires caused an estimated average of 2470 civilian deaths and 12,890 civilian injuries each year. For the 2006–2009 period, there were an estimated annual average of 35,743 firefighter fire ground injuries in the U.S. [4]. Thanks in part to significant research and development by fire protection engineers that has focused on installed detection and suppression systems as well as structural fire protection, the total number of fires and fatalities due to fire have been steadily reducing. At the same time, the rate of traumatic firefighter deaths occurring outside structures, or from cardiac arrest, has declined. Unfortunately, firefighter deaths occurring inside structures has continued to climb over the past 30 years [5]. However, relatively little research has been conducted to scientifically inform the Fire Service on intervention techniques that can further reduce risk to occupants who may be trapped in structures where installed systems are not present.

Firefighters have two primary means in which they can impact the tenability of a room and contents fire for potentially trapped occupant: they can control air flow, typically through ventilation or they can absorb the energy being produced, most commonly by applying water to the fire. In firefighting, ventilation refers to the process of creating openings to remove smoke, heat and toxic gases from a burning structure and to replace them with fresh air. If used properly, ventilation improves visibility and reduces the chance of flashover or back draft. If used improperly, ventilation can cause the fire to grow in intensity and potentially endanger the lives of fire fighters who are between the fire and the ventilation opening [6].

While no known studies describe statistics for ventilation-induced fire injuries and fatalities, there are several examples of recent ventilation-impacted fires that resulted in fire fighter injuries and fatalities [7–10]. A recent NIOSH publication documents the extent of the situation: “Lives will continue to be lost unless fire departments make appropriate fundamental changes in fire-fighting tactics involving trusses. These fundamental changes include the following: Venting the roof using proper safety precautions” [11].

Firefighters have many tactical choices for water application, including interior attack, transitional attack, and exterior-only application of water [12–14]. The interior attack method typically involves firefighters entering the structure to apply water to the fire from a location where the fire has not yet spread, theoretically cutting off its ability to advance into the uninvolved part of the structure [12]. A transitional attack involves an initial rapid (on the order of 10 s) application of water from the exterior of the structure into the fire compartment to provide the initial knockdown, which holds the fire in check while crews transition to an interior position to fully suppress the fire [13]. The exterior focused attack attempts to completely suppress the fire from the outside of the structure and is typically employed when the structural elements of the building may be compromised and/or when no immediate occupant life safety hazard exists [14]. Each method has advantages and disadvantages, with the interior attack presenting the highest risk for exposure or collapse danger to the firefighter, while the exterior attack keeps the firefighter in a safer position but may present a challenge to accessing the seat of the fire. The transitional attack theoretically reduces the firefighters' initial exposure risk and allows the fire crews to operate an interior attack under relatively safer conditions. However, there are concerns that application of water from the exterior may cause detrimental changes to trapped occupants and cause a delay in locating potentially trapped victims.

In addition to different attack methods, firefighters also have the option to use different nozzle types, with smooth-bore and combination nozzles being the most commonly used in the US. The combination nozzle has multiple settings, from a wide-angle cone-like fog stream pattern to a narrow, relatively focused straight stream pattern. The smooth bore nozzle and straight stream pattern have the advantage of providing increased forward momentum to the water and greater penetration into the seat of the fire. The wide-angle fog stream pattern has the advantage of delivering smaller, more dispersed droplets and thus greater potential for cooling of the gases due to more rapid conversion to steam [15]. Previous work has also shown that reaching the burning fuel of the fire is a limiting factor for firefighters [16].

As previous research has shown [17], fire rooms and even some non-fire rooms can become untenable before fire service arrival, yet victims in remote rooms, particularly those behind closed doors, may still be viable. In order to affect a rescue, firefighters may need to make important decisions regarding ventilation and/or water application to the fire room. In some cases, the typical egress path for occupants may be through a common room, such as a living room or family room. Potentially viable victims may be negatively impacted if firefighters evacuate them through conditions that rapidly expose them to high heat or concentrations of toxic gases. The impact of firefighting operations on the fire environment will be quantified by examining how the different tactics influence tenability for occupants potentially trapped by the fire. Tenability can be used to mean many things, but in this study tenability will be measured using the ISO 13571 criteria for heat exposure and toxic gases [18]. This methodology has been used on many other studies to examine occupant tenability in different fire scenarios. In 2000, Purser examined the effect of ventilation on fire growth and tenability using rigs constructed to simulate compartment fires [19]. The methodology has also been used to assess the risk to occupants in legacy residential housing [20], one-bedroom apartment fires [21], and basement fires [22].

The purpose of this study was to gain knowledge of the effects of vertical ventilation and the impact of different suppression techniques on occupants which may remain within the structure. The experimental results can be used to develop tactical considerations outlining firefighting ventilation and suppression practices to reduce occupant and firefighter casualties.

This study focuses on room and content fires within the living space of a residential structure. These experiments were also meant to simulate initial fire service operations by an engine company or engine and truck company arriving together in short order with approximately national average response times.

2. Experimental Setup

To examine ventilation practices as well as the impact of changes in modern house geometries, two houses were constructed inside the UL large fire experimental facility in Northbrook, IL (USA). Seventeen experiments were conducted varying fire location, ventilation locations, the size of ventilation openings and suppression techniques, though this report will only focus on 6 of those scenarios (Table 1).

The experimental series was designed to examine several scenarios that were identified as gaps in current fire service knowledge of fire dynamics, ventilation and suppression [23]. These gaps include: impact of door control; impact of vertical ventilation hole size; and impact of exterior suppression. Experiments in each house were conducted 3 days apart to allow for ambient conditions inside the houses between 15°C and 22°C and below 50% relative humidity prior to ignition. While the entire study conducted 17 experiments, the focus of this paper is on the

Table 1
Experimental Details (Experiment # Refers to UL Report [23])

Experiment #	Structure	Location of ignition	Ventilation locations
3	One-story	Living room	Front door partially open (0.1 m by 2.0 m) + Roof (1.2 m by 1.2 m)
5	One-story	Living room	Front door (0.8 m by 2.0 m) + Roof (1.2 m by 1.2 m)
7	One-story	Living room	Front door (0.8 m by 2.0 m) + Roof (1.2 m by 2.4 m)
4	Two-story	Family room	Front door partially open (0.1 m by 2.0 m) + Roof (1.2 m by 1.2 m)
6	Two-story	Family room	Front door (0.8 m by 2.0 m) + Roof (1.2 m by 1.2 m)
8	Two-story	Family room	Front door (0.8 m by 2.0 m) + Roof (1.2 m by 2.4 m)

six experiments outlined in Table 1 and the effectiveness of the different ventilation tactics used.

2.1. One-Story Structure

Four of the experiments took place in the one-story structure. The structure was designed to be representative of a home constructed in the mid-twentieth century. The one-story structure had an area of 112 m^2, with 2.4 m ceilings and included 3 bedrooms, 1 bathroom and 8 total rooms (Figure 1). The home was wood framed, lined with two layers of gypsum board (base layer 16 mm, surface layer 13 mm) to protect the structure and allow for multiple experiments. All of the windows were closed with removable inserts so that window opening could be controlled at the time specified for each experiment. A roof ventilation system was created above the living room to allow for remote roof ventilation. Hinged openings were used to simulate a roof cut being "pulled open" and a section of ceiling was able to be removed simulating the ceiling being "pushed" through from above to ventilate the fire in the living space.

2.2. Two-Story Structure

The two-story structure had an area of 297 m^2; with 4 bedrooms, 2.5 bathrooms and 12 total rooms (Figures 2, 3). The structure incorporated features common in early twenty-first century construction, such as an open floor plan, two-story great

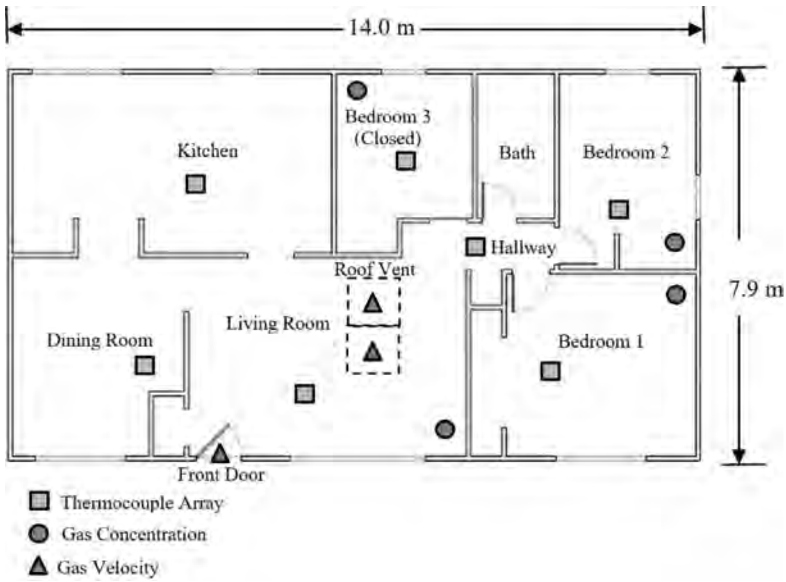

Figure 1. One-story house floor plan with instrument locations.

room, open foyer, and half landing stairs. The home was also a wood framed structure lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm). The windows had similar removable inserts. A roof ventilation system was created above the family room to allow for remote roof ventilation. Hinged sections of roof could be opened to simulate a roof cut being completed. This section did not have an interior ceiling to be "pushed" because this section of the roof above the great room was simulated to be a cathedral style ceiling, i.e. the interior volume of the compartment extended to the ceiling of the second floor, with a height of 5.2 m, having no void below the flat roof. The area of the family room that extended to the ceiling of the second floor is indicated by the dotted line encompassing the family room in Figure 2.

2.3. Fuel Load

The living room in the one-story house and the family room in the two-story house were furnished similarly with two sofas, television stand, television, end table, coffee table, chair, ottoman, two pictures, lamp with shade, and two curtains The floor was covered with polyurethane foam padding and polyester carpet. The fuel loading was approximately 29 kg/m^2. Pictures of the fuel load for each structure can be found in Figure 4. Additional rooms in the house were fully furnished with typical residential bedroom, dining room, and kitchen furnishings. However, these materials did not contribute to the fuel load involved in the fires of interest to this manuscript.

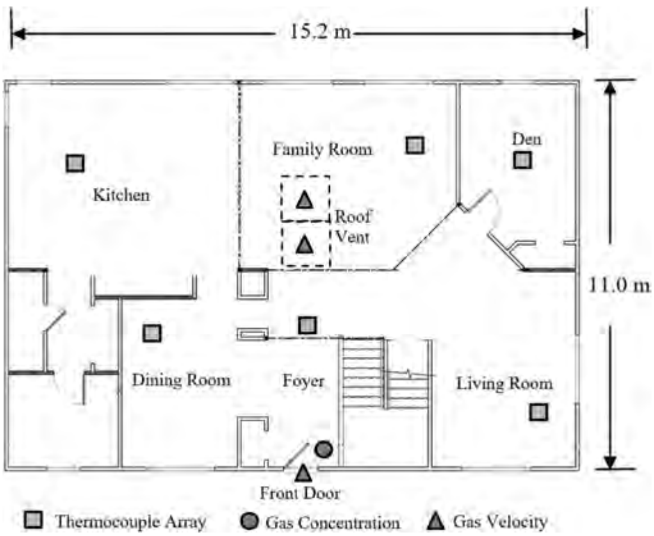

Figure 2. Two-story house first floor plan with instrument locations.

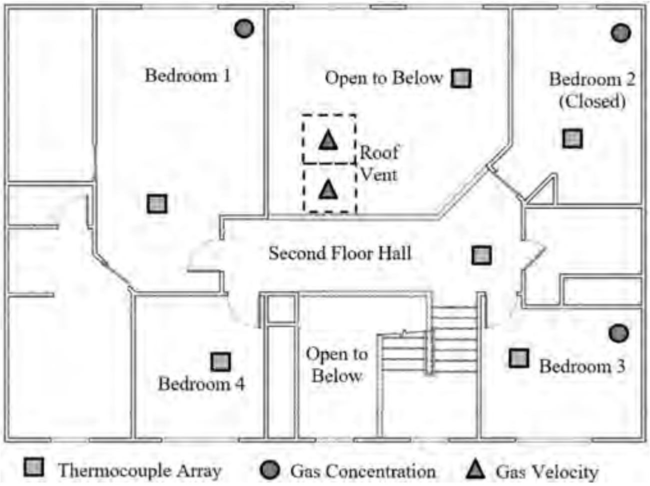

Figure 3. Two-story house second floor plan with instrument locations.

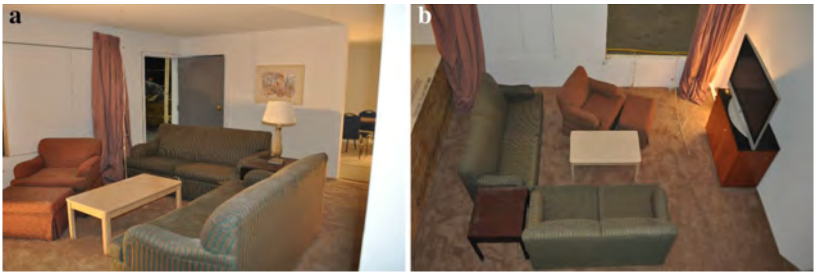

Figure 4. (a) One-story living room fuel load (picture from hallway of one-story). (b) Two-story family room fuel load (picture from roof vent down into family room).

In order to characterize the living/family room fuel load, the fuels were placed in a 5.5 m wide by 4.0 m deep room by 2.4 m high room underneath an oxygen consumption calorimeter. The room had a 3.1 m wide by 2.1 m tall opening on the front wall. The measured peak heat release rate of the fuel load was 8.8 MW [23].

2.4. Instrumentation

The measurements taken during the experiments included gas temperature, gas velocity, gas concentrations, and video recording. Gas temperature was measured with bare-bead, type K thermocouples, with a 0.5 mm nominal diameter. Thermocouple array locations are shown in Figures 1, 2, and 3. Thermocouples were located in the living room and hallway in the one-story house and foyer and second floor hallway in the two-story house. Each location had an array of thermocouples with measurement locations of 0.03, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 m below the ceiling. Thermocouple arrays were also located in the dining room, kitchen, den and bedrooms had measurement locations of 0.3, 0.9, 1.5, and 2.1 m below the ceiling. The family room had thermocouple locations every 0.3 m below the ceiling down to the floor. The uncertainty in type K thermocouple measurements is less than 1–2% of the measured value for temperatures up to 1250 K [24].

Gas velocity was measured utilizing differential pressure transducers connected to bidirectional velocity probes, located in the front doorway and the roof ventilation opening (Figures 1, 2, and 3). There were five probes on the vertical centerline of each doorway located at 0.3 m from the top of the doorway, the center of the doorway, and 0.3 m from the bottom of the doorway. Thermocouples were co-located with the bidirectional probes to complete the gas velocity measurement.

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured (Ultramat 23 NDIR; Siemens) at 0.9 m from the floor adjacent to the front door and in bedrooms 1, 2 and 3 for both houses. Gas concentration measurements after water flow into the structure are not reliable may not be accurate due to the effect of moisture on the gas measurement equipment. The uncertainty of the measured concentration is 1% of the maximum concentration measurement. The maximum concentration measurements were 1% for CO and 10% for CO_2. When this occurs, values are estimated at the saturation level for both gasses, resulting in some FED values that are conservative estimates, and subsequently increasing the uncertainty and bias of the FED values (as the reported values will be smaller than the actual exposure). All samples are collected at 1 Hz.

2.5. Experimental Methodology

All of the experiments started with the exterior doors and windows closed, the roof vents closed, and all of the interior doors open except for Bedroom 3 in the one-story and Bedroom 2 in the two-story structure. For the six experiments that will be the focus of this manuscript, the fires were ignited on a sofa in the living room (one-story) or family room (two-story). Additionally, it should be noted that none of the fires spread from the compartment of origin to any additional rooms.

The fire was allowed to progress in the closed structures until ventilation operations were simulated. The one-story house was ventilated at 8 min after ignition, and two-story house vented 10 min after ignition. This was timeline determined based on three factors; time to achieve ventilation limited conditions in the house, potential response and intervention times of the fire service, and window failure times from previous window failure experiments [23]. The additional 2 min for the larger structure ensured ventilation-limited conditions were achieved, as the available oxygen in the larger volume required more time to be consumed.

On the fireground, vertical and horizontal ventilation are performed at different time scales. There is an obvious difference between ventilating a glass window with a tool from the ground versus climbing to the roof and creating a ventilation hole through the roof membrane. Therefore, the timing of the vertical ventilation openings (which were created above the fire room) was done based on interior conditions and not a specific time. The criterion chosen was a temperature of 200°C at a height of 0.9 m in the area that a firefighting crew could be operating. This approach was chosen because a crew operating in that area could request vertical ventilation to improve the conditions. In addition, front door ventilation was conducted either fully open (80 cm) or partially open (10 cm wide, but since the door swings open the actual width of opening was 46 cm from door jamb to corner of the door to allow for hose movement). The ventilation operation with only 10 cm width of front door ventilation is representative of a firefighting tactic that may be used to limit the inflow of oxygen to the seat of the fire, while also still allowing for hose movement in the structure. After ventilation, the fire was allowed to grow until the maximum burning rate occurred, as determined by the temperatures measured in the fire room, observation of exterior conditions, and monitoring of the internal video. A hose stream was flowed in through the front door (which, if opened only 10 cm wide during fire development, was fully opened for suppression), with the firefighter on one knee and directing the hose stream to the ceiling of the fire room and to the burning fuel for both the one- and two-story structures.

The stream of water (45 mm line with a combination nozzle creating a flow of approximately 380 lpm) was directed into the front door for approximately 15 s. The 15 s water application was used to approximate the typical timing of a "transitional attack" tactic and not meant to completely suppress the fire. The potential for regrowth of the fire after this short application was an important aspect of this tactic to be studied. Two types of flow patterns were utilized during the experiments: straight stream and fog stream. During straight stream application, the nozzle was adjusted to a tightly focused pattern and directed into the structure with the guidance of putting water on what was burning, so the nozzle was not held stationary. During the fog stream application, the nozzle was adjusted to create an approximate 30° fog pattern with a broken stream and directed into the structure with the intent to move the nozzle as necessary to extinguish the visible fire. The experiment was terminated at least 1 min after application of the hose stream, and suppression was completed by the firefighting crew.

As an example, Figure 5 shows a typical time–temperature evolution (collected at a height of 0.9 m) in the one-story structure (Experiment 3). This figure shows the growth of the fire along with some key benchmark times of the experimental procedure. In every experiment, the procedure followed these important steps: (1) firefighters arrive 8–10 min after ignition, (2) first firefighter intervention is front door ventilation and lasts for 1.5–4 min, (3) second intervention is vertical ventilation and lasts until flashover, (4) third intervention is water application after which the fire is allowed to persist for another minute prior ro the experiment being brought to an end.

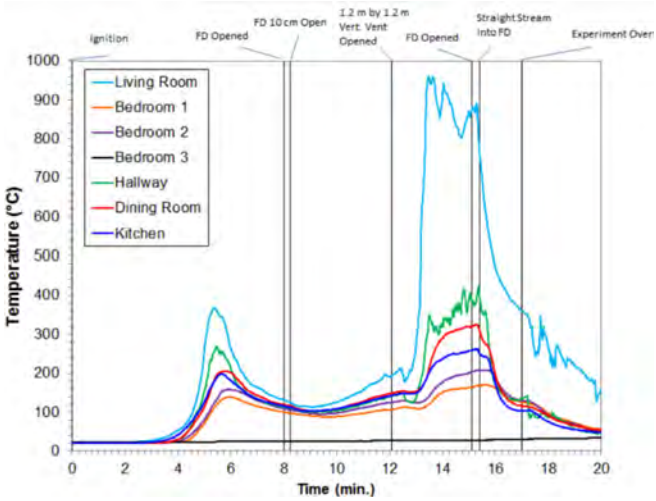

Figure 5. Temperatures at 0.9 m above the floor in every room of Experiment 3, which had the front door only 10 cm open as the initial ventilation operation.

For comparison, Figure 6 shows the time–temperature curve from an experiment with the front door fully opened (0.8 m), showing the more rapid transition to flashover after firefighter ventilation with the larger opening for make-up air.

2.6. Fractional Effective Rate Methodology

Occupant tenability, which is the survivability of occupants in the fire environment, is a primary concern for any firefighting operation. Two measures of occupant tenability were used during these experiments; temperature and gas concentration based on the fractional effective dose (FED) methodology that is outlined in ISO 13571 [18]. This methodology allows for the calculation of time to incapacitation based on an accumulated exposure to either heat or toxic gases and provides specified thresholds that are commonly utilized to estimate risk. Based on a lognormal distribution, FED = 0.3 is the criterion used to determine the time for incapacitation of susceptible people (11% of the population, includes young children, elderly, and/or unhealthy occupants) and FED = 1.0 is the value at which exposure would be considered untenable for 50% of the population.

FEDs were calculated at an elevation of 0.9 m above the floor for both houses, representative of a person lying or crawling on the floor. Any individual lying in bed or attempting to evacuate a structure while standing are likely to be exposed to a higher temperature and likely larger gas concentrations. The equations used to calculate the FED values at each time are given by Equations 1, 2a and 3a.

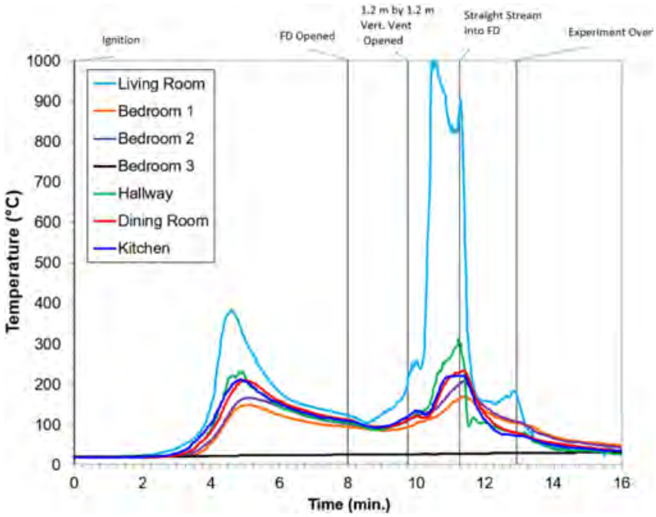

Figure 6. Temperatures at 0.9 m above the floor in every room of Experiment 5, which had the front door fully opened (0.8 m) as the initial ventilation operation.

$$\upsilon_{CO_2} = exp\left(\frac{\varphi_{CO_2}}{5}\right) \tag{1}$$

$$FED_{CO} = \sum\left[\frac{\varphi_{CO}}{3.5}\upsilon_{CO_2} \cdot \Delta t\right] \tag{2a}$$

$$FED_{heat} = \sum\left[\left(\frac{T^{3.61}}{4.1 \times 10^8}\right) \cdot \Delta t\right] \tag{3a}$$

where υ_{CO_2} is a frequency factor to account for the increased rate of breathing due to carbon dioxide, φ_{CO_2} and φ_{CO} are the mole fractions (%) of carbon dioxide and carbon monoxide, T is the temperature near the occupant (°C), and Δt is the time increment of the measurements made in the experiments in minutes. According to ISO 13571, the uncertainty in Equation 2a is ± 20% and the uncertainty in Equation 3a is ± 35%. Equation 3 only applies for temperatures greater than 120°C.

Traditionally, risk estimates are based on the entire timeframe of an exposure. For the scenarios of interest here, we are studying transient exposures that may be experienced while firefighters are attempting to affect rescue for a potentially trapped occupant with the goal of informing fire service tactics that may minimize the additional exposure risk for those who are being rescued. To better understand the instantaneous exposure, we will utilize the fractional effective rate (FER), which is the accumulation of FED with respect to time (units of FED/s).

$$FER_{CO} = \frac{\varphi_{CO}}{3.5} \cdot \upsilon_{CO_2} \cdot \frac{1}{60} \tag{2b}$$

$$FER_{heat} = \left(\frac{T^{3.61}}{4.1 \times 10^8}\right) \cdot \frac{1}{60} \tag{3b}$$

As an example, Figure 7 shows the Fractional Effective Rate (FER) as a function of time for Experiment 3 in the living room at 0.9 m above the floor for both CO and heat exposure. If, for instance, an occupant was rescued from a closed room at 8 min and then exits the structure at 12 min, then the total exposure to the occupant would be the area under the curve. Over the span of those 4 min, the accumulated exposure would be FED = 1.92. In the fire room, thermal exposure typically accumulates faster than gas exposure for most of the burn scenarios unless ventilation limited conditions are present. Through the initial growth of the fire, CO exposure rates are very slow until approximately 5 min, when the temperatures begin to decrease and the burning rate reduces. Exposures based on gas levels would then accumulate faster near the occupants until vertical ventilation is provided after which the fire rapidly transitions to flashover. It should also be noted that the flat portion of the CO exposure near 6 min and near 14 min is due to the saturation of the gas sampling equipment.

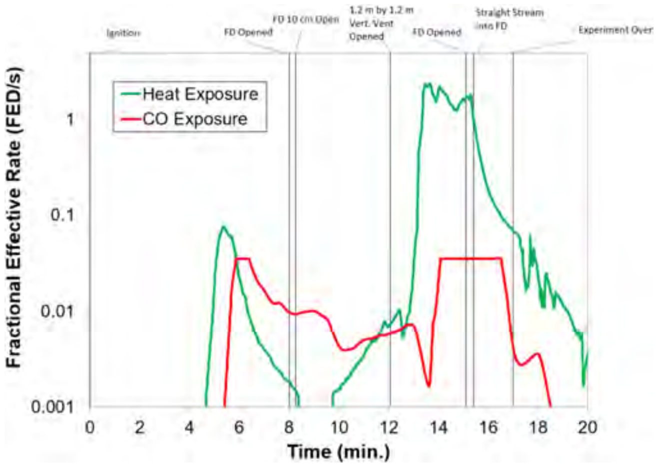

Figure 7. Fractional effective rate (FED/s) in fire room for Experiment 3 for both heat and toxic gases exposure.

The focus of this paper is on the effect of different firefighting tactics on the fire environment. However, for the experiments studied in this paper, the FED exposure prior to firefighter arrival is important for fire department decision making and is shown in Table 2. The exposure prior to fire department intervention can be large, especially in bedrooms with open doors in the one-story structure. These data show the inherent variability in fire development and potential occupant exposure, even for identical conditions prior to initial ventilation. While the best effort was made to compare similar experiments, and control as many variables as possible, fires themselves significantly contribute to the variability in the data and further research is needed to quantify the sources of variability in fire growth and response. For a full discussion on tenability prior to fire department arrival, see Part I [25]. The major takeaway though is that outside of closed bedrooms, occupants have likely received a lethal dose from the toxic gases. However, the occupants trapped behind closed doors are still facing tenable conditions and could be rescued.

3. Results and Discussion

As previous research has shown, occupants may have received minimal exposure to heat and toxic gases prior to firefighter intervention if behind closed doors. While they may have some level of safety when protection is in place, fireground actions which can reduce the risk for egress through common areas such as family rooms and living rooms can improve the likelihood of safe rescue. On the other hand, in areas of the structure away from the fire, they may have a significant exposure to fireground gases, such that immediate rescue and medical attention is necessary. Fireground actions that can reduce exposure to these gases and increase the rate at which firefighters can access these victims is critical. Fire Service intervention, through ventilation or water application, can impact the ability to safely evacuate these surviving individuals. We included data from both non-fire rooms, where surviving victims may be impacted by the fire service even if they stay in place, as well as fire rooms, through which victims may attempt self—rescue or be evacuated by firefighters.

3.1. The Effect of Firefighter Ventilation Tactics on Occupant Tenability

3.1.1. Fire Room This section will examine the impact of ventilation tactics on occupant tenability within the fire environment. Figures 8a, 8b show the FER for heat exposure as a function of time after front door ventilation, up until vertical ventilation takes place. Vertical vents were opened when the fire room temperature at 0.9 m exceeded 200°C. Thus for Experiment 3 this was approximately 4 min after the door was opened (See Figure 5), but between 1.5 min and 2 min for the 0.8 m door opening cases. The blue solid lines are for 10 cm door opening with 1.2 × 1.2 m vent, the red dashed lines are 0.8 m door opening with 1.2 × 1.2 m vertical vent, and the black dotted line is for 0.8 m door opening with 1.2 x 2.4 m vertical vent. The scenarios where the front door was fully opened, tenability rapidly reduced about 50 s after opening of the front door for both the

Table 2
FED Exposure Prior to Fire Department Arrival in the Fire Room and Bedrooms (Number in Parentheses Marks the Percent of Occupants Reaching Untenability for the Given FED Exposure) [adopted from 25]

Location of the fire, experiment #		Fire Room (mm:ss)	Master bedroom (mm:ss)	Target bedroom with door open (mm:ss)	Target bedroom with door closed (mm:ss)	
One-story living room	3	CO	3.17 (88%)	0.80 (41%)	4.51 (93%)	0.11 (1%)
(*FD intervention at 8:00*)		Temp	4.01 (92%)	0.14 (2%)	0.31 (12%)	*<0.01 (<0.1%)*
	5	CO	3.72 (91%)	1.85 (73%)	EM	0.05 (0.1%)
		Temp	4.45 (93%)	0.21 (6%)	0.41 (19%)	*<0.01 (<0.1%)*
	7	CO	4.53 (93%)	1.84 (73%)	1.79 (72%)	*<0.01 (<0.1%)*
		Temp	6.82 (97%)	0.22 (6%)	0.44 (21%)	*<0.01 (<0.1%)*
Two-story family room	4	CO	0.34 (14%)	0.16 (3%)	0.19 (5%)	*<0.01 (<0.1%)*
(*FD intervention at 10:00*)		Temp	3.77 (91%)	*<0.01 (<0.1%)*	0.46 (22%)	*<0.01 (<0.1%)*
	6	CO	0.47 (23%)	0.23 (7%)	0.26 (9%)	0.05 (0.1%)
		Temp	5.84 (96%)	*<0.01 (<0.1%)*	0.55 (28%)	*<0.01 (<0.1%)*
	8	CO	0.49 (24%)	0.21 (6%)	0.27 (10%)	0.04 (0.1%)
		Temp	9.77 (99%)	0.14 (2%)	0.70 (36%)	*<0.01 (<0.1%)*

one-story (Exp 5, 7) and two-story (Exp 6, 8) structures. However, with the front door only partially opened (Exp 3 and 4), the time to when FER increased in the fire room was dramatically delayed. In the one story structure, FER increased to 0.005 at about 200 s compared to 80 s with the door fully open. For the two story structure, there was no measurable increase in FER with the door control compared to a rapid increase from about 0.01 to 0.03 in about 60 s with the door fully opened. While FER does begin to increase due to the change in ventilation conditions, the accumulation of FED for potentially trapped victims to be removed through fire room is relatively small in the one story structure if rescue can be affected rapidly.

Figures 9a, b show the heat exposure FER for the fire rooms as a function of time after vertical ventilation for the one-story and two-story structure. Vertical ventilation resulted in the FER reaching values greater than 1 FED/s in 5 of the 6 experiments, which is very rapid when considering that FED = 1 corresponds to 50% of occupants reaching untenability. The vertical ventilation clearly resulted in significant growth in the fire. Occupants that are evacuated through rooms under these conditions will be rapidly impacted by the thermal conditions, even if they were behind closed doors and relatively unexposed prior to fire service intervention. The experiments with the front door only 10 cm open delayed the increase in fractional effective rate by 30 s in the one-story structure, and for the entirety of the experiment for the two-story structure. However, in both structures, there were negligible differences in the changes in FER in the fire room for the different vertical ventilation areas. For these scenarios, after vertical ventilation a unidirectional exit flow path is created with exhaust through the vertical vent and make up air provided by the open front door. Even with the make up air limited to the relatively small front door opening, enough fresh air is allowed to enter the fire room to reach flashover conditions. The increase in incoming air flow after vertical ventilation is seen in Figure 10, which shows the velocity at the centerline (height of 1.05 m) of the door (negative velocities represent incoming air). In particular, note the increase in incoming air at the onset of vertical ventilation, as the neutral plane of the doorway clearly rises. With both the 1.4 m^2 and the 2.9 m^2 vertical vent openings, thermal conditions in the fire room rapidly deteriorated. The larger opening for make-up air by the fully opened front door was sufficient to achieve flashover for the one-story structure. However, the reduction in make-up air based by the partially closed door significantly impacted the fire behavior. In fact, in the two-story structure, flashover was not achieved, possibly due to the high ceilings and reduced compartmentation in the fire room.

3.1.2. Non-fire Rooms Outside of the fire room, the heat exposure and temperatures in the non-fire room do not significantly change after front door ventilation. In fact, there were no significant differences in the heat exposure for non-fire rooms for any of these experiments after front door ventilation and *before* vertical ventilation.

However, *after* vertical ventilation, the thermal conditions in the non-fire rooms did begin to deteriorate in both the one-story (Figure 11) and two-story (Figure 12a, b) structures. In the one-story structure, vertical ventilation area had little

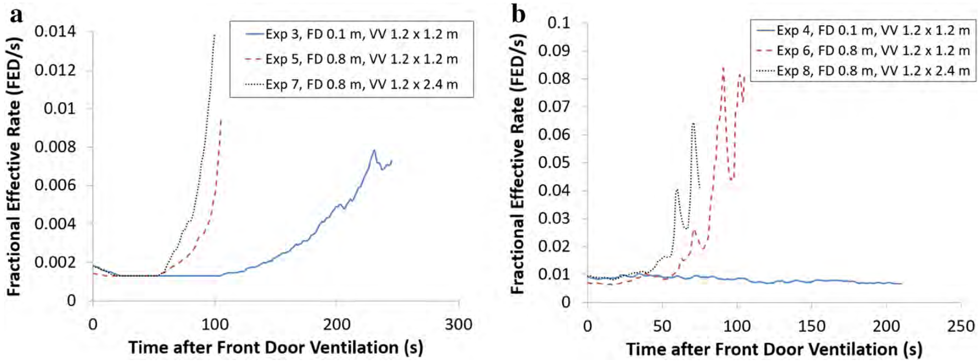

Figure 8. (a) Changes in heat exposure FER after front door ventilation in one-story fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size). (b) Changes in heat exposure FER after front door ventilation in two-story fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

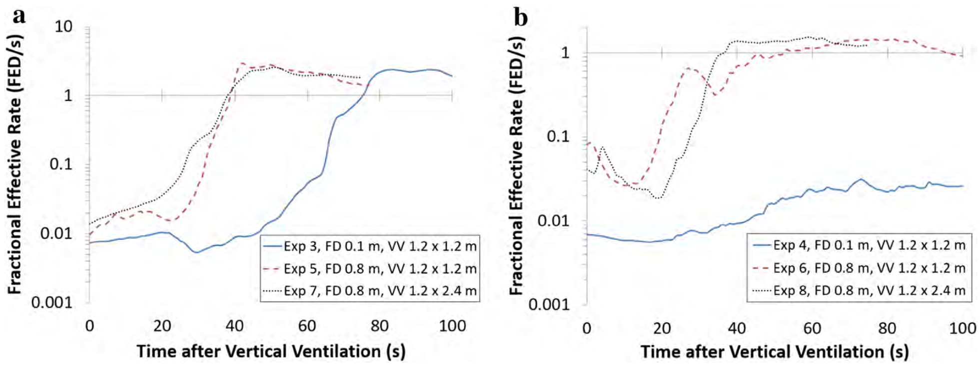

Figure 9. (a) Changes in heat exposure FER (log-scale) after vertical ventilation in one-story fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size). (b) Changes in heat exposure FER (log-scale) after vertical ventilation in two-story fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

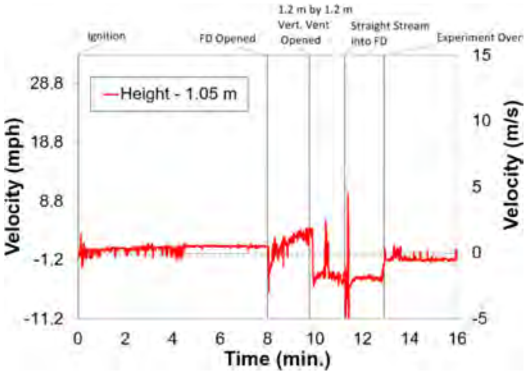

Figure 10. Velocity at the centerline of the doorway at the 1.05 m height for Experiment 5. Negative velocities indicate gases flowing into the structure. Positive velocities indicate gases flowing out of the structure.

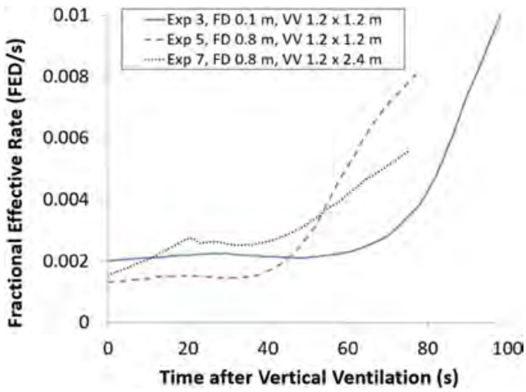

Figure 11. Changes in heat exposure FER after vertical ventilation in one-story non-fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

effect on the heat exposure FER for the non-fire rooms (Exp 5 and 7). However, reducing the inlet flow by controlling the front door opening (Exp 3) again delayed the onset of increasing FER values by more than 30 s.

In the two-story structure, non-fire rooms on the second floor consistently have higher FER values than the first floor non-fire rooms. This is due to the buoyant nature of the hot gases, which leads to higher temperatures in the second floor rooms than the first floor rooms. Limiting the influx of air by opening the front door only 10 cm impacted the rate of change of the FER values, as it took more than 180 s after vertical ventilation to reach an average FER greater than 0.015 FED/s for the second floor rooms compared to 45 s after vertical ventilation for the fully open front door (with same vertical vent area). In these scenarios, the total vertical ventilation area does appear to have an impact on non-fire room thermal conditions. The time to reach an average FER of 0.015 FED/s on the second floor rooms for the 1.44 m^2 vertical ventilation scenario was less than 40 s. However, for the experiment with 2.9 m^2 vertical ventilation, it was more than 75 s before reaching an average FER value greater than 0.015 FED/s. The lower FER values for the larger ventilation area experiment suggests that in the two-story structure, the increase in the exhaust of hot gases could be large enough to meaningfully reduce the spread of hot gases to the non-fire rooms. Relatively speaking, controlling the front door only 10 cm open was more effective than the increased vertical ventilation area in limiting the risk from heat exposure (and operationally more rapidly employed, while likely reducing the risk to the firefighters).

In addition to heat exposure for potentially trapped occupants, the effect of carbon monoxide exposure on tenability must also be considered. Figures 13a, b show the changes in FER values for the master bedroom (bedroom 1 in one-story and bedroom 3 in two-story) after front door ventilation for the one-story and two-story structures, respectively. In the one-story structure, the toxic gases FER values are already greater (in some cases by more than 2.5×) in bedroom 1 than the highest heat exposure FER values after vertical ventilation. In the two-story structure, however, the toxic gases FER values are actually relatively low compared to the largest FER heat exposure values observed after different ventilation tactics (approximately 1/10th of the heat exposure values on the second floor non-fire rooms). Importantly, it appears that front door ventilation tactics have little impact on the toxic gases FER values. Opening the front door alone does not provide significant relief from gas exposure for potentially trapped victims.

Likewise, changes in CO FER values after vertical ventilation are largely independent of both the vertical ventilation opening size and inlet air opening size (Figure 14a, b). There were two experiments that saw increases in the CO FER values but both of those increases occurred because the ventilation tactic led to quickly to flashover and sustained flashover for long enough to fill the structure with carbon monoxide before water was applied to the structure. If the other experiments had waited longer to apply water it is expected that similar observations would be made for all of the experiments. It is clear that prior to flashover, the changes in CO FER values in the structure are minimal compared with the changes witnessed for heat exposure FER values (5-50% change in the toxic gases FER values compared to 500 + % increase for heat exposure FER values after front door ventilations).

In the specific scenarios studied here, vertical ventilation alone does not provide significant improvements in life safety for trapped occupants. The 60–80 s of relatively small changes after front door ventilation and similar times prior to rapid increase in thermal conditions after vertical ventilation can provide a critical win-

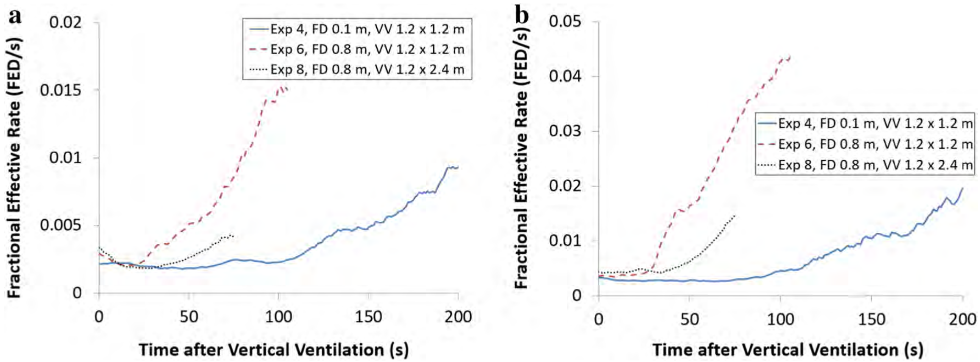

Figure 12. (a) Changes in heat exposure FER after vertical ventilation in two-story first floor non-fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size). (b) Changes in heat exposure FER after vertical ventilation in two-story second floor non-fire rooms for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

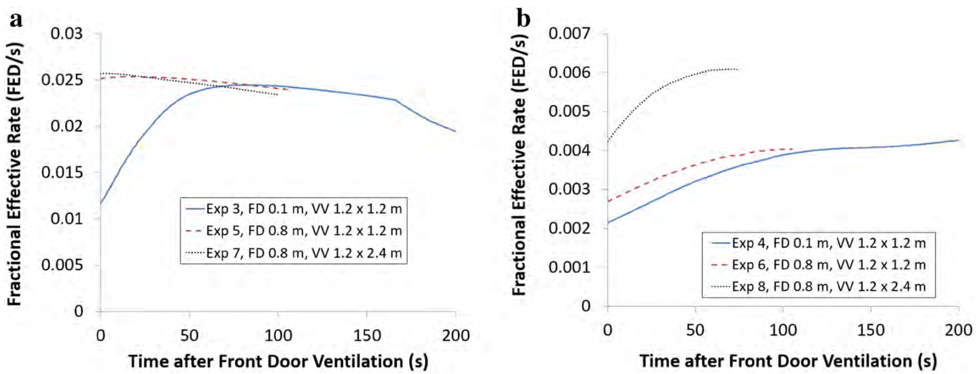

Figure 13. (a) Changes in toxic gases FER after front door ventilation in bedroom 1 of one-story structure for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size). (b) Changes in toxic gases FER after front door ventilation in bedroom 3 of two-story structure for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

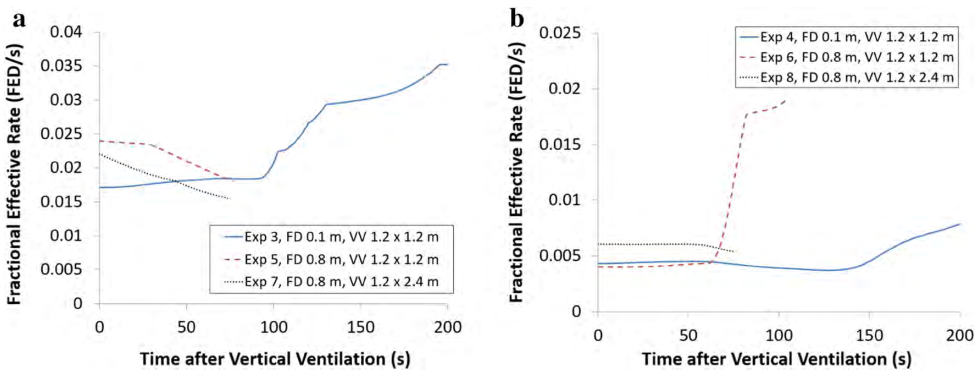

Figure 14. (a) Changes in toxic gases FER after vertical ventilation in bedroom 1 of one-story structure for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size). (b) Changes in toxic gases FER after vertical ventilation in bedroom 3 of two-story structure for 3 separate experiments with differing ventilation conditions (FD—front door opening, VV—vertical vent size).

dow for finding and rescuing victims. This timeframe also provides the firefighters with a critical opportunity to put water on the fire prior to reaching flashover conditions.

3.2. Effect of Water Application on Tenability in the Fire Environment

The second tool that firefighters have to control fireground conditions is application of water. Unfortunately, the gas concentration measurement technique utilized in this study is not reliable in the presence of water, so the effect of water application on gas exposure could not be assessed. However, the impact of water application on heat exposure tenability can be characterized. Figures 15 and 16 show the average change in FER values after water application for the one-story and two-story structure. Water application results in a significant reduction of the heat exposure FER values, especially in the fire room. The FER values change from greater than 1 FED/s to lower than 0.01 FED/s in approximately 20 s. The changes in the non-fire rooms is less drastic but still substantial in both structures. The average FER prior to water application in the one-story structure was greater than 0.01 FED/s, however approximately 60 s after water application, the average was reduced to 0.0015 FED/s, an 85% reduction in heat exposure risk to occupants. In the two-story structure, the water application reduced the risk significantly for both the first floor rooms (0.01 FED/s to 0.0013 FED/s) and the second floor rooms (0.03 FED/s to 0.01 FED/s). However, the second floor rooms have substantially higher FER throughout the scenarios due to the convective nature of the gases. Interestingly, after approximately 15 s past suppression, the temperatures in the second floor rooms are greater 0.9 m above the floor than are the corresponding temperatures in the fire room. Irregardless of impact on toxic gas exposure, this reduction in temperatures throughout the structure highlights the importance of water application prior to evacuating potentially trapped occupants through common rooms.

Figure 15 also shows the maximum and minimum FER values for fire and non-fire rooms in the one-story structure. This data highlights the variability in risk exposure from fire to fire and even room to room in the same fire. As can be seen, the difference in FER values varies by up to an order of magnitude even for non-fire rooms, and in the case of fire rooms can vary by more than 2 orders of magnitude at the same point in time after water application. In the cases where substantial decreases in FER were observed (FER < 0.01 FED/s), the water application had been able to successfully suppress much of the fire. However, in the cases where the FER values remain greater than 0.1 FED/s the water application was successful in cooling the hot gases and suppressing part of the fire, but residual heat and potentially small pockets of fire still remained after water application. Even in the cases where the fire room would still expose occupants to large FER, there was a reduction in the FER values in the non-fire rooms. It is important that, after initial exterior water application, the firefighter rapidly transition to the interior in order to locate any remaining hot spots and fully suppress the fire even if there is no life safety hazard in the structure. Importantly, in every one of these scenarios, temperatures in all fire and non-fire rooms never increased as a

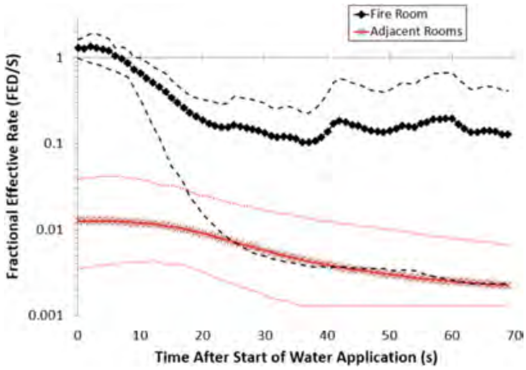

Figure 15. Average FER values at 0.9 m high in the fire room and the non-fire rooms after water application in the one-story structure (Exp 3, 5, 7). ***Solid lines*** **with markers represent the average FER of the data set.** ***Dashed lines*** **represent the max and min of the fire room data set.** ***Dotted lines*** **represent the max and min of the adjacent room data set.**

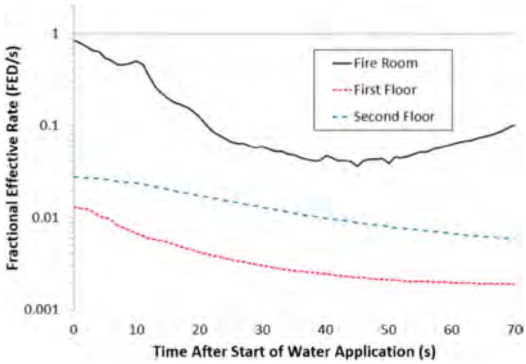

Figure 16. Average FER values after water application at 0.9 m high in the fire room, first floor rooms, and second floor rooms the two-story structure (Exp 4, 6, 8). data shows the FER value averaged for the 3 experiments and for all the rooms in the data series.

result of water application. In other words, none of these scenarios, where water was introduced from the exterior, resulted in fire or hot gasses being displaced from the fire room to a non-fire compartment. In each case, the risk to the occupant during egress reduced in both the fire and non-fire rooms.

The temperature reduction in non-fire rooms due to a straight stream applied directly to the fuel source can drastically improve the thermal tenability for occupants in non-fire rooms in the timeframe applicable to a firefighter's transitional attack tactics. In order to visualize the information in a different manner, we can plot the change in non-fire room temperature as function of the compartment temperature immediately prior to water application (Figure 17). The data presented in Figure 17 comes from every straight stream water application during the 17 experiment study. When water is applied with a straight stream setting temperatures are always reduced in the non-fire rooms (positive temperature reduction), with a larger effect in the rooms with higher initial temperature (typically those closer to the fire room). There are several interesting analyses that can be performed with this data. For example, on the plot is an overlay of the criteria for firefighter thermal tenability threshold of 260°C [26]. All of the data points left of the vertical line correspond to non-fire rooms that were tenable for firefighters before water application (n = 67). Data points between the vertical tenability line and inclined tenability line represent compartments where temperature was initially larger than the temperature threshold, but, 60 s after water application, the temperature was below the temperature threshold (n = 25). Data points to the right of the respective inclined tenability lines represent rooms where the temperature remained above the temperature threshold both before and 60 s after water application (n = 0). Temperatures in every non-fire room 60 s after straight stream water application were below the 260°C threshold for firefighters. Therefore, applying water from the exterior was able to improve tenability conditions in

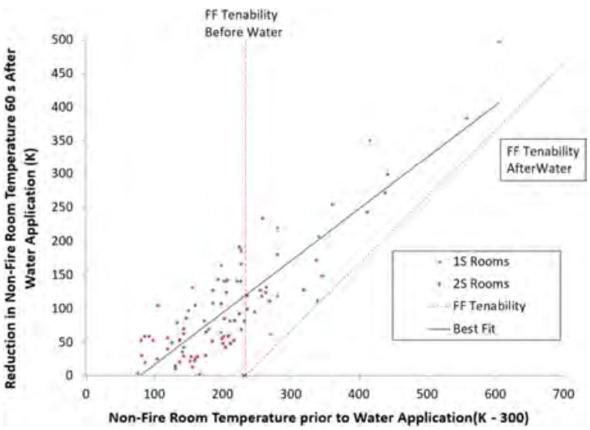

Figure 17. Effect of water application on firefighter tenability. The *vertical dotted line* shows the fire fighter tenability criteria prior to water application, and the *slanted dotted line* shows the firefighter tenability criteria 60 s after water application. The *solid line* is the best fit line for the data set.

the non-fire rooms and hallways and reduce the risk for firefighters searching the structure.

While this manuscript focuses mainly on the scenarios that were conducted with straight stream nozzle settings, a few experiments were also conducted using fog stream suppression. Performing an analysis similar to Figure 17 on this data set showed that the temperature 60 s after fog stream water application was above the thermal tenability threshold for firefighters for 3 out of the 22 non-fire room and hallway observations. Both nozzles were operated at the same nominal flow rate, so this difference in effect can largely be explained by the time dependence of the cooling effects of the two stream types.

To characterize the effectiveness of water application in the fire room with respect to a range of non-fire room temperatures, we can analyze Figure 17 in a slightly different manner. By calculating a best fit line to this data set (black solid line in Figure 17) at various different times after water application, we can begin to characterize the time rate of change of thermal conditions in these rooms as well as compare different suppression techniques.

Figures 18 and 19 shows the time dependence of cooling for the straight stream and fog stream data at 0 s, 10 s, 30 s, and 60 s after water application has ended. For the straight stream nozzle, while no temperatures were seen to increase, there is no measureable effect in the non-fire rooms immediately after the water stops flowing. However, cooling increases consistently with time after water application. With the fog stream application, cooling in non-fire rooms occurs even before water application ends and achieves the largest reduction in temperatures 30 s after water application. Importantly, the slope of this best fit line changes throughout the time-course of cooling and the effect becomes less pronounced in non-fire rooms with a higher start temperature (i.e. closer to the fire room). The

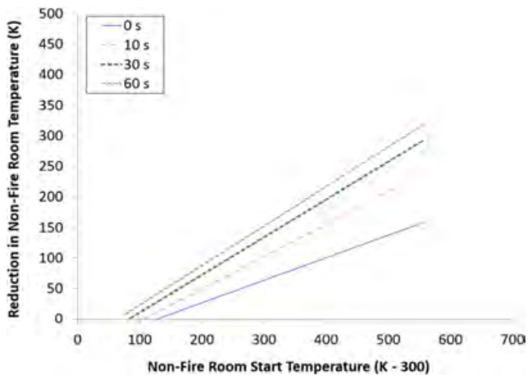

Figure 18. Temperature reductions in non-fire rooms for straight stream applications at 0 s (*blue, solid*), 10 s (*red, long dash*), 30 s (*green, dotted*), and 60 s (*black, short dash*) after water application (Color figure online).

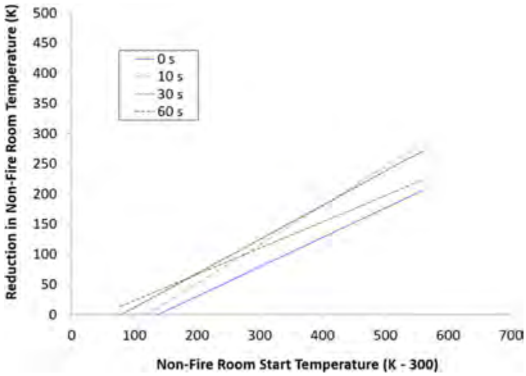

Figure 19. Temperature reductions in non-fire rooms for fog stream applications at 0 s (*blue, solid*), 10 s (*red, long dash*), 30 s (*green, dotted*), and 60 s (*black, short dash*) after water application (Color figure online).

fog stream produces smaller, more dispersed droplet sizes that are capable of more effectively cooling the hot gases, as has been shown in previous literature [27]. However, the straight stream water focuses the momentum of the water to allow increased penetration through the hot gases to reach the fuel sources and directly cool the burning material. Therefore, the fog stream accomplishes quick cooling of the compartments due to cooling of the gases (and potentially contraction of the hot upper gas layer), but since the source of the heat is not as significantly impacted, the temperatures in the structure begin to recover quicker than for straight stream water applications.

3.3. Firefighter Tactical Considerations

One of the major takeaways from this research is the importance of limiting the air supply to the fire for ventilation limited fires. The experiments where the door was opened to allow access and then closed the width of a hoseline slowed the growth of the fire, which maintained lower interior temperatures and better gas concentrations than if the door were opened completely. This allows for fire department intervention while keeping the fire at a lower heat release rate, which makes it easier to extinguish.

There was not a ventilation hole size used in these experiments that slowed the growth of the fire. All vertical ventilation holes created flashover and fully developed fire conditions more quickly. Once water was applied to the fire, however, the larger the hole was, and the closer it was to the fire, allowed more products of combustion to exhaust out of the structure, causing temperatures to decrease and visibility to improve. Ventilating over the fire is a viable option if your fire attack is coordinated.

Water was applied to the fire from the exterior during every experiment, in some experiments through the doorway and some through the window. In almost all of the experiments, tenability was improved everywhere in both structures with the application of water into the structure, even in locations downstream of the fire in the flow path. The data demonstrated the potential benefits of softening the target prior to making entry into the structure; the inability to push fire, as fire was never close to being forced from one room to another with a hose stream; and the benefits of applying water to the seat of the fire in a large open volume.

The fire dynamics of home fires are complex and challenging for the fire service. Ventilation is paramount to understand for safe and effective execution of the mission of the fire service to protect life and property. Vertical ventilation is especially important because it requires being positioned above the fire and can have a fast impact on interior fire conditions. This research study developed experimental fire data to demonstrate fire behavior resulting from varied ignition locations and ventilation opening locations in legacy residential structures compared to modern residential structures. This 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.

4. Summary and Conclusions

The impact of important firefighter interventions; front door ventilation, vertical ventilation, and water application, were quantified by analyzing the rate of change in heat-exposure- and CO-FED over time (FER) in a one-story and two-story residential structure. It was observed that in all cases, venting the structure resulted in FER values that either did not improve occupant tenability or, at worst case, significantly reduced occupant tenability. However, the tactic of controlling the opening of the front door to 10 cm open was shown to delay the time for increasing FER values and resulted in less rapid growth of the fire for both the one-story and two-story structure. In contrast, for the experiments where the front door was fully open upon vertical ventilation, the FER values increased from less than 0.01 FED/s to greater than 1 FED/s in the fire room in less than a minute after vertical ventilation.

Two different vertical ventilation sizes were used in the experiments, 1.4 m^2 and 2.9 m^2. The only observed difference between the two vertical ventilation areas was in the two-story structure, where the non-fire rooms had slightly less rapid growth of the FER values for the larger ventilation area.

After ventilation of the structure, the exposure to toxic gases remained a hazard to occupants with typical FER values larger than 0.01 FED/s in the one-story structure and larger than 0.002 FED/s in the two-story structure. However, the observed changes in FER values after different tactics was negligible compared to the changes observed in the heat exposure FER values after the same tactics.

Water application reduced the FER values in all cases for both the one-story and two-story structures. On average, in the fire rooms, 60 s after water application, the FER values decreased by 1–2 orders of magnitude. In the non-fire rooms on the second floor of the two-story structure, the final FER values were less than 33% of the pre-water application values, and in the non-fire rooms on the first floor of both structures the final FER values were less than 20% of the pre-water application values.

It was observed that 60 s after every water application, the conditions in all of the non-fire rooms were below the firefighter tenability threshold for all straight stream water applications. However, for fog stream water applications, 3 out of the 22 non-fire rooms were above the temperature tenability threshold. The increased effectiveness of the straight stream water application was attributed to the cooling action of the two stream types and was characterized by a time-rate of change analysis in non-fire room temperatures.

While this study provides new insight into the impact of firefighting tactics on conditions that may be experienced by escaping occupants in residential structures, it is necessary to further quantify the repeatability and variability of fire growth and fire response to different tactics. Furthermore, additional tactical options can be considered for future study as well as the impact of different structural geometry and layout, particularly the location of ventilation openings with respect to the fire and suppression locations.

Acknowledgments

Funding was provided by the Department of Homeland Security (Grant No. EMW-2010-FP-00661).

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A.5 Paper V: Effect of Firefighting Intervention on Occupant Tenability during a Residential Fire

Fire Technology, 55, 2289–2316, 2019

Manufactured in The United States
https://doi.org/10.1007/s10694-019-00864-2

Effect of Firefighting Intervention on Occupant Tenability during a Residential Fire

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Received: 12 October 2018/**Accepted:** 16 April 2019

Abstract. This study examines the impact of firefighting intervention on occupant tenability to provide actionable guidance for selecting firefighting tactics that are based upon empirical rather than anecdotal evidence. Twelve fire experiments were conducted utilizing a full-sized residential structure to assess the impact of firefighting tactics on occupant exposure. Six groups of firefighters, recruited from fire departments throughout the country, participated in two experiments each. Two attack tactics were examined: (1) interior attack—water applied from the interior while a search team searched for simulated trapped occupants, and (2) transitional attack—exterior water application before transitioning to the interior while a search team searched for simulated trapped occupants. Gas concentration and temperature measurements were analyzed using a fractional effective dose (FED) approach to determine the impact of firefighter tactics on the exposure for potential trapped occupants. Water application by the fire attack teams resulted in a rapid drop in temperatures throughout the structure, followed shortly afterward by a decrease in the FED rate. There was no significant difference between the magnitude of the temperature decrease or the time until the inflection point in the FED curve between transitional attack and interior attack. As the removal time for the occupant increased, the toxic exposure to the occupant increased, despite the decreasing FED rate due to suppression. Occupant tenability analysis showed that the most threatened occupants are not always closest to the seat of the fire, while occupants near the fire but behind closed doors may have received a low exposure. As such, the results emphasized the need for rapid removal of occupants and coordination of suppression and ventilation tactics to limit toxic exposures.

Keywords: Firefighting, Tenability, Fire service, Fire dynamics

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1. Introduction

A primary goal of firefighting is to extinguish fire in order to protect life and property. While this basic goal may seem straightforward to a civilian, the tactics used by the fire department to accomplish this goal may vary considerably. Based on an accumulating body of evidence, many fire departments are emphasizing the need to apply water to the fire as soon as possible to improve conditions inside the structure [1]. While there are many possible means for accomplishing rapid water application, two distinct approaches have been debated in recent years. One such approach is often called a ''transitional attack'' in which firefighters apply water through a window to initially suppress the fire before they enter the building to completely extinguish the fire and ensure there is no further fire growth. This approach contrasts the ''interior attack'' method that many firefighters have been taught, which is that it is best to initially enter the house through the front door with a charged hose line. The goal of this ''interior'' fire attack is to find the seat of the fire and extinguish it as soon as possible to protect potential occupants. Locating the seat of the fire from the exterior of a structure can be challenging if it is not venting from compartment windows, but several size up techniques can be employed to allow firefighters and fire officers to focus their efforts on rapid suppression coordinated with ventilation and search and rescue operations. An important aspect of the decision making process in determining one suppression technique versus the other is how employing such a tactic may impact tenability for trapped occupants.

Several previous studies have examined fire service tactics for their effectiveness and efficiency [2–8]. Each of these studies was focused on a specific fire service tactic and simulated those tactics in a controlled manner to examine the impact on the fire environment. In 2017, Traina et al. [9] examined the impact of firefighter transitional attack on occupants during a series of vertical ventilation experiments. They concluded that transitional attack was able to reduce the thermal fractional effective rate (FER) by 1/5 in a ranch home geometry 60 s after water application. They did not examine interior attack and were not able to assess the impact of suppression on toxic gas exposure and FER. This study builds on these previous reports by including both interior attack and toxic gas measurements. Importantly, this study utilizes firefighters to perform the tasks, incorporating multiple operations and multiple firefighting teams as would occur in typical fireground operations. Additionally, by incorporating a search and rescue component valuable insights were gained on the impact of tenability of the simulated occupants as suppression, ventilation and search were performed to remove the simulated occupants from the hazardous environment.

Occupant tenability, which is related to the survivability of occupants in the fire environment, is a primary concern for any firefighting operation. Occupant tenability was estimated separately for two routes of exposure, temperature and gas concentration, using the fractional effective dose (FED) methodology from the SFPE Handbook [10]. FED relates to the probability of the conditions being non-tenable for a certain percentage of the population through a lognormal distribution. For reference, FED = 0.3 is the criterion used to determine the time of incapacitation for susceptible individuals (young children, elderly, and/or unhealthy occupants) and corresponds to untenability for 11% of the population, and FED = 1.0 is the value at which 50% of the population would experience untenable conditions. Untenability as a result of exposure to products of combustion is considered the point where the occupant would no longer be able to affect their own rescue. The method used to consider the time-dependent exposure of an occupant to toxic products of combustion is defined in Eq. 1.

$$FED_{toxic} = (FED_{CO} + FED_{HCN}) * v_{CO_2} \tag{1}$$

In Eq. 1, (FED_{CO}) and (FED_{HCN}) are the fractional doses for carbon monoxide (CO) and hydrogen cyanide (HCN), respectively. These terms are the fraction of an incapacitating dose at a discrete time step, Δt. A study conducted by Fent et al. [11] examined the fireground exposure of firefighters to various chemicals, including HCN. The study found that the interior and exterior teams (attack and outside vent) may be exposed to immediately dangerous to life and health (IDLH) concentrations of HCN if SCBA were not worn. Although HCN was not measured in these experiments and the tenability analysis does not include oxygen and irritant gas contributions, it is reasonable to assume that it would contribute to the toxic exposure of occupants trapped in the structure. Therefore, the results presented here are conservative. CO is often considered to be the most important asphyxiant gas that trapped occupants will encounter [10]. The expression for FED_{CO} is shown in Eq. 2, where ϕ is the CO concentration in parts per million and dt is the time step, V is the volume of air breathed each minute, in liters, and D is the exposure dose, in percent COHb, required for incapacitation.

$$FEDCO = \int_0^t 3.317 * 10^{-5} [\phi CO]^{1.036} (V/D) dt \tag{2}$$

Values of V and D vary depending on the level of work being conducted by the subject. The default case is often taken to be light work, which corresponds to D = 30% COHb and V = 25 L/min. ISO 13571 [12] lists the uncertainty associated with the calculated *FEDCO* as 20%. The uptake rate of CO and other products of combustion can vary considerably with V, and is dependent on a number of factors, including hyperventilation due to CO_2. This increase in respiration rate due to CO_2 inhalation is accounted for in Eq. 1 by the hyperventilation factor, v_{CO_2}.This factor is defined in Eq. 3, where ϕ_{CO_2} is the mole fraction of CO_2.

$$v_{CO_2} = exp\left(\frac{0.1903(exp(\phi_{CO_2})) + 2.0004}{7.1}\right) \tag{3}$$

ISO 13571 [12] lists the uncertainty associated with the calculated v_{CO_2} as 35%. There is no FED criteria to conclusively predict lethality, as the pathology of toxic inhalation becomes complicated in the period between incapacitation and death. The incapacitating and lethal effects of CO inhalation are related to the carboxyhemoglobin (COHb) level in the blood stream. Carboxyhemoglobin is formed when CO bonds with hemoglobin. Since hemoglobin has a higher affinity for CO than for oxygen (O_2), high COHb levels have an asphyxiating effect on vital organs, notably the brain. Incapacitating levels of COHb in the bloodstream are between 30% and 40% for the majority of the population, although susceptible populations may experience loss of consciousness at levels as low as 5%. Death is predicted at COHb levels of 50%–70%. Autopsy data indicates that survival is rare among fire occupants with COHb levels between 50% and 60%, with 50% COHb typically taken as the median lethal dose. Incapacitating levels of COHb are commonly found in surviving fire occupants [10]. Active subjects are more severely affected by COHb concentrations than sleeping subjects. Often, relatively minor increases in activity can result in the loss of consciousness to a previously sedentary subject.

A FED analysis was also conducted to examine the impact of thermal exposure to potential trapped occupants. The FED_{temp} tenability limit is commonly used as the expected onset of second degree burns. FED_{temp} is composed of two components: a convective component and a radiative component, as shown in Eq. 4, where t_{conv} is the time (minutes) to incapacitation due to convective heat transfer and t_{rad} is the time (minutes) to incapacitation due to radiant heat transfer. Since t_{rad} is a function of the heat flux from the gas layer, which was not measured, the radiative contribution was not considered in these experiments. Rather, the FED_{temp} was calculated by considering the convective contribution, shown in Eq. 5, at an elevation of 0.9 m above the floor, representative of a person crawling on the floor (which will likely be higher than someone lying on the floor).

$$FED_{temp} = \int_0^t (1/t_{conv} + 1/t_{rad}) \tag{4}$$

$$FED_{conv} = 4.1 \times 10^8 T^{-3.61} \tag{5}$$

This series of experiments was also designed to examine the cardiovascular and carcinogenic risks of firefighting [13]. Analysis was done to characterize the thermal burden experienced by firefighters [14]. Measurements were made to characterize the area and personal air concentrations of combustion byproducts produced during controlled residential fires [15] and to determine what contaminants got onto the firefighters personal protective equipment and skin and how effective different decontamination procedures are [16]. This paper will focus on occupant survivability and the effectiveness of firefighter suppression (transitional attack and interior attack) and search and rescue tactics on occupant survivability. This will be accomplished by utilizing building gas temperature and gas concentration measurements placed close to two simulated occupants.

This analysis will focus primarily on comparing the relative magnitudes of FEDs in different locations within the structure, to compare the exposure to occupants that may have become trapped or incapacitated at those locations. Similarly, the FED rate of change can be used to assess the rate at which the exposure to a potential occupant would be improving or deteriorating. The FED itself can only increase or remain stagnant, it can never decrease, but a decreasing FED rate would indicate that an intervention is improving conditions. This can give insight into how the fire department actions are affecting the survivability of any occupants exposed to the environment.

2. Methods

2.1. Subjects

Subjects were recruited through a nationwide multimedia effort, along with a focus on a statewide network of firefighters who teach and train at the Illinois Fire Service Institute (IFSI). Forty (n = 40) firefighters (36 men, four women) from departments in Illinois, Georgia, Indiana, Ohio, South Dakota and Wisconsin participated in this study. On average, firefighters were 37.6 ± 8.9 years old, 1.80 ± 0.08 m tall, weighed 89.8 ± 14.5 kg and had an average body mass index of 27.6 ± 3.4 kg/m^2 [14].

All subjects were required to have completed a medical evaluation consistent with National Fire Protection Association (NFPA) 1582 [17] in the 12 months prior to participation. An emphasis was placed on recruiting 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 self-contained breathing apparatus (SCBA) prior to entering the structure. The research team supplied all personal protective equipment (PPE) for the subjects to enhance standardization and to ensure that all protective equipment adhered to NFPA standards.

The number of subjects recruited were necessary for statistical power required to examine the cardiovascular and carcinogenic exposure to the firefighters. Had the sole purpose been to examine occupant tenability we could have used the same four firefighters and had them accomplish the tasks in a repeatable manner. However, we were able to capture and analyze the variability of execution that could happen on the fireground everyday around the world where there are far fewer controls in place.

2.2. Study Design

A total of 12 experiments, each on separate days, were conducted. For each experiment, a team of 12 firefighters was deployed to suppress fires in a realistic firefighting experiment that involved a multiple-room fire (two separate bedrooms) in a 111 m^2 residential structure. Each team of 12 firefighters worked in pairs to perform six different job assignments that included operations on the inside of the structure during active fire (fire attack and search and rescue), on the outside of the structure during active fire (command, pump operator and outside ventilation), and both inside and outside the structure after the fire had been suppressed (overhaul, during which firefighters searched for smoldering items and removed items from the structure). This manuscript will focus on those firefighters operating in the fire attack and search and rescue roles. These firefighters forced entry into the structure, suppressed the fire, searched for and removed two simulated occupants.

Experiments differed only in the tactics or methods used by the fire attack team: (a) traditional interior attack from the ‘‘unburned side’’ (advancement through the front door to extinguish the fire) and (b) transitional attack (water applied into the bedroom fires through an exterior window prior to advancing through the front door to extinguish the fire). The firefighters performed the same role using both methods. The tactics and tools used during these experiments are representative of those that may be used in the United States and may not be universally applicable.

In each experiment, the attack team of two firefighters approached the fireground at the time of dispatch, proceeded to the attack pumper, and deployed the hoseline with a smooth bore nozzle pumped at a pressure to flow approximately 570 lpm. The attack team was directed to execute either a transitional attack or an interior attack. For the interior attack experiments, the attack team deployed their hoseline to the front door of the structure, donned their SCBA, and made entry after the search team had simulated forcing entry. In the transitional attack experiments, the teams positioned their hoseline so that they could apply water to the bedroom on the A-side (front) of the structure. Once applying water to this window, the teams maneuvered their hoseline to the second window on the side of the structure, applied water to that window, before repositioning their hoseline to the front door to make entry. The duration of flow in each window varied between groups, and the average values are presented in Table 1.

The search team was delayed by 60 s following dispatch, to simulate companies arriving at different times. Upon arrival on the scene, the search team donned their SCBA masks and simulated forcing entry through a door on a training prop before entering the structure. The search team of two firefighters were instructed to search the structure beginning in the side of the house opposite the fire room (Fig. 1). The search team was not instructed how to search, but to use the techniques they are trained in and familiar with. As the teams searched, they found

Table 1
Times for Hose Deployment and Water Application

Event	Transitional attack time (s)	Interior attack time (s)
Time to firefighter interventions	82 ± 9	127 ± 11
Duration of water application in Bedroom A	15 ± 6	n.a.
Duration of water application in Bedroom B	13 ± 6	n.a.
Time between entry and flowing water on interior	16 ± 6	10 ± 6

the first simulated occupant, located in the corner of the dining room, propped against the far bedroom door. Once they removed this occupant, they continued their search pattern through the far closed bedroom, the kitchen, and the living room, before reaching the closed bedroom closer to the fire bedrooms, where the second simulated occupant was located.

2.3. Study Protocol

To ensure the fire experiments were conducted as repeatable as possible, a structure was designed and built to have interior finishes and features of a single family dwelling common in the United States and identical furnishings were used in each

Figure 1. Layout of burn structure, location of occupants, and instrument locations for left (top) and right (bottom) layouts, key: triangle = thermocouple array, circle} = gas concentration, diamond = ignition location.

experiment. To ensure safety, specialized safety systems and hardened construction were employed. A residential architectural company designed the house to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings. The home had an approximate floor area of 111 m^2, with eight total rooms, including four bedrooms and one bathroom (closed off during experiments). Interior finishes in the burn rooms were protected by 15.9 mm Type X gypsum board [18] on the ceiling and 12.7 mm gypsum board on the walls. To maximize the use of the structure and minimize time between experiments, the house was mirrored so that there were two bedrooms on each side where the fires were ignited. During each experiment a temporary wall was constructed at the end of the hallway to isolate two bedrooms so that they could be repaired for the next experiment. The left and right layouts are shown in Fig. 1.

Furniture was acquired from a single source such that each room was furnished identically (same item, manufacturer, make model and layout of all furnishings) for all 12 experiments. The bedrooms where the fires were ignited, 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. All other rooms of the structure were also furnished to provide obstacles commonly encountered by firefighters, but those furnishings were not involved in the fire. Figure 1 provides a plan view rendering of the structure to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the white floor shows the cement floor or simulated tile locations. Prior to ignition, all windows and doors were closed with the exception of the doors and windows of the two fire rooms (Bedrooms A and B).

Fires were ignited in the stuffed chair in Bedrooms A and B using a remote ignition device and a book of matches to create a small flaming ignition source. The flaming fire was allowed to grow until temperatures in the fire rooms reached levels determined to be near peak values based on pilot studies (i.e. room had 'flashed over') [1, 19]. For standardization purposes, dispatch was simulated when interior temperatures of both fire rooms exceeded 600°C at the ceiling (4–5 min after ignition). The fire crews arrived to a ventilation limited fire with fire extending out of the windows in Bedroom A and B. Firefighters responded by walking approximately 16 m from the data collection bay to the front of the structure.

2.4. Measures

2.4.1. Building Temperature Measurements To assess fire dynamics throughout the experiments, measurements included gas temperature, gas concentrations, thermal imaging, and video recording. Detailed measurement locations can be found in Fig. 1 and [13]. Gas temperatures were measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.5 mm nominal diameter. Thermocouple arrays were located in every room. The thermocouple locations in the living room, dining room, hallway, both closed bedrooms, and kitchen had an array of thermocouples with measurement locations of 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m and 2.1 m above the floor. The thermocouple locations in Bedroom A and Bedroom B had an array of thermocouples with measurement locations of 0.3 m, 0.9 m, 1.5 m, and 2.1 m above the floor. All data was collected at a frequency of 1 Hz.

2.4.2. Building Gas Concentration Measurements Ambient concentrations of O_2, CO, CO_2 in the local environment were measured (OxyMat 6 and Ultramat 23 NDIR; Siemens) at 0.9 m from the floor inside and outside of the closed bedrooms. This measurement height corresponds with the height of the head adjacent to the simulated occupant sitting outside of the far bedroom and the simulated occupant lying on the bed in the near bedroom. This measurement height is also consistent with the height of the head of a potential occupant crawling to escape the fire. The uncertainty of the measured concentration is 1% of the maximum concentration measurement. The maximum concentrations measured were 5% for CO and 20% for CO_2. All data was collected at a frequency of 1 Hz.

2.4.3. Firefighter Intervention Measurements For each experiment, firefighter intervention was monitored and recorded utilizing standard video cameras placed outside and throughout the structure. Thermal imaging cameras were also placed inside the structure to examine firefighter movements and search and rescue techniques and tactics. Portable cameras were attached to the simulated occupants to qualitatively capture their exposure and movements from their locations to the outside of the structure as the firefighters rescued them.

2.5. Occupant Tenability

To estimate trapped occupant tenability, Eqs. 2 and 4 were numerically integrated using an Euler scheme and a discrete time step of 1 Hz using the building gas concentration measurements and building temperature measurements described above. The time to exceed the thresholds for all of the experiments in each house for both heat (only convection considered) and CO/CO_2 are calculated inside and outside of the near and far closed bedrooms. It should be noted that the values assume the simulated occupant was in that location for the duration of the experiment. It is again reinforced that these estimates may be considered lower bounds as additional thermal risks may be present from exposure to large radiant heat exposures or from the additive effects of exposure to a variety of different fireground gases such as HCN.

For any FED analysis, it is important to consider the large uncertainty associated with the measurements. Additionally, both heat exposure and toxic gas exposure will increase with increasing height in the structure. This fact is particularly important when considering an occupant walking out of the structure or a firefighter attempting to remove an occupant at standing height, which can result in higher FED values and lower times to untenability than at the 0.9 m height. However, the focus of this study is on the tenability at the crawling height of an occupant.

2.6. Statistical Analysis

The combined uncertainty of Type K thermocouples is listed as 15% [20, 21] and the combined uncertainty of the gas analyzers used in these experiments is 12%. To assess the repeatability between experiments, the average temperatures at each occupant location in the 30 s prior to firefighter intervention were computed and compared to the uncertainty of these sensors.

A student's t-test was used to compare groups of variables, such as the method of attack, side of the structure, or group of firefighters. Because of the limited number of experiments, the sample sizes available to compare these variables were often quite small. Each of these analyses were performed with an alpha, or null value of 0.05.

3. Results

3.1. Building Temperature Measurements

The 0.9 m above the floor (crawling height) temperature was used to assess the thermal exposure to which an occupant trapped at different locations within the structure may be subjected. The average temperature in the 30 s prior to firefighter intervention in the hallway, outside of the fire rooms was $320 \pm 64°C$. In the dining room, remote from the seat of the fire, the average temperature was $135 \pm 34°C$. The coefficients of variance were 20% and 25% for the hallway and dining room locations, respectively. These values are greater than the combined instrument uncertainty of 15%, a difference which can partially be attributed to the wind. Since the test structure was not located in a controlled lab space, the presence or absence of wind could have an effect on flow paths within the structure. The wind conditions are shown in Table 2. Winds gusted as high as 7.3 m/s during Experiment 5 however did not average more than 3.2 m/s in any of the

Table 2
Wind Speed (m/s) and Direction

Experiment	Average	Minimum	Maximum	Direction
Exp. 1	2.8	0.6	6.9	W
Exp. 2	2.6	0.2	6.0	SW
Exp. 3	1.9	0.1	5.3	NE
Exp. 4	0.9	0.0	2.0	SE
Exp. 5	3.2	0.5	7.3	SW
Exp. 6	1.5	0.0	5.3	NW
Exp. 7	1.0	0.0	2.7	W
Exp. 8	1.6	0.0	5.9	NW
Exp. 9	1.7	0.1	4.8	NW
Exp. 10	2.0	0.0	5.2	SW
Exp. 11	1.2	0.0	3.3	W
Exp. 12	1.2	0.0	3.2	W

experiments. The 0.9 m above the floor temperatures measured in the closed bedrooms were significantly lower than those measured in the areas of the structure open to the fire. The average temperature in the 30 s prior to intervention was $23 \pm 2°C$ in the near bedroom and $21 \pm 1°C$ in the far bedroom. The coefficient of variation for these sensors are 7.0% and 5.8% for the near and far bedrooms, respectively, less than the 15% combined uncertainty of the thermocouples. Representative temperature versus time graphs for each room and occupant locations are included in [13].

The high temperatures at 0.9 m above the floor in the open areas of the structure resulted in FED_{temp}s in the hallway that exceeded the criteria for second degree burns. In the interior attack experiments, an FED_{temp} exceeding 1.0 was reached in 322 ± 48 s and was reached in 322 ± 34 s during the transitional attack experiments. For each attack method, this value was reached prior to firefighter intervention (442 ± 24 s for interior and 399 ± 16 s for transitional). The maximum FEDs for each experiment and simulated occupant location are listed in Table 3. At the dining room simulated occupant location distant from the fire rooms, only Experiments 1 and 2 reached a FED_{temp} in excess of 1.0. For the other experiments, the FED at the end of the experiment was $0.69 \pm .17$ for the interior attack experiments and $0.62 \pm .30$ for the transitional attack experiments.

The least severe thermal conditions were observed in the two closed bedrooms where temperatures at the time of firefighter intervention were lower in both locations than in the areas immediately outside of the closed door. Once firefighter intervention was initiated, whether from the interior or the exterior, there was no immediate effect on the temperatures or FED_{temp} within the room. In the experiments where the closed bedroom doors were opened for search and rescue, however, there was a corresponding temperature increase and FED_{temp} rate increase. Although opening the bedroom door to facilitate search often resulted in a measurable increase in the FED_{temp} rate, the total FED in both closed bedrooms

Table 3
Final FED_{temp} Values at Each Measurement Location

Experiment	Near hall	Dining room	Near closed bedroom	Far closed bedroom
Exp. 1	7.92	1.28	0.02	0.01
Exp. 2	12.02	3.25	0.04	0.04
Exp. 3	9.69	0.87	0.04	0.03
Exp. 4	35.43	0.56	0.02	0.03
Exp. 5	33.25	0.76	0.07	0.03
Exp. 6	8.86	0.24	0.03	0.02
Exp. 7	16.64	0.68	0.03	0.02
Exp. 8	9.15	0.29	0.02	0.03
Exp. 9	39.07	0.43	0.04	0.03
Exp. 10	1.96	0.43	0.03	0.03
Exp. 11	19.76	0.86	0.04	0.03
Exp. 12	7.97	0.71	0.03	0.04

remained below 0.10 for both bedrooms and the 0.9 m above the floor temperature never exceeded 40°C. Even the most severe thermal conditions within the bedrooms to which a trapped occupant would be subjected were less severe than those encountered in areas of the structure connected to the fire rooms.

3.2. Building Gas Concentration Measurements

At the time of firefighter intervention, the FED calculations varied considerably between experiments. At the near hallway location, just outside of the bedroom fires, the average FED value at the time of firefighter intervention was 1.06 ± 0.96. In the dining room location, next to the first simulated occupant, the average FED was 0.34 ± 0.36. The coefficients of variation were higher than those calculated for the building temperatures, and were 90% and 105% for the hallway and dining room, respectively. The variation that was noted in these measurements can be attributed to variations in the CO, CO_2, and O_2 measurements. The variation in these measurements was greater than the uncertainty of the sensors. Additionally, because the FED equations presented in Eqs. 2 and 3 are exponential in nature, small measurement variations will result in larger variations in the FED calculation. Further, ISO 13571 [12] lists the uncertainty for the FED calculations as high as 35%. In the closed bedrooms, the average FED value at the time of firefighter intervention was 0.007 ± 0.005.

Incapacitation levels were reached at 467 ± 67 s and 453 ± 31 s in the hallway gas sample location for the transitional and interior attacks, respectively. On average, the dining room occupant location reached incapacitating levels of exposure at a later time than the hallway, at 533 ± 78 s and 618 ± 136 s from ignition, for the transitional and interior attack, respectively. These times occur after the average firefighter intervention times (390 ± 16 s for transitional attack, 442 ± 24 s for interior attack). Table 4 lists the maximum FEDs observed for each measurement location in each experiment. The average total FED values for the locations open to the fire rooms were 3.08 ± 1.17 and 2.31 ± 1.03 for the near hallway and dining room locations, respectively. These values were substantially higher than the FEDs recorded in the closed bedrooms, which were 0.63 ± 0.58 and 1.09 ± 0.54 for the near and far closed bedrooms, respectively. There was no significant difference between the two bedrooms ($p = 0.22$). This indicates that the closed bedroom door can provide an important reduction in an occupants exposure to products of combustion, which are noted in high concentrations low to the floor in the open areas of the house. Even in the near closed bedroom, the FED values measured behind the closed door are significantly lower ($p = 0.005$) than in the hallway immediately outside the bedroom. The near bedroom sample point was also significantly lower ($p = 0.003$) than the sample point located in the dining room, next to the simulated occupant. Representative gas concentration versus time graphs for each sample location are included in [13].

3.3. Firefighter Intervention Measurements

Each group of firefighters participated in one transitional attack experiment and one interior attack experiment. The only direction given to the groups performing

Table 4
Final FED_{gas} Values at Each Measurement Location

Experiment	Near hall	Dining room	Near closed bedroom	Far closed bedroom
Exp. 1	n.a	4.62	0.51	0.19
Exp. 2	3.31	n.a	0.45	1.08
Exp. 3	4.13	3.26	1.64	0.55
Exp. 4	1.85	1.00	0.14	2.38
Exp. 5	3.58	1.39	1.89	1.13
Exp. 6	2.27	1.68	0.43	1.04
Exp. 7	4.19	2.44	0.83	0.83
Exp. 8	1.91	1.75	0.62	1.43
Exp. 9	2.86	1.90	0.31	1.06
Exp. 10	1.26	1.59	0.09	n.a
Exp. 11	5.42	3.50	n.a	1.17
Exp. 12	3.05	2.27	0.07	n.a

n.a indicates a sensor malfunction at that location

these tasks was which method of attack to perform and which direction the search team should begin their search. A considerable amount of variation was noted in the time that the various groups took to complete fireground tasks such as hoseline deployment, hoseline advancement, and occupant location and removal. Table 5 lists the average times (with standard deviations) that the groups took to perform these actions. The least amount of variation (defined by the coefficient of variation), approximately 20%, was noted in the hoseline deployment, which was defined as the time that the firefighter removed the hoseline from the fire engine to the time that the nozzle was "bled," ensuring that the attack team had a serviceable hoseline with water to the nozzle. The variability in the hoseline advancement, which was defined as the time from when the attack team entered the door to when they reached the hallway, was higher at 55%. The highest variability was noted in the forcible entry task, which was 95%.

The timeline of firefighter interventions varied with both the method of attack (transitional vs. interior) and the actions taken by the subjects during their execu-

Table 5
Times for Firefighting Tasks

Task	Mean time for task completion ± standard deviation (s)	Coefficient of variation (%)
Hoseline deployment	79 ± 16	20
Hoseline advancement	29 ± 16	55
Forcible entry	22 ± 21	95
Time to locate dining room occupant	48 ± 22	35
Time to remove dining room occupant	37 ± 13	45
Time to locate bedroom occupant	140 ± 54	39
Time to remove bedroom occupant	60 ± 38	63

tion of the fire attack (Table 1). From the time that the hoseline was pulled from the engine, the transitional attack resulted in significantly faster water application to the fire ($p < 0.001$) than the interior attack method. For the transitional attack, water was applied to the front bedroom in 82 ± 9s, whereas in the interior attack experiments, entry to the structure was made in an average of 127 ± 11 s after pulling the hoseline. Most of the interior attack teams utilized a "shut down and move" technique, where water would be applied from a stationary position, before advancing and repeating the maneuver. The teams applied water sometime between entering the structure and reaching the hallway. The first interior water application occurred 10 ± 6 s following entry, and most teams applied water for 3 ± 2 s on this initial application.

The average time between dispatch and entry for the search company was 204 ± 24 s for the interior attack experiments and 227 ± 29 s for the transitional attack experiments, which was not significantly different ($p = 0.21$). The longer average entry time in the transitional attack experiments was attributed to the additional time required to reposition the line to make entry in these experiments. In Experiments 1, 5, 7, and 8, the search teams missed the far closed bedroom, and the door was never opened. Table 6 shows the average times for the search team to find and remove each occupant during each fire attack method. While there is large variability in each of these times, method of attack (and its subsequent impacts on visibility and thermal conditions) was found to not have a significant difference on the time required to find the dining room occupant ($p = 0.75$) or the bedroom occupant ($p = 0.32$). Similarly, time required to remove the dining room occupant ($p = 0.38$) and bedroom occupant ($p = 0.85$) was not found to be significantly different between attack methods.

As the search company opened the doors to the near and far bedrooms in order to gain access and complete their search, the bedroom was no longer isolated from the rest of the structure. Out of the twelve experiments, eight search teams made entry into the far closed bedroom and searched it, and four passed over the bedroom, leaving the door closed and not searching. In the cases where the remote bedroom was opened and searched, an increase in FED rate was observed as products of combustion filled the room. For the four tests in which the door was not opened during the initial part of the search, this increase in FED rate was not observed. The peak FED rate calculated in the experiments where the search team opened the door (0.0030 ± 0.0010) was significantly higher ($p = 0.003$) com-

Table 6
Times to Find and Remove Occupants

Event	Interior attack time (s)	Transitional attack time (s)
Time to find dining room occupant	36 ± 15	38 ± 10
Time to remove dining room occupant	42 ± 21	54 ± 21
Time to find bedroom occupant	218 ± 62	264 ± 74
Time to remove bedroom occupant	50 ± 64	56 ± 21

pared to the peak FED rate for experiments where the door to the far closed bedroom was not opened and searched (0.0010 ± 0.0002). For the far closed bedroom, which was opened and searched earlier in the timeline of the experiment, opening the door resulted in an increase in the FED rate for any potential occupants located in the room.

The significant increase in FED rate following the opening of the door to the far bedroom was not observed in the near bedroom. The near bedroom door was opened in all twelve of the experiments. There was no significant difference between the maximum FED rate prior to and following the search team's entrance of the near closed bedroom. This is likely due to this room being opened later into the experiment after suppression had taken place and ventilation was occurring.

When considering the impact of suppression on occupant tenability within the structure, Experiments 3 (transitional) and 5 (interior) were treated as outliers, and neglected from the comparisons. In Experiment 3, the attack team applied water for only 4s in each window, which allowed the fire to regrow by the time that the interior teams entered the structure. In Experiment 5, when the attack team reached the hallway, they did not have a sufficient length of hose to apply water into the fire rooms, reducing the effectiveness of the attack.

For the other experiments, after water was applied, whether from the interior or the exterior, the FED rate in open areas of the structure began to decrease. For the gas sample location in the hallway outside of the fire rooms, this inflection point occurred 43 ± 28 s from the time that water was first applied for the transitional attack experiments and 35 ± 30 s from the time that the attack team made entry for the interior attack experiments ($p = 0.73$). For the gas sample location in the dining room, this inflection point occurred 100 ± 43 s from the time that water was first applied for the transitional attack experiments and 27 ± 24 s from the time that the attack team made entry for the interior attack experiments. This difference may not be statistically significant, but may be important in a real fire ground scenario. Apart from the two outliers experiments discussed previously, the FED rate did not increase at any time following water application. Thus, this FED rate inflection point can be taken as the time at which conditions would start to improve for occupants in an areas of the structure not isolated by a closed door or other barrier. For the near hallway position, there was no significant difference between attack methods, but for the dining room location, the interior attack method did improve conditions significantly more rapidly than the transitional attack method ($p = 0.02$). A possible reason for the more rapid improvement in the interior attack case is the ventilation that accompanies the opening of the front door and line advancement. As a flow path through the front door is established and fresh air enters the structure, products of combustion are displaced. The entrainment of fresh air, accompanied by the ongoing suppression, likely work in tandem to result in the improvement of conditions remote from the fire room. Table 1 shows that in the transitional attack experiments, water was applied to the fire approximately 45 s sooner after dispatch. The time from dispatch until the FED_{gas} rate inflection is 205 ± 36 s for interior attack and $169 \pm$

24 s for transitional attack, which is not a significant difference between the experiments ($p = 0.14$). Similarly, in the dining room sample location, the time from dispatch to the inflection point was 225 ± 46 s for transitional attack and 192 ± 12 s for interior attack, a difference which is also not significant ($p = 0.27$). Thus, while the interior attack resulted in a more rapid improvement in conditions in the dining room location from the time of water application, it also took longer from the time of dispatch to apply water to the fire, resulting in no significant difference when considering the two attack methods from a common time frame. There were a relatively small number of replicates and this difference may be important in practice even if not statistically significant.

Similarly, following the application of water, temperatures decreased throughout the structure at the 0.9 m elevations, and continued to decrease for the remainder of the experiment. Temperatures gradually approached ambient as spot fires were extinguished and ventilation was provided. In order to evaluate the effectiveness of the suppression mode, a 60 s window after the time of initial firefighter intervention was examined. This window encompasses the time required to position the hoseline to apply water to both bedroom fires, and captures the highest rate of temperature decrease following suppression. In the hallway between the fire rooms, this temperature decrease was 261 ± 101°C for the transitional attack experiments and 313 ± 69°C for the interior attack experiments, which was not significantly different between the two attack experiments ($p = 0.42$). The maximum rate of decrease, however, occurred more quickly ($p = 0.004$) after suppression for the transitional attack (8 ± 4 s) than for the interior attack (33 ± 8 s). This is likely because the limited visibility and geometry hinders the interior attack, an obstacle which is not present in the transitional attack.

The temperatures in the dining room area distant from the fire rooms also improved following suppression, although a larger decrease in temperature was noted for the interior attack than for the transitional attack. For the interior attack method, the temperature decrease was 103 ± 29°C compared to a 30 ± 16°C decrease for the transitional attack ($p = 0.004$). While this temperature difference is significant, the time between firefighter intervention and the time the minimum FED rate was observed (29 ± 19 s for transitional attack experiments and 13 ± 8 s for the interior attack experiments), was not significant. Thus, while the time at which the temperature rate of change begins to decrease rapidly is not significantly different between the two attack methods, the magnitude of this rate difference is more pronounced for the interior attack method. Again, this is likely due to the fact that during the interior attack, the opening of the front door provides an immediate access route for fresh air to enter the structure and hot gases to exit, unlike the transitional experiment where there is no established inlet for fresh air other than the bidirectional flow path at the window until the team transitioned to the front door and opened it. The entrainment of fresh air, combined with the water application of the attack team, may be responsible for the more rapid decrease in FED rate and temperature. In the transitional attack, the opening of the front door was delayed until the attack team has repositioned, so the positive effects of suppression are delayed until ventilation is provided.

4. Discussion

4.1. Repeatability of Fireground Skills

The variation in the times to task presented in Table 5 can be attributed to several factors. The age of the subjects, their level of experience conducting fireground operations, and the frequency and quality of their training can all affect the proficiency of firefighters in fireground skills. The variations in these times are often quite large when put into context on the fireground. For example, the slowest hoseline advancement group took 4.75 times longer to advance from the front door to the hallway than the fastest group. The minimum time that the search team breached the forcible entry prop was 5 s, while the maximum time was 71 s. The longest removal times for the dining room and bedroom occupants, respectively, were 93 s and 96 s, whereas the shortest times were 13 s and 20 s, respectively.

Although the actions of most teams adhered to a common timeline, several groups' actions deviated from this standard. In most of the transitional attack experiments, the attack team applied water to the front bedroom (Bedroom A), then moved to apply water to the rear bedroom (Bedroom B), before repositioning their line to the front door to make entry. In Experiment 6, however, after applying water to Bedroom B, the nozzle firefighter briefly applied water to Bedroom A for a second time before repositioning their hoseline to the front door and making entry. Incidentally, this attack team also became disoriented and advanced their line into the kitchen, rather than through the living room and down the hallway, taking 254 s to advance their line to the hallway. During this time, the temperatures within the fire rooms never rebounded, since their initial actions had suppressed the fire. Upon finding the occupants, the search teams in the majority of the experiments removed the simulated occupant out of the front door of the structure. In Experiment 4, however, the search team removed the bedroom occupant out the door in the rear of the bedroom to the exterior of the structure. This was the shortest removal time for that occupant (13 s).

Although firefighters of similar experience and training levels were sought for this study, there was a significant amount of variability in the amount of time required to complete fireground tasks. This variability between groups is compounded when operating in a dynamic fireground under poor visibility conditions. Therefore, when considering fireground operations such as search and rescue or fire attack, it must be understood that the same fire department, and indeed the same firefighters, are not arriving at every fire scene, and there is a significant amount of variability in how even common fireground tasks are performed. The scenarios presented here were realistic, yet relatively straightforward considering the involved compartments were visible to firefighters as they approached the scene. Additional delays and variability might be encountered if the fires had not vented from the structure and a search for the fire location were necessary.

4.2. Open Versus Isolated Areas

The FED analysis indicated that the open areas of the structure, specifically the hallway and the dining room, experienced a maximum FED that was far higher than the maximum FEDs that were observed in the closed bedrooms that were isolated by residential hollow-core doors with no fire rating. Figure 2 provides a comparison between the maximum FEDs that were observed for the hallway and the near closed bedroom. The greatest thermal insult to a potential occupant was observed in the hallway close to the fire room, with the FED_{temp} at the end of the experiment ranging from nearly twice the incapacitating dose to almost 40 times the incapacitating dose. The dotted black line in Fig. 2 indicates the line of equivalence, the line where the gas exposure is equally severe to the temperature exposure. For an occupant in the near hallway location, all of the points lie above this equivalence line, the magnitude of the temperature exposure would be greater than the magnitude of the gas exposure. The high FEDs close to the fire room can be attributed to the high temperatures from the flows escaping the fire rooms, and the high concentration of products of combustion in the smoke near this area. The hallway was the only simulated occupant location where incapacitation due to temperature occurred before incapacitation due to gas concentration (322 ± 44 s compared to 458 ± 70 s). When comparing the final FED_{temp} magnitudes, note that if the radiative contribution had been considered, the FED value

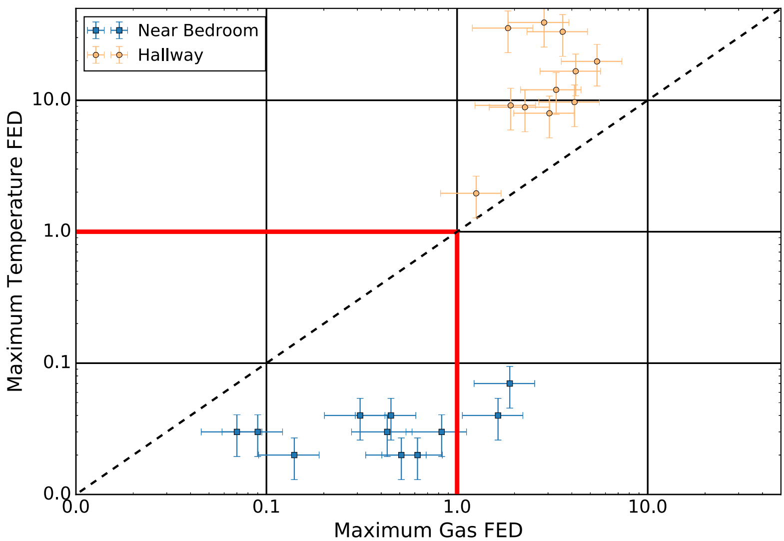

Figure 2. Maximum hallway and near bedroom FED values. FED_{gas} is shown on x-axis and FED_{temp} is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0).

at the time of the end of the experiment would have been higher. This effect is likely to be much more significant in the hallway near the fire rooms, where radiant energy from the flames are likely to impact potential trapped occupants, compared to the opposite side of the structure.

The maximum FED_{temp} in areas remote from the fire room and in areas behind closed doors was dramatically lower than in the hallway outside of the fire rooms. Figure 3 compares the maximum FEDs calculated for each experiment in the dining room and far bedroom sample locations. In the dining room, the temperature tenability threshold was only exceeded in two experiments. In the closed bedrooms, none of the experiments exceeded a FED_{temp} of 0.07, far less than the threshold of 0.3, where 11% of the population would receive second degree burns. In each location other than the hallway outside the fire rooms, the FED_{gas} is significantly higher than the FED_{temp}, indicating that the exposure to products of combustion is a greater threat than the thermal insult. In the open areas of the structure, both locations reached the gas tenability limit, with the exception of the dining room location in Experiment 4. In the closed bedrooms, the FEDs were lower than in open areas of the structure, and the FEDs were lowest in the areas where the door was kept closed the longest. The final FEDs were 1.09 ± 0.54 and 0.63 ± 0.58 for the far and near closed bedrooms, respectively. Additionally the

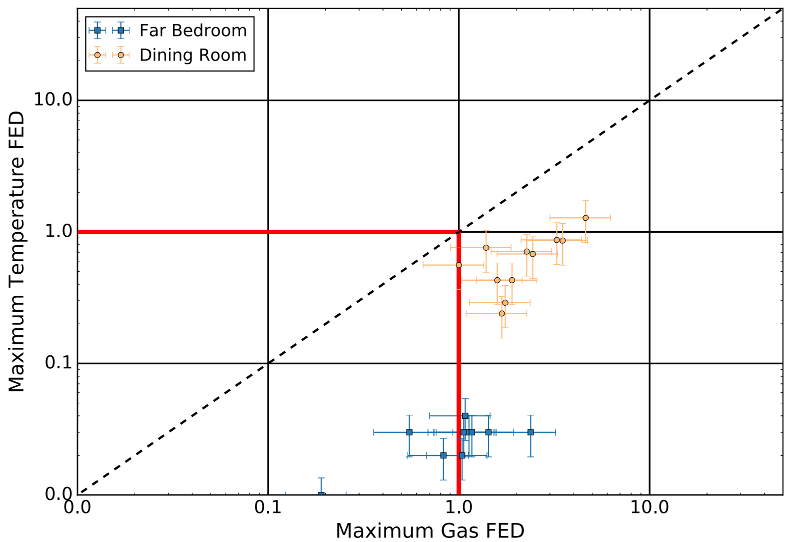

Figure 3. Maximum dining room and far bedroom FED values. FED_{gas} is shown on x-axis and FED_{temp} is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0).

FED rates in the open locations were higher than those observed in the closed areas.

The reason for the difference between the two bedrooms is likely due to the different points in the experimental timeline at which the door is opened and the room was searched. The near bedroom door was opened 113 ± 52 s after the far bedroom. By the time that the search team reached the near bedroom, the smoke layer had already descended within the room to the gas sample point on top of the bed. Additionally, suppression had already occurred and smoke was venting from the area outside of the bedroom. In this case, the team that opened the door allowed the gases trapped behind the closed door to ventilate into the rest of the structure, improving conditions, as opposed to increasing the concentration of toxic gases. Thus, the effect of opening a closed door on the conditions behind it is dependent on the conditions in both rooms that the door connects.

4.3. Search Methods and Simulated Occupant Removal

The time to find and remove the simulated occupants in the dining room and the near closed bedroom varied more between the six groups of firefighters that participated in the experiment than between the attack methods, side of the structure, or whether the group had been through the experiment previously. There was no statistically significant difference in the times to locate or remove the occupants between the transitional attack method versus the interior attack method. This could indicate that there was not a sufficient improvement in visibility as a result of the early water application in the transitional attack experiments that aided the search team in finding the occupant more rapidly. While temperatures and FED rates dropped following initial exterior water application, as described in Sect. 3.3, the structure was still filled with optically dense smoke, indicated by zero visibility on cameras placed on the floor throughout the structure, at the time of firefighter entry. While suppression slows the production of products of combustion, the expulsion of products of combustion from the structure is a time-dependent process, and the rate at which smoke is exhausted and visibility is improved is related to the time of suppression, the methods of ventilation used, the wind speed and direction and the number, location and area of ventilation openings. While ventilation prior to suppression can increase the burning rate of the fire, and thus increase the production rate of toxic gases, ventilation closely coordinated with suppression is important for timely evacuation of products of combustion.

Common firefighting texts [22, 23] suggest that areas close to the suspected seat of the fire should be searched first, as occupants trapped in these areas are exposed to the greatest risk. In these experiments, occupants trapped in the near hallway are indeed at the greatest risk of thermal exposure, but this area is also the least likely location to find a tenable occupant. The other locations, while likely to reach untenable conditions for many occupants by the end of simulated activities, experienced significantly lower FEDs at the time of intervention. Figure 4 shows the FED values in the dining room and hallway at the time that the first occupant was found. These locations are approximately equidistant from the front door, and therefore can be used to compare if the search team first went towards the fire and found an occupant compared to a location on the opposite side of the structure. By searching away from the fire, the team may be more likely to find a viable occupant than when the search team first moves towards the fire. It is difficult to say conclusively whether the conditions at a certain point within a structure would be lethal, but the occupant found next to a post-flash-over compartment fire has a higher likelihood of sustaining lethal burn injuries or incurring a lethal dose of toxic gases than one located remotely in the structure, as shown in Fig. 4. Occupants trapped close to the fire room should not be abandoned or neglected, but high priority should also be placed on the potential for viable occupants trapped remote from the seat of the fire that may also be in need of rapid removal. The search method employed by firefighters on the fireground is ultimately dependent on local policies and procedures and the circumstances of the specific incident.

It is important to note that the searches in these experiments were conducted in a single-story structure with a relatively simple geometry. Occupants were only required to be moved about 6 m to be extracted from the structure. If the floor plan were larger or more complicated, the times required to find and remove occupants likely would have been longer. Following suppression, the rate of gas concentration decrease was not as high as the rate of temperature decrease as described in Sect. 3.3. Although the FED rate was decreasing in the time that the

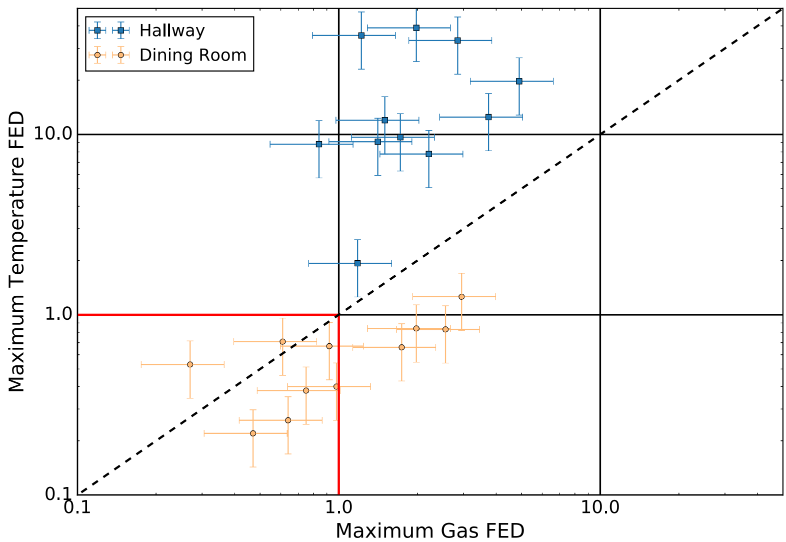

Figure 4. Near hallway versus dining room FED values at time of intervention. FED$_{gas}$ is shown on x-axis and FED$_{temp}$ is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0).

search crew took to find and remove the occupants, the occupants would still be exposed to high concentrations of toxic gases. Because of the nature of the governing equations, even though the hazard was decreasing, the FED of any occupant would continue to increase until they were removed from the structure. This is demonstrated in Fig. 5, which plots the increase in FED toxicity from the time that the search crew made entry to the time that they located the dining room occupant. To control for variation in search crew effectiveness and variation in fire dynamics, the FED was calculated at the search time for all search groups and applied to each experiment. The increase in FED toxicity from the time of search team entry to the time of victim location was calculated for the 11 experiments with data for the dining room victim. The box and whisker plots show the distribution of the FED increase for each experiment, with the whiskers representing the FED increase corresponding to the maximum and minimum victim location times, the box corresponding to the middle quartile of increase, and the red line represents the FED increase for the median search time. The chart shows that as the time to find the simulated occupant increases, the tenability of the occupant is affected significantly. The time between the fastest and slowest victim removal was 46 seconds, yet in some experiments this time difference resulted in a 60%

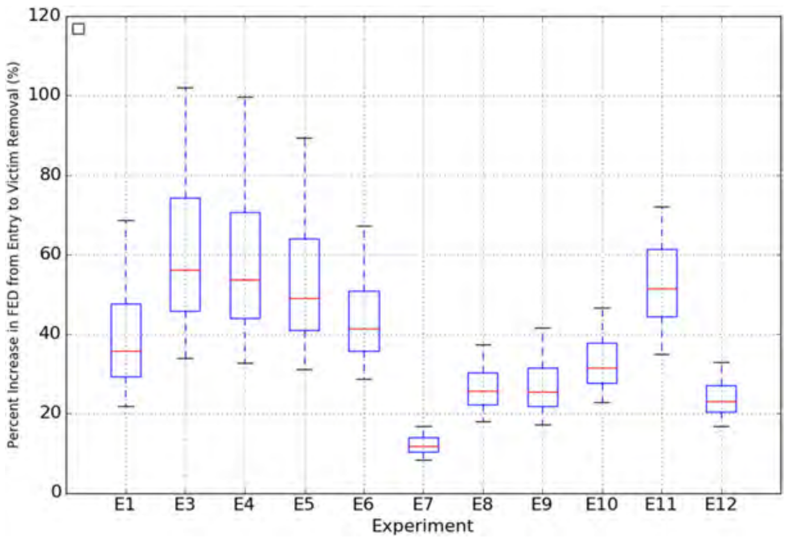

Figure 5. Relationship between occupant location time and % increase in FED between entry of search team and location of dining room occupant. Whiskers represent highest and lowest times to occupant found, red lines represent the FED increases of the middle two quartiles of the location times, and red line indicates FED increase corresponding to median location time.

greater difference in FED increase. It follows that once the victim is found, the toxicity exposure to the victim will continue to increase during the removal process, as long as the occupant is still breathing. This emphasizes the importance of rapid removal of occupants located during the search in an effort to minimize the toxic exposure of these occupants.

In this series of experiments, most of the simulated occupants were removed from the structure out the front door from the location that they were found. The shortest occupant removal time, however, was observed in Experiment 4, where the search crew removed the bedroom occupant out of the rear door of the near closed bedroom. This removal method exposed the occupant to toxic gases for the shortest duration, but also avoided dragging the occupant through the hallway and living room, where the concentrations of products of combustion were higher than in the closed bedroom. Depending on the conditions within the structure, the location of the occupant within the structure, and the knowledge of the search company of alternative means of egress, the ideal path for occupant removal may be out of an opening separate from the one which the search team entered through, such as a rear or side door, or even through a window or down a ladder. This emphasizes the importance of situational awareness among the members of the search company and coordination of occupant removal.

4.4. Attack Methods and Outliers

With the exception of Experiment 3, the attack teams in the transitional attack experiments applied at least 9s of water through the window of each fire room. In the majority of these experiments, the water application resulted in a temperature reduction throughout the structure, but most drastically in the fire rooms and hallway immediately connected to these rooms. The decrease continued until the attack team could advance their hoseline to the hallway for final suppression. The attack team in Experiment 3 directed their hose stream through the window for a shorter duration than the rest of the experiments, 4 s into Bedroom A and 3 s into Bedroom B. This short water application, combined with a delay in entry while the search team forced entry into the structure, allowed for a significant period of regrowth before the attack team reached the hallway to complete final extinguishment. The initial temperature decreases at the 0.9 m elevation in each of the fire rooms and the subsequent increases due to regrowth prior to final suppression are listed in Table 7. Following suppression, the 0.9 m temperatures decreased by 463°C in Bedroom A and by 235°C in Bedroom B. Because of the delay between the short initial attack and the final suppression when the attack team reached the hallway, the 0.9 m above the floor temperatures increased 269°C and 567°C in Bedrooms A and B, respectively. The temperatures in Bedroom B at the time that the attack team reached the end of the hallway were consistent with a post-flashover compartment fire. If the delay between initial and final suppression were longer, it is likely that conditions remote from the fire room would have started to deteriorate. This regrowth was not observed in the remainder of the transitional attack experiments, where the initial water application was longer. In many of these experiments, temperatures in the two fire rooms were still decreas-

Table 7
Temperature Reduction and Subsequent Regrowth in Experiment 3

Event	Experiment 3		Transitional attack average	
	Bedroom A 0.9 m (3 ft.)	Bedroom B 0.9 m (3 ft.)	Bedroom A 0.9 m (3 ft.)	Bedroom B 0.9 m (3 ft.)
Temp. (°C) prior to exterior suppression	617	820	542	759
Minimum temp. (°C) following exterior suppression	154	585	91	162
Maximum temp. (°C) prior to final, interior suppression	282	1152	104	175

ing when the attack team reached the hallway. In the experiments where temperatures did begin to rebound, the increase was not of the same magnitude noted in Experiment 3. The average temperature prior to suppression, the average minimum temperature following suppression, and the average maximum temperature before the attack team reached the hallway for the other transitional attack experiments are listed in Table 7. The regrowth following the exterior attack in Experiment 3 resulted in a longer gap between suppression and the time at which the FED rate began to decrease. Thus, by failing to apply a sufficient amount of water during transitional attack, the effectiveness of the attack in improving conditions within the structure is limited.

Just as the duration of water application is important to the effectiveness of the attack, the location to which the water is applied is important. In the transitional attack experiments, the exterior water application occurred directly into the two fires rooms, resulting in a drastic reduction in temperatures when a sufficient amount of water was used. In the interior attacks, several groups applied water between the time they entered the front door and the time they reached the hallway. The poor visibility within the structure during this time makes it difficult to assess the effectiveness of these initial bursts of water, but the most effective cooling in the interior attack experiments occurred once the attack teams had reached the hallway, allowing them to apply water directly to the contents of the burning rooms. In one experiment, Experiment 5, the attack team did not apply any water until reaching the hallway. Upon reaching the hallway, an issue was encountered with the hose advancement, and the nozzle firefighter opened the nozzle, but was only able to apply water to the ceiling of the hallway for a brief period of time. The hose advancement issue was thereafter resolved, and the nozzle firefighter was once again able to advance and complete extinguishment. Prior to this final extinguishment, the temperature decreases in the area of the fire room were negligible, indicating that the water application was ineffective. The results of this experiment indicated that for effective and definitive suppression, water must be applied directly to burning fuels.

In the transitional attack, water was applied earlier in the experimental timeline, resulting in a reduction in temperatures sooner than when compared to the interior attack experiments. After deploying their attack line, the teams conducting transitional experiments were able to immediately apply water to the fire, resulting in water application significantly faster than the interior attack groups and a reduction in temperatures sooner than when compared to the interior attack experiments. Once the interior attack groups deployed their hose line, they were often delayed while waiting for the search team to simulate forcing entry into the building. Despite the delay, the interior attack groups entered the structure faster (174 ± 10 s) when compared to the transitional attack groups (213 ± 29 s) ($p = 0.02$). Despite the early water application in the transitional attack experiments, there was no significant difference in the time at which the FED rate began to decrease between the two attack methods due to similar times to force entry and provide ventilation for clearing smoke.

4.5. Limitations

The equations used to compute the FEDs at each of the sample points for these experiment have a great deal of uncertainty associated with them, as high as 35%. This high uncertainty, combined with the uncertainty of the measurements themselves, resulted in a large amount of scatter in the gas concentration data. Additionally, significant gas concentrations were not measured until the gas layer had descended to the point of the sample location, which in some experiments occurred later than others. A similarly large variation was not noted in the temperature measurements, indicating that although the thermal conditions within the structures were within a reasonable margin of uncertainty, the gas concentrations may be more susceptible to scatter. The gas sample locations in this series of experiments were fixed, which made accounting for the toxic exposure to simulated occupants during their removal from the structure difficult. Future work should attempt to assess how the occupants' toxic exposure changes during the removal process by using portable gas measurement techniques. Future studies may also focus on the impact of the fire size (including spreading outside the compartment(s) of origin), fire dynamics (vitiated, flaming, smoldering), multi-story structures, or the possibility that the occupant is located within the room of fire origin.

5. Conclusions

Utilizing a full sized single family residential structure with two fully involved compartments typical of room and contents fires, this study provides new data and insights into exposure conditions for trapped occupants and how variability in firefighting activities may affect tenability for those occupants. Consistent with fatality data from structure fires, occupants close to the origin of the fire sustained the most severe thermal exposures, likely reaching incapacitation from heat exposure prior to the exposure to products of combustion. These occupants also sustained the highest gas exposures of any simulated occupant location. Distant from this location but in areas open to the fire rooms, gas exposure levels reach FED values that were on average 169% higher than the thermal FED at this location but also 25% lower than those near the fire. The FEDs within the two closed bedrooms were found to be significantly lower than locations just outside of the closed door such that occupants trapped in the closed bedrooms would likely have been tenable well into the experiment, particularly if doors remained closed until rescue is affected.

Water application by the fire attack teams was associated with a rapid drop in temperatures throughout the structure, followed shortly afterward by a decrease in the FED rate. There was no significant difference between the magnitude of the temperature decrease or the time until the inflection point in the FED curve between transitional attack and interior attack. For the transitional attack experiments, water was applied to the fire significantly earlier in the experimental timeline than in the interior attack experiments, while in the interior attack experiments, the attack team made entry to the structure significantly sooner than in the transitional attack experiments. For both attack methods, significant improvements in interior conditions were observed following effective water application, while ineffective water application reduced or delayed the positive effects.

The coefficient of variations of the groups' times to execute various fireground actions ranged from 20% to 95%. This emphasized the importance of training to develop proficiency in tasks such as hose advancement, forcible entry, and search techniques, as well as coordination between companies on the fireground to minimize miscommunication and improve efficiency. Importantly, as the removal time for the occupant increased, the toxic exposure to the occupant increased, despite the decreasing FED rate due to suppression. These results emphasized the need for rapid removal of occupants and coordinated ventilation with suppression to limit toxic exposures.

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A.6 Paper VI: Thermal Response to Firefighting Activities in Residential Structure Fires: Impact of Job Assignment and Suppression Tactic

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

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To cite this article: Gavin P. Horn, Richard M. Kesler, Steve Kerber, Kenneth W. Fent, Tad J. Schroeder, William S. Scott, Patricia C. Fehling, Bo Fernhall & Denise L. Smith (2018) Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic, Ergonomics, 61:3, 404-419, DOI: 10.1080/00140139.2017.1355072

To link to this article: https://doi.org/10.1080/00140139.2017.1355072

Accepted author version posted online: 24 Jul 2017.
Published online: 31 Jul 2017.

ERGONOMICS, 2018
VOL. 61, NO. 3, 404–419
https://doi.org/10.1080/00140139.2017.1355072

Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic

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ABSTRACT
Firefighters' thermal burden is generally attributed to high heat loads from the fire and metabolic heat generation, which may vary between job assignments and suppression tactic employed. Utilising a full-sized residential structure, firefighters were deployed in six job assignments utilising two attack tactics (1. Water applied from the *interior*, or 2. Exterior water application before *transitioning* to the interior). Environmental temperatures decreased after water application, but more rapidly with transitional attack. Local ambient temperatures for inside operation firefighters were higher than other positions (average ~10–30 °C). Rapid elevations in skin temperature were found for all job assignments other than outside command. Neck skin temperatures for inside attack firefighters were ~0.5 °C lower when the transitional tactic was employed. Significantly higher core temperatures were measured for the outside ventilation and overhaul positions than the inside positions (~0.6–0.9 °C). Firefighters working at all fireground positions must be monitored and relieved based on intensity and duration.

Practitioner Summary: Testing was done to characterise the thermal burden experienced by firefighters in different job assignments who responded to controlled residential fires (with typical furnishings) using two tactics. Ambient, skin and core temperatures varied based on job assignment and tactic employed, with rapid elevations in core temperature in many roles.

ARTICLE HISTORY
Received 11 January 2017
Accepted 7 July 2017

KEYWORDS
Firefighting; core temperature; heat stress; heat strain; body temperature

1. Introduction

Heat stress is one of the most common challenges that firefighters routinely encounter. Because firefighters perform strenuous work while wearing heavy, insulating personal protective equipment (PPE), a rise in body temperature almost always accompanies firefighting activity. High heat loads from the fire can also add to the heat stress experienced by firefighters. The physiological and thermal strain of firefighting activities have been documented based on simulated fireground work. The change in core temperature associated with firefighting activities has been reported by several research groups (Colburn et al. 2011; Horn et al. 2013; Hostler et al. 2010; Walker et al. 2015). Firefighting involves strenuous work that leads to maximal or near-maximal heart rates (HR) and, in some cases, rapid changes in core temperature (Tco) (Barr, Gregson, and Reilly 2010). Horn et al. (2011), reported average changes of 0.70 °C during short bouts of firefighting activity typical of residential 'room and contents' fires. The researchers noted that repeated bouts of firefighting or the use of multiple cylinders of air is associated with further increases in body temperature. It is important to note, however, the vast majority of work that has been done characterising the thermal stress of firefighting has occurred during training fires or in controlled laboratory conditions. Training fires differ considerably from residential fires in terms of the geometry of the structure, building materials and fuel loads. Because of these factors, firefighters may experience different thermal environments, as well as different chemical exposures, during actual fires in residential buildings than in a training burn. Recent measurement of ambient temperatures inside common structure fires have further detailed risks posed by firefighting activities in modern structure fires (Kerber 2013). However, these studies have not included human subjects. Portable thermal data acquisition systems carried by firefighters have

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been used to characterise risks faced by firefighters in live-fire training scenarios (Willi, Horn, and Madrzykowski 2016) and historically for firefighting activities that were largely exterior focused (Abeles, Delvecchio, and Himel 1973; Gempel and Burgess 1977). However, to date, these data acquisition systems have not been deployed in structure fire scenarios with typical residential fuel packages or linked to data from physiological status monitoring.

In order to investigate physiological responses to firefighting, many researchers (e.g. Havenith and Heus 2004; von Heimburg, Rasmussen, and Medbo 2006; Holmér and Gavhed 2007; Ilmarinen et al. 2008; O'Connell et al. 1986; Smith, Manning, and Petruzzello 2001) have each participant perform a set of 'typical' firefighting tasks, such as climbing stairs or ladders, advancing a hoseline, forcing a door, performing search and rescue, and completing overhaul tasks. These studies have been critical to advancing our understanding of the physiological strain associated with the various stressors that firefighters face. Unfortunately, such approaches that require performing 'typical' firefighting activities may obscure the fact that at actual fires, firefighters often perform distinct work and may operate in very different thermal environments depending on the jobs they are assigned to do. Smith and colleagues investigated cardiac strain during high-rise fireground operations and found that truck crews assigned to search and rescue operations and to material transport had different levels of cardiac strain than engine crews who were assigned fire suppression activities in a simulated fire scenario (Smith et al. 2015).

A primary goal of firefighting is to extinguish the fire to protect life and property. While this basic goal may seem obvious and straightforward to a civilian, the tactics used by the fire department to accomplish this goal may vary considerably. Based on an accumulating body of evidence, many fire departments are emphasising getting water on the fire as soon as possible to improve conditions inside the structure (Kerber 2013). Such an approach is often called a 'transitional' attack in which firefighters apply water through a window to initially suppress the fire before they enter the building to completely extinguish the fire and ensure there is no further fire growth. This approach contrasts with many departments that have been taught that it is best to enter the house through the front door with a charged hoseline. In theory, the goal of this 'interior' fire attack is to find the seat of the fire and extinguish it as soon as possible to protect potential victims. To date, there is no research that has considered the effect of different firefighting tactics on the firefighter's physiological responses to their work.

The increase in body temperature associated with firefighting is due to multiple factors, including, performance of heavy muscular work, the use of heavy insulative gear that adds to the metabolic work that is performed and that interferes with heat dissipation; and the high ambient temperatures (Smith, Manning, and Petruzzello 2001; Smith et al. 2016). Although some research has attempted to understand the effect of the ambient temperature (Smith et al. 1997) and the effect of PPE (Fehling et al. 2015) on body temperature, surprisingly little research has been done to investigate the effect of different thermal environments experienced by firefighters on body temperature responses.

The purposes of this study were to expand previous research on thermal responses of firefighters by (a) characterising the thermal environment in which firefighters operate in a modern residential fire with realistic fuel loads, (b) documenting the temperatures encountered by the firefighters in different job assignments, (c) evaluating core and skin temperature changes of firefighters assigned to different job assignments and (d) investigating the effect of firefighting tactic on the environmental conditions encountered and the temperature responses of firefighters.

2. Methods

2.1. Participants

Participants were recruited through a nationwide multimedia 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 (Horn et al. 2016). Participants provided informed written consent indicating that they understood and voluntarily accepted the risks and benefits of participation. This study was approved by the University of Illinois Institutional Review Board. Forty (n = 40) firefighters (36 male, 4 female) from departments in Illinois, Georgia, Indiana, Ohio, South Dakota and Wisconsin participated in this study. The firefighters were 37.6 ± 8.9 years old, 1.80 ± 0.08 m tall, weighed 89.8 ± 14.5 kg and had an average BMI of 27.6 ± 3.4 kg/m^2 with an average of 14.9 ± 8.5 years of experience in the fire service.

All participants were required to have completed a medical evaluation consistent with National Fire Protection Association (NFPA) 1582 in the past 12 months. 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 self-contained breathing apparatus (SCBA) prior to entering the structure. The research team supplied all PPE for the participants to enhance standardisation and to ensure that all protective equipment adhered to NFPA standards.

2.2. Study design

Teams of 12 firefighters were deployed to suppress fires in a realistic firefighting scenario that involved a multiple-room fire (two separate bedrooms) in a 111 m^2 residential structure. Each team of 12 firefighters worked in pairs to perform six different job assignments that included operations on the *inside* of the structure during active fire (fire attack and search & rescue), on the *outside* of the structure during active fire (command & pump operator and outside ventilation), and to conduct *overhaul* operations after the fire had been suppressed (firefighters searched for smouldering items and removed items from the structure). The job assignments are described in Table 1.

In all, 12 different trials were conducted (one per day) each with twelve firefighters as described above. The firefighters responded to two scenarios that differed only in the tactics used by the Inside Attack team: (a) traditional *interior* attack from the 'unburned side' (advancement through the front door to extinguish the fire) and (b) *transitional* attack (water applied into the bedroom fires through an exterior window – from the 'unburned side' – prior to advancing through the front door to extinguish the fire). The firefighters performed the same role using both tactics, then were reassigned to different job assignments and performed another two scenarios – again using the same two tactics on separate days. While most firefighters attended four sessions of the study ($n = 31$), a small group were only available for two sessions ($n = 9$) and one firefighter withdrew from the study and wasn't replaced until after the first two scenarios.

2.3. Study protocol

Following recruitment, participants completed all required paperwork and anthropomorphic measurements (height, weight) were collected. Firefighters received a core temperature pill that they ingested 6–12 h prior to data collection. Upon arrival on each day, firefighters were instrumented with skin temperature patches on the back of their neck and upper arm that they wore throughout the trial. Multiple pre- and post-firefighting cardiovascular measurements and chemical exposure samples (biological and PPE) were collected prior to the initiation of the live fire evaluation (these data will be reported elsewhere). The firefighter participants were then deployed to complete their firefighting work in a purpose-built live-fire research test structure.

In order to safely and reliably conduct this study, a structure was designed and built to have all of the interior finishes and features of a single family dwelling, yet contained specialised safety systems and hardened construction techniques that ensured participants' safety as described in Horn et al. (2016). The house was based on a design 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 2.4 m ceilings. The home had an approximate floor area of 111 m^2, with 8 total rooms, including 4 bedrooms and 1 bathroom (closed off during experiments). Interior finishes in the burn rooms were protected by 15.9 mm Type X gypsum board on the ceiling and 12.7 mm gypsum board on the walls. To maximise the use of the structure and minimise time between experiments, the house was mirrored so that there were 2 bedrooms on each side where the fires were ignited. During each experiment a temporary 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.

Furniture was acquired from a single source such that each room was furnished identically (same item, manufacture, make model and layout of all furnishings) for all 12 experiments. The bedrooms, where the fires were ignited, 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

Table 1. Deployment protocol, job assignments and response times.

Job assignment	Apparatus	Specific tasks	Median time (min)	
			Outside structure	Inside structure
Outside command/pump	Engine 1	Incident command and operate the pump	20	0
Inside attack		Pull primary attack line (fire hose) from engine and suppress all active fire	3	8
Inside search	Truck 1	Forcible entry into the structure and then search for and rescue 2 victims (75 kg manikins)	2	8
Outside vent		Deploy ladders to the structure and create openings at windows and roof (horizontal and vertical ventilation)	19	0
Overhaul/backup	Engine 2	Pull a second attack line and support the first-in engine (from outside the structure) and then perform overhaul operations (remove drywall from walls/ceiling and furniture from room to locate any hidden fire) inside the structure after fire suppression	11	16
Overhaul/RIT		Set up as a rapid intervention team (RIT) and then perform overhaul operations inside the building after fire suppression	11	17

polyester carpet. All other rooms of the structure were also furnished to provide obstacles for the firefighter, but those furnishings were not involved in the fire. Figure 1 provides a rendering of the structure with the roof cut away to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the white floor shows the cement floor or simulated tile locations.

Fires were ignited in the stuffed chair in Bedrooms 1 & 2 (labeled Bedrooms 5 & 6 for the mirrored configuration) using a remote ignition device and a book of matches to create a small flaming ignition source. The flaming fire was allowed to grow until temperatures in the fire rooms reached levels determined to be near peak values based on pilot studies (i.e. room had 'flashed over'). When interior temperatures of both fire rooms exceeded 600 °C at the ceiling, the fire department dispatch was simulated and firefighters responded by walking approximately 40 metres from the data collection bay to the front of the structure. The time of dispatch was between 4 and 5 min after ignition for all 12 experiments.

2.4. Measures

2.4.1. Building thermal measurements

To assess fire dynamics throughout the fire scenarios, measurements included air temperature, gas concentrations, pressure, heat flux, thermal imaging and video recording. Detailed measurement locations can be found in Figure 1 and described in Horn et al. (2016). This report will focus on the thermal measurements.

Air temperature was measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.5 mm 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 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 m above the floor. The thermocouple locations in Bedroom 1/5, Bedroom 2/6 and Bedroom 3 had an array of thermocouples with measurement locations of 0.3, 0.9, 1.5 and 2.1 m above the floor.

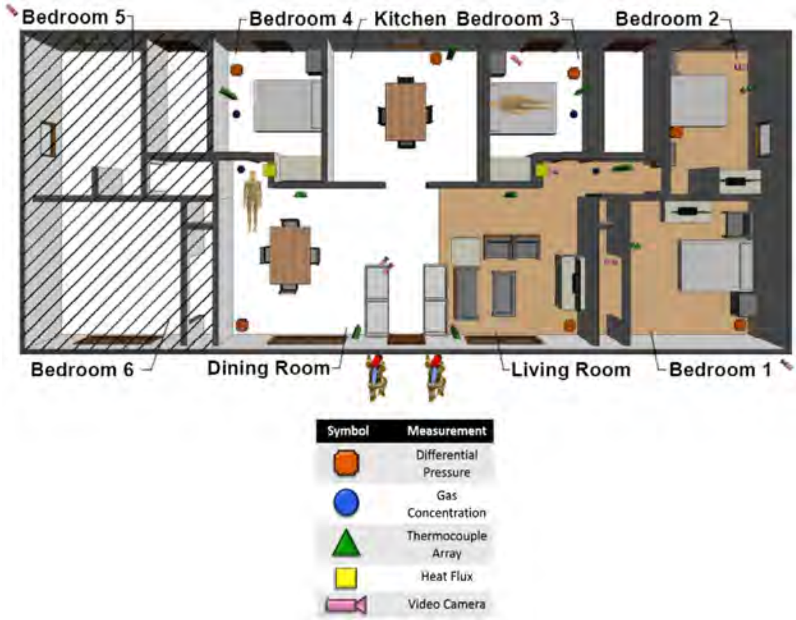

Figure 1. Schematic of data acquisition instrumentation location with the fire bedrooms (Bedroom 1 & 2) in the right side configuration.
Notes: The floor area with hash marks (Bedroom 5 & 6, part of hallway) was behind a movable false wall that could be moved to the same location on the opposite end of the structure to allow measurements on back-to-back days in a mirrored structure.

Heat flux (the speed of thermal energy transfer) measurements were made using a 25.4 mm 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: 0.3, 0.9 and 1.5 m above the floor in the hallway just outside Bedroom 3 and facing the fire in Bedroom 2. When the fire was on the opposite side of the structure, measurement locations were mirrored (outside bedroom 4, facing the fire in bedroom 5). These locations were chosen to characterise the heat flux a firefighter might face at a location where they can start to direct their water stream into both of the burning bedrooms from the interior.

2.4.2. Firefighter local temperatures

For each scenario, two of the firefighters operating at the front of their crews on the inside of the structure (nozzleman on the attack line and lead firefighter on the search team) wore a portable temperature sensor and data acquisition system affixed to the front of the helmet. Type K thermocouples with a 0.5 mm nominal diameter in conjunction with Omega Engineering UWTC wireless temperature sensors were used to monitor temperatures of firefighting crews. The wireless sensors incorporated internal cold junction compensation. Data was logged to an internal solid state memory and downloaded after each experiment. The sensors, programmed to a sampling rate of 0.5 Hz, synced to the main data acquisition system before each experiment. The resolution of the sensor was 1 °C, with an accuracy of 0.5% of the reading or 1 °C whichever is greater.

2.4.3. Assessment of firefighter core and skin temperature

Skin (neck and arm) and core body temperatures were continuously measured throughout all data collection sessions (Horn et al. 2016). A monitor (MiniMitter Vital Sense, Phillips Respironics, Bend, OR) was clipped to their belts before and after firefighting and carried in their bunker coat after donning their PPE. 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, which is designed to pass through the body and be eliminated in faeces within ~24 h. While the sensor was in the GI tract it transmitted temperature information to the remote recording device. If a firefighter retained a pill from a prior measurement day, the one ingested 6–12 h prior to activity was utilised for consistency.

2.5. Statistical analysis

Variables were checked for normal distribution using Shapiro-Wilk tests. A relatively small number of distributions were found not to be Gaussian, but differences between means and median values were typically less than 1%. Therefore, means and standard deviations are reported for results. Statistical comparisons were performed using parametric tests. Confirmatory analyses were conducted on log-transformed data for the few non-normal data-sets, which in all cases resulted in the same determination of statistical significance. Each of these analyses was performed in SPSS (v. 23 IBM, Armonk, NY) with significance set at an alpha of 0.05.

Data describing the environmental conditions within the structure at 0.9, 1.5 and 2.1 m above the floor are reported in various rooms of interest (Living Room, Dining Room, Hallway, Fire Bedrooms) for scenarios in which interior and transitional attack tactics were implemented. Maximum temperatures and hallway heat flux values recorded at each height and location throughout the structure are determined for the 'Interior attack' and 'Transitional attack' tactics and compared between these tactics using Student *t*-test to determine if conditions were similar prior to firefighter intervention. To characterise the impact of firefighting tactics on environmental temperatures, the values recorded from the same locations when firefighters arrived in the hallway were summarised and compared with a series of *t*-tests.

Local firefighter temperature exposures for the Inside job assignments were analysed using repeated measures 2×2 analysis of variance (ANOVA) to study the impact of specific Inside job assignment (Attack vs. Search) and tactic (Interior vs. Transitional). The average temperatures experienced by the Inside, Outside and Overhaul crews were compared using repeated measures ANOVA, followed by *post hoc t*-tests.

Finally, firefighters' skin and core temperatures exposures were analysed using repeated measures ANOVA to study the impact of four job assignments (Inside, Outside Command, Outside Vent and Overhaul) and tactic (Interior vs. Transitional), followed by *post hoc t*-tests where appropriate. Unfortunately, due to some 'lost' core temperatures pills near the beginning of the scenarios, loss of communications with sensors during data collection and skin temperature patches coming off due to heavy sweat, there was significant data loss. For these comparisons, we only report data from participants who had valid neck skin, arm skin and core temperature data for both Interior and Transitional attack scenarios ($n = 47$ of 72).

3. Results

3.1. Building temperature & heat flux profiles

Figure 2 provides example plots of the air temperatures at each of the 10 different measurement locations at

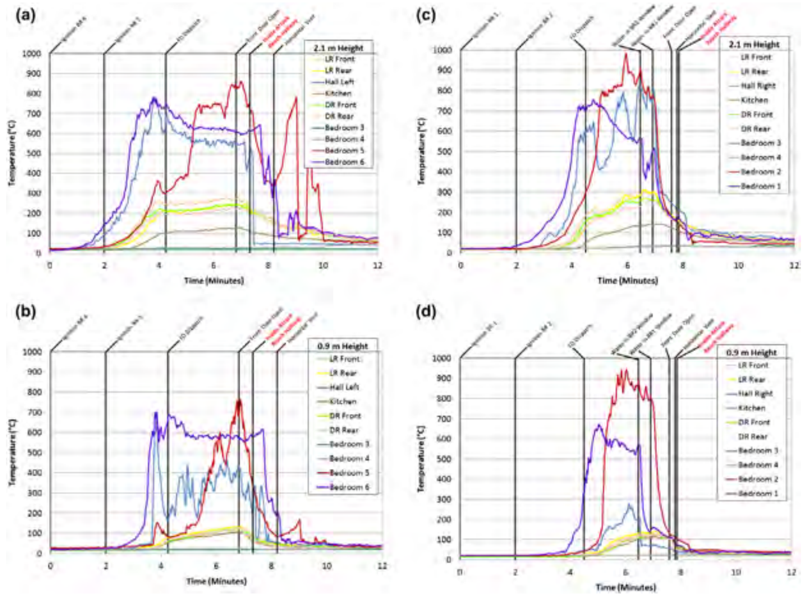

Figure 2. Building air temperatures at each of the measurement locations of the structure for an example and Interior attack scenario (a,b) and Transitional attack scenario (c,d) at measurement heights of 2.1 m (a,c) and 0.9 m (b,d).
Notes: Temperatures remain stable after minute 12, so the data is only shown to this time in order to better visualise the changes during Inside activities. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

the ceiling (2.1 m) and the crawling level of a firefighter (0.9 m) for a pair of scenarios completed by the same crew. Figure 2(a) and (b) are representative of the Interior attack scenarios and Figure 2(c) and (d) are representative of the Transitional attack scenarios. In each of the twelve fires, the two bedrooms where fires were ignited progressed to room flashover (full fire involvement with temperatures above 500 °C throughout the room) prior to firefighters entering the front door (Interior) or applying water through the window (Transitional). Table 2 provides a summary of maximum temperatures reached prior to firefighter intervention (averaged over the 6 Interior and 6 Transitional attack scenarios) at three heights (ceiling – 2.1 m, firefighter standing – 1.5 m, firefighter crawling – 0.9 m) at locations where firefighters would be operating. There were no statistically significant differences in these temperatures by tactic other than near the entrance to the structure (Living Room Rear at 0.9 m height). Firefighters conducting Transitional attack applied water to the fire significantly faster (on average 6:30 ± 0:26 (minutes:seconds) after the fires were ignited) than it took for firefighters conducting the Interior tactic to enter the front door (7:21 ± 0:26) ($p = 0.009$). Upon entry to the structure, firefighters began flowing water towards the hallway where the bedroom fires were located; however, it is not possible to compare the time to which the first water actually reached the burning materials and began suppressing the fire for the Interior attack scenarios.

Table 3 provides a summary of temperatures at the same locations and heights as reported in Table 2 (again averaged over the 6 Transitional and 6 Interior attack scenarios) at the time when the Inside Attack firefighters had made it to the hallway as identified by interior camera feeds. As Table 3 shows, there were statistically significant differences by tactic at nearly all locations other than near the front door (0.9, 1.5 and 2.1 m in the Living Room Rear location) and at 0.9 m in Bedrooms 2/5. Note the large standard deviation in the temperatures measured in Bedrooms 2/5. This large variability is the result of a single scenario where firefighters applied water into

Table 2. Mean (SD) of the maximum air temperatures and hallway heat flux (averaged over the 6 scenarios for each tactic) reached prior to firefighter intervention (water in window or front door open) at three heights at various locations.

		Maximum temperature pre-firefighter intervention (°C)							Heat flux
Height (m)	Tactic	LR front	LR rear	DR front	DR rear	Hallway	BR2/5	BR 1/6	(kW/m²)
2.1	Interior	309.6 (33.3)	308.5 (61.3)	280.1 (30.5)	240.4 (22.1)	809.4 (124.5)	978.2 (156.1)	774.8 (43.2)	
	Transitional	283.7 (20.3)	274.8 (27.9)	238.5 (47.3)	219.1 (16.4)	748.8 (104.0)	890.4 (75.4)	740.8 (35.7)	
1.5	Interior	278.4 (32.8)	209.8 (29.2)	250.6 (40.1)	233.4 (30.9)	739.7 (157.4)	952.1 (116.0)	810.9 (57.7)	28.22 (10.4)†
	Transitional	263.3(16.6)	167.4 (36.3)	211.9 (25.0)	202.3 (17.1)	648.0 (125.2)	910.3 (60.7)	756.0 (46.7)	22.35 (3.93)
0.9	Interior	114.1 (28.7)	165.8 (32.7)	130.5 (17.0)	160.8 (40.0)	435.7 (146.3)	954.3 (105.6)	709.3 (94.6)	13.39 (10.04)†
	Transitional	126.6 (15.4)	127.9 (12.3)*	120.0 (12.1)	132.1 (24.9)	393.0 (75.5)	875.8 (121.9)	662.6 (50.6)	9.00 (4.72)

Notes: LR = Living Room, DR = Dining Room, BR = Bedroom.
*Significantly different than Interior ($p < 0.05$); **Significantly different than Interior ($p < 0.001$); †$n = 5$ due to data acquisition malfunction.

Table 3. Mean (SD) of the air temperatures and hallway heat flux measured at the instant when the Inside Attack firefighters had reached the hallway at each of these three heights at different locations (averaged over the 6 scenarios for each tactic).

		Temperature when 'inside attack reaches hallway' (°C)							Heat Flux
Height (m)	Tactic	LR front	LR rear	DR front	DR rear	Hallway	BR2/5	BR 1/6	(kW/m²)
2.1	Interior	286.2 (39.9)	244.7 (84.4)	254.5 (30.7)	228.0 (21.7)	581.5 (154.4)	744.0 (133.3)	642.0 (50.2)	
	Transitional	158.3 (69.6)*	163.0 (80.3)	142.5 (64.4)*	137.2 (57.3)*	210.7 (182.9)*	357.7 (352.6)*	340.7 (128.8)**	
1.5	Interior	240.5 (51.6)	161.7 (107.8)	209.7 (41.0)	201.5 (31.2)	520.0 (90.6)	726.7 (123.5)	641.7 (46.4)	19.34 (4.95)†
	Transitional	107.8 (53.7)*	107.8 (53.7)	124.2 (65.1)*	114.2 (57.8)*	135.5 (121.4)**	338.5 (366.4)*	176.5 (110.5)**	5.21 (5.00)*
0.9	Interior	114.7 (20.7)	90.7 (36.8)	95.2 (15.2)	99.2 (22.2)	311.3 (73.9)	650.3 (184.1)	583.3 (38.4)	7.94 (4.60)†
	Transitional	72.0 (28.9)*	61.5 (35.6)	63.7 (29.9)*	54.3 (21.0)*	65.5 (42.8)**	345.8 (373.5)	112.2 (51.1)**	2.98 (3.73)

LR = Living Room, DR = Dining Room, BR = Bedroom.
*Significantly different than Interior ($p < 0.05$); **Significantly different than Interior ($p < 0.001$); †$n = 5$ due to data acquisition malfunction.

the fire rooms (Bedrooms 5 and 6) from the exterior for approximately 15 s each, then transitioned to the front of the structure where their entry was delayed while the front door was forced open. This water application successfully suppressed the bulk of the fire in Bedroom 6, but not in Bedroom 5. Prior to entering the structure, the fire in this second room regrew to nearly the same magnitude as it was prior to the exterior attack.

Firefighters conducting Transitional attack reached the hallway on average 8:56 ± 1:48 after the fires were ignited, which was not significantly different than the Interior firefighters who reached the hallway at 7:46 ± 0:26 after ignition ($p = 0.158$). The large variability in time for the Transitional Attack scenario is a result of one scenario where firefighters transitioned into the structure after exterior water application, but were disoriented in the smoke and were significantly delayed in making progress to the fire rooms (12:20). If this scenario were removed, the mean time to reach the hallway for Transitional Attack is 8:15 ± 0:46. While the difference in time to reach the hallway is not statistically significant when comparing the two tactics, this delay in progress to the hallway using the Transitional attack approach can impact time to locate a victim and may have important implications in a real situation.

Representative hallway heat flux data from the same two Interior attack and Transitional attack scenarios referenced in Figure 2 are shown in Figure 3. These figures show the heat flux that might be experienced while firefighters are standing (1.5 m), crawling (0.9 m), or very near the floor (0.3 m). Aforementioned Tables 2 and 3 also include maximum heat flux prior to firefighter intervention and heat flux that the firefighters might face when they reach the hallway when employing Transitional and Interior firefighting tactics. Heat flux at 1.5 m height when the firefighters had reached the hallway was significantly lower during Transitional attack than Interior attack (and nearly significant at 0.9 m height ($p = 0.080$)).

3.2. *Firefighter local temperature exposure data*

While Figures 2 and 3 provide a quantification of the thermal conditions firefighters may be exposed to if they remained in a stationary location, Figure 4 shows a representative measurement of local temperatures from firefighters as they move through the structure, from the helmet mounted temperature sensors on the attack (nozzleman) firefighter and the lead search team member from the same two scenarios as presented in Figure 2. Table 4 provides a summary of the maximum and average temperatures experienced by both Inside job assignments (Inside Attack, Inside Search). For comparison purposes, the average working temperatures measured inside the structure during Overhaul operations and exterior temperatures experienced by the Outside operations are also presented.

Based on helmet temperatures, firefighters operating on the hoseline (Inside Attack) were exposed to a significantly higher maximum and average temperatures than

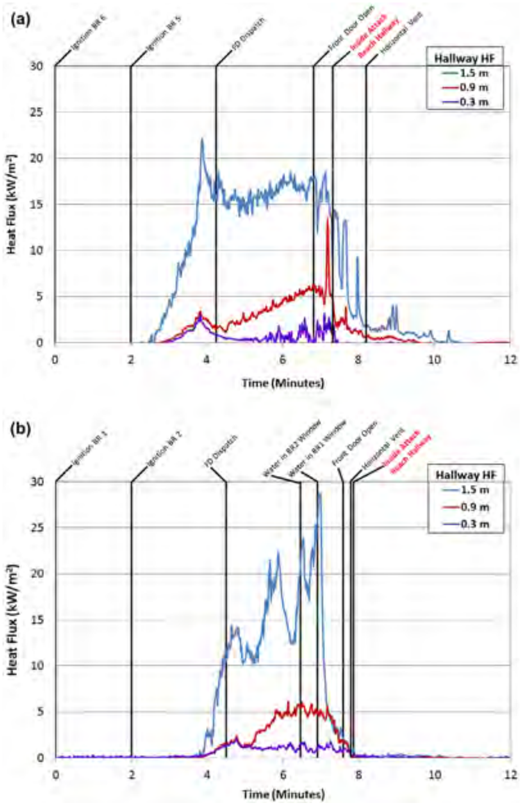

Figure 3. Heat flux measurements from the hallway immediately adjacent to the fire rooms with open doorways for an example (a) Interior attack and (b) Transitional attack scenario. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

the Inside Search team ($p < 0.001$ *each*). We also found significantly lower maximum and average temperatures for the Inside Attack crews when they used a Transitional attack compared to Interior attack ($p = 0.006$ *each*), with no significant impact of tactic on the Inside Search crew's thermal exposures (although the average temperature exposure difference was borderline significant, $p = 0.075$).

When comparing the average ambient temperatures among the Inside, Overhaul and Outside crews (Table 4), a significant main effect of job assignment was found (ANOVA $p < 0.001$). In *post hoc t*-tests, there was a significant difference in ambient temperatures experienced by each of the job assignments: Inside Attack > Inside Search > Overhaul > Outside ($p \leq 0.001$). Tactical choice did not significantly affect the ambient temperatures for the Overhaul or Outside assignments.

3.3. Skin temperature

Table 5 provides the mean values for arm and neck skin temperature by job assignment performed and firefighting tactic employed. We found a significant effect of job

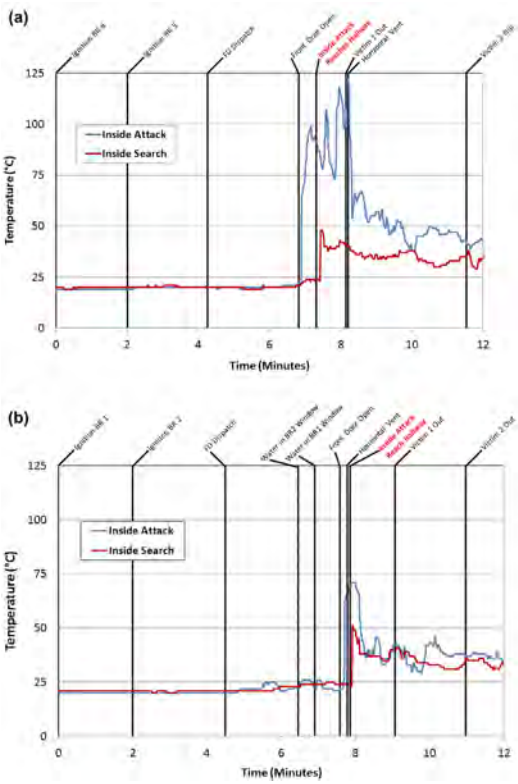

Figure 4. Helmet mounted temperature measurements collected from the nozzleman on the attack team and lead search team member for an example (a) Interior attack and (b) Transitional attack scenario. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

assignment on both skin temperature measurements (ANOVA $p < 0.001$). There was no difference between temperature measurements for the Inside crews (Inside Attack vs. Inside Search), so they were collapsed to a single 'Inside' group. Post hoc analysis revealed that when compared to the Outside Command operations (incident command and pump operator) as the referent, all other job assignments had higher arm and neck skin temperatures ($p < 0.001$). Additionally, neck skin temperatures for the Inside crews (averaged over both tactics) were significantly lower than Overhaul crews ($p = 0.048$). There were no detectable differences between the other job assignments despite significantly different ambient conditions reported in Table 4.

When analysing the full data-set, there were no significant main effects for tactic on skin temperatures. This finding is not surprising as the tactic only had a significant impact on environmental temperatures for the Inside crews. The effect of tactic on skin temperatures was also explored for inside crews (Inside Attack and Inside Search combined). Neck skin temperature was found to be significantly lower during Transitional attack than Interior attack

Table 4. Mean (SD) of maximum and average helmet mounted temperature measurements collected from nozzleman on the attack team and lead search team member.

Measure	Job assignment	Interior attack	Transitional attack	Significance
Helmet temperature (°C)				
Maximum	Inside attack	191.0 (48.6)	95.7 (54.9)	*p* = *0.006*
	Inside search	63.2 (13.0)	54.7 (101)	ns (0.245)
Average	Inside attack	57.6 (7.0)	42.2 (7.8)	*p* = *0.006*
	Inside search	39.7 (4.6)	34.9 (3.9)	ns (0.075)
Ambient temperature (°C)				
Average	Overhaul	25.0 (3.0)	26.6 (2.8)	ns (0.375)
	Outside	19.2 (1.2)	19.8 (1.4)	ns (0.505)

Note: For Overhaul and Outside job assignments, reported temperatures are the average hallway temperatures (1.5 m) during overhaul and exterior temperature throughout the scenario, respecitvely.

Table 5. Mean (SD) of the maximum skin temperature for firefighters operating in different job assignments and attack tactics.

Measure	Job assignment	Interior attack	Transitional attack	*N*
Maximum arm skin Temperature (°C)	Outside command/ pump	36.14 (1.32)	36.09 (1.36)	8
	Outside vent**	37.65 (0.71)	37.76 (0.62)	8
	Inside**	37.51 (1.07)	37.20 (0.82)	16
	Overhaul**	37.65 (0.76)	37.96 (0.43)	15
	Total	37.35 (1.09)	37.35 (1.02)	47
Maximum neck skin temperature (°C)	Outside command/ pump	36.40 (1.24)	36.20 (1.18)	8
	Outside vent**	37.72 (0.15)	37.67 (0.54)	8
	Inside**	37.67 (0.76)	37.21 (0.63)	16
	Overhaul**	37.81 (0.99)	38.06 (0.46)	15
	Total	37.50 (0.99)	37.39 (0.93)	47

*Significantly different than Outside Command/Pump ($p < 0.05$); **Significantly different than Outside Command/Pump ($p < 0.001$).

(ANOVA $p = 0.046$). There was no significant effect of tactic on Arm skin temperature for Inside firefighters.

3.4. Core temperature

The participants' core temperatures were monitored throughout the study and baseline and maximal values were recorded. Mean and standard deviation of the maximum core temperatures recorded and the change in core temperature from baseline are reported in Table 6. Figure 5 shows representative core temperature data from firefighters who completed four different job assignments (Inside Search, Outside Command/Pump, Outside Vent and Overhaul/RIT) from a single Transitional attack scenario. It is not possible to indicate the exact time of firefighting activities on this Figure as with earlier plots due to the limitations in linking between the different data acquisitions systems utilised. However, for this scenario, Inside operations were conducted for a little over 10 min after dispatch, while overhaul operations were conducted for 17 min after Inside operations ended. Similar trends in core temperature were found for the other scenarios, regardless of tactic employed. Prior to firefighting operations, the average core temperature of the group was 37.0 ± 0.4 °C. While there was some variation between groups (e.g. Outside Command/Pump group had slightly higher baseline core temperatures), there were no statistically significant differences among job assignments. During these scenarios, core temperatures for the firefighters operating on the Inside of the structure increased rapidly and prior to other assignments as they were the first deployed and began rigorous activity soon after dispatch. The Outside Command/Pump group also typically experienced increased core temperature early in the scenario, but the rise was less dramatic due to the lower physical exertion and lower ambient temperatures. Core temperature of Outside Vent crews increased later in the scenario as they were deployed later and typically began their rigorous activities after the initial advancement of the hoseline. Overhaul firefighters typically had the highest core temperatures, but the increase in core temperature was delayed while conducting low intensity activities outside of the structure (median time of 11 min) prior to entering for overhaul after the Inside firefighters completed their activities. Peak heart rates during firefighting activity were recorded for each crew. Using Outside Command/Pump as the referent group (152.9 ± 14.2 bpm), we found that peak heart rates were significantly higher for the Inside (178.4 ± 12.7 bpm), Outside Vent (187.9 ± 16.9 bpm) and Overhaul crews (180.0 ± 16.5 bpm).

Table 6. Mean (SD) of the maximum core temperature and core temperature changes for firefighters operating in different job assignments and attack tactics.

Measure	Job assignment	Interior attack	Transitional attack	*N*
Maximum core temperature (°C)	Outside command/ pump	37.81 (0.40)	37.68 (0.26)	8
	Outside vent**	38.63 (0.37)	38.54 (0.42)	8
	Inside	37.91 (0.21)	37.99 (0.43)	16
	Overhaul**	38.88 (0.38)	38.81 (0.58)	15
	Total	38.32 (0.57)	38.29 (0.58)	47
Core temperature change (°C)	Outside command/ pump	0.85 (0.31)	0.64 (0.24)	8
	Outside vent**	1.84 (0.49)	1.64 (0.41)	8
	Inside*	0.93 (0.27)	1.15 (0.55)	16
	Overhaul**	1.74 (0.46)	1.77 (0.48)	15
	Total	1.33 (0.58)	1.34 (0.61)	47

*Significantly different than Outside Command/Pump ($p < 0.05$); **Significantly different than Outside Command/Pump ($p < 0.001$).

Table 6 provides the mean values for the maximum core temperature and core temperature change by job assignment and firefighting tactic. While there was no main effect of Tactic on core temperature response, there was a main effect of job assignment for both maximum core temperature and rise in core temperature (ANOVA $p < 0.001$). Firefighters assigned to Overhaul had the highest core temperatures followed by Outside Vent. Using

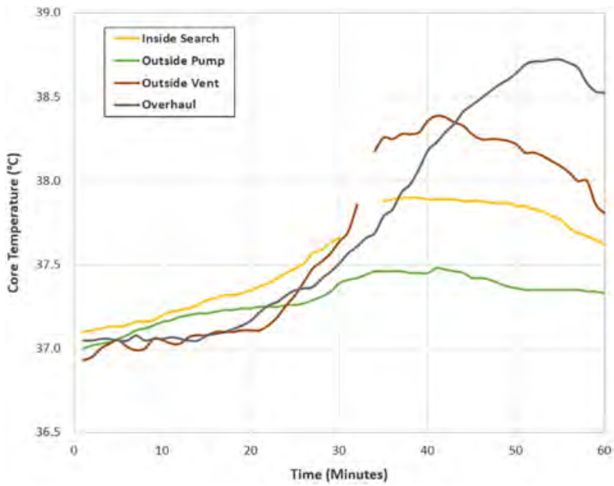

Figure 5. Typical core temperature plots from firefighters operating at 4 representative job assignments (Inside, Outside [Pump, Vent], and Overhaul) on the fireground.
Note: Discontinuities in the data occur when core temperature pill temporarily loses communication with the monitor.

Outside Command/Pump as the referent group, we found that maximum core temperature and core temperature changes were significantly higher for the Outside Vent and Overhaul crews (*p's* < 0.001). While Inside firefighters' maximum core temperatures were slightly higher in magnitude, they did not differ significantly from the Outside Command firefighters. However, their total change in core temperature was significantly larger ($p = 0.002$). This apparent discrepancy is attributed in part to a slightly (but not significantly) different baseline temperatures between these groups. Inside job assignments also had lower maximum core temperatures and core temperature changes than Outside Vent and Overhaul (*p's* < 0.001).

As with the skin temperature analysis, the tactic employed did not have a significant main effect on the core temperatures for the entire population. A follow-up repeated measures ANOVA was conducted for the Inside crews (Attack and Search) that are most likely to be affected by the differing environmental conditions, but there was no significant effect of tactic or job assignment on the core temperature response for this group of firefighters.

4. Discussion

This study provides the most complete characterisation of the thermal environment and temperature responses of firefighter working in a realistic residential fire common in the twenty-first century in the United States (and other countries with comparable building construction and employing similar tactics). For the first time, fireground operations were simulated with high fidelity using fires produced by a full scale room and contents structure fire using common furnishings and structure finishes. Furthermore, we provide the first description of firefighters' temperature responses based on fireground job assignment and firefighting tactic.

4.1. Building temperature & heat flux profiles

The environmental thermal data reported here complements the existing literature, with important additions. To date, the most detailed description of the modern fireground has been conducted by Kerber (2013) in a structure similar to that used here. The scenarios reported in Kerber (2013) were conducted inside a large laboratory where the ambient was carefully controlled, as were the firefighting actions. Furthermore, these scenarios were typically conducted with the structure closed during fire development, resulting in severly (ventilation limited fires) prior to firefighter intervention. Compared to Kerber (2013), the environmental temperatures in our study remained elevated in fire rooms until water was applied. In these cases, the rooms typically flashed over 2–4 min after ignition and the fire rooms remained above 500 °C until water was applied. While our scenarios were ventilation limited, we did have an open window in both rooms to provide some air exchange. Thus, we did not observe the drop in temperatures from lack of oxygen as was reported in Kerber (2013).

Temperatures measured near the ceiling level (i.e. 2.1 m from the floor in Figure 1) are similar to those commonly reported during fire tests as they represent the maximum temperatures of concern for structural stability. Temperatures that occupants might experience while crawling on the floor (e.g. 0.9 m) are also similar to those previously reported (Kerber 2013; Traina et al. 2017). Temperatures at these heights may also be representative of the exposure to firefighters in their operational roles as much of the work of firefighting during active fire, such as fire suppression and search and rescue, is performed while crawling or in the crouched position. In addition, we report temperatures at 1.5 m, which may be experienced by firefighters who are walking in the fire environment as opposed to crawling. While not a commonly recommended practice due to visibility concerns, there are occasions where firefighters will stand and move through the structure on foot. Prior to firefighter intervention (Table 2), the temperatures in the fire rooms were in excess of 600 °C and fairly consistent from floor to ceiling, which indicates that each room had reached the flashover stage. Even in full firefighting PPE, these conditions would rapidly overwhelm protection provided by the PPE resulting in compromise of the equipment (particularly SCBA facepieces (Willi, Horn, and Madrzykowski 2016)) and create risk for rapid and dangerous burn injuries. However, in the hallway just outside the burn rooms, the temperatures were more stratified. Hallway temperatures at the ceiling and 1.5 m level were still well above 600 °C, with heat flux values at 1.5 m at 22–28 kW/m^2, but firefighters operating in the crawling position would have significantly reduced ambient temperatures (~415 °C) and heat flux (~11 kW/m^2). Further from the fire room, in the living room and dining room, standing level (1.5 m) temperatures remained on average above 225 °C, while crawling temperatures averaged closer to 135 °C.

One way to interpret these data is through thermal classifications established by the National Institute of Standards and Technology (NIST). In 2006, researchers from NIST reviewed existing thermal environment classification data and proposed four thermal classes, shown in Table 7, to be used in defining standardised test criteria for electronic safety equipment used by firefighters (Donnelly et al. 2006). Operating in the hallway prior to water application would expose firefighters to NIST Thermal Class IV conditions. In fact, firefighters operating at the 1.5 m level

Table 7. National Institute of Standards and Technology (NIST) thermal classes (Donnelly et al. 2006)

Thermal class	Maximum time (min)	Maximum air temperature (°C)	Maximum heat flux (kW/m^2)
I	25	100	1
II	15	160	2
III	5	260	10
IV	<1	>260	>10

in the living room and dining room could expect to be near the upper limit of Class III and possibly into the Class IV region. However, at the crawling level, nearly all of the temperatures in the Dining and Living rooms remained within the Class II region. NIST recommends that operations at Class IV are conducted for less than 1 min, while Class II conditions are recommended for less than 15 min. These criteria presume that the PPE has not already been preheated during earlier operations that were necessary to reach the hallway. While not a focus of this study, if a firefighter is searching ahead of the line as may be deemed necessary for rescuing a known trapped victim, he/she may experience these high-heat conditions, significantly increasing the risk of equipment failure and burn injury. Extended duration exposure to high heat flux, even in the absence of high ambient temperatures has been shown to be detrimental to firefighting PPE, particularly facepieces that may crack, bubble and deform even if the air temperature is relatively low (Putorti et al. 2013; Willi, Horn, and Madrzykowski 2016).

The impact of firefighters flowing water into the fire rooms is apparent when comparing data from the same rooms and heights in Table 2 and Table 3. By the time the Inside Attack firefighters made their way to the hallway, water had either been applied through the exterior window during Transitional tactic or flowed towards the bedrooms while inside the structure during Interior attack. With the Interior tactic, slight reductions in ambient temperatures after water flow were seen throughout the structure, although fire room temperatures remained mostly above 600 °C. Hallway temperatures were over 500 °C with heat fluxes approximately 19 kW/m^2, still well beyond the Class III/IV condition limit. In comparison, using the Transitional tactic, temperatures in Bedroom 1/6 averaged less than 180 °C at walking height and 112 °C at crawling height by the time the firefighters had transitioned to the interior of the structure and made their way to the hallway. Note that average temperatures in the second fire bedroom were much higher as a result of the single scenario where entry was delayed and the fire regrew; the other five scenarios resulted in temperatures similar to Bedroom 1/6. When compared to the Interior tactic, the Transitional attack tactic resulted in lower hallway temperatures (135 °C vs. 520 °C [Class II vs. Class IV]) at standing height, with even more dramatic reductions at crawling height (65 °C vs. 310 °C [Class I vs. Class IV]). Likewise, heat fluxes were 5 kW/m^2 vs. 19 kW/m^2 (Class III vs. Class IV) at standing height and 3 kW/m^2 vs. 8 kW/m^2 (both Class III) at crawling height. Throughout the living room and dining room, temperatures were below 160 °C (Class II) at the standing level and well below 100 °C (Class I) at the crawling level when the Transitional attack was employed. Importantly, this study is the first to provide a direct comparison of attack tactics on environmental conditions inside a residential structure, quantifying the marked improvement in temperatures when water is applied early. In addition to the PPE that firefighters wear, choice of tactic can also provide a significant level of protection against thermal stress on the fireground.

4.2. Firefighter local temperatures

While ambient temperature measurements in stationary locations have value for describing fire dynamics and characterising risk for firefighters who may become trapped (or remain static for other reasons), it is also critical to better understand the thermal environment encountered by firefighters as they perform their typical work. This study provides the first measurement of thermal exposure to firefighters operating in (i.e. moving through) a structure with room and contents fires typical of the twenty-first century. Gempel and Burgess (1977) measured the thermal environment during structural firefighting in 1977, and found median maximum temperatures of 33 °C and that maximum temperatures in excess of 80 °C are only expected in about 1% of structure fires. Willi, Horn, and Madrzykowski (2016) provided measurements of firefighters moving throughout a training fire scenario with pallet and straw fuel loads. The structures and the fuels they contain have changed significantly over the past several decades and are very different than training environments, resulting in more rapid fire progression that subjects firefighters to significantly more intense thermal conditions (Kerber 2013).

While both Inside Attack and Inside Search are firefighting job assignments that may require operating inside a structure during active fire, there was significantly different environmental thermal exposures for these two groups of firefighters based on the tasks they performed. Regardless of tactic, the maximum and average temperatures (at helmet) of the Inside Attack firefighters were significantly higher than the Inside Search firefighters. Maximum temperatures recorded by the search team helmet never exceeded 80 °C, thus remaining NIST Class I throughout the scenarios, but Inside Attack firefighters often experienced temperatures that exceeded this threshold, most likely because they were operating much closer to the fire.

Importantly, firefighting tactic significantly impacted the local ambient temperatures of the Attack team. Both average and peak temperatures encountered by Attack crews inside the structure were higher when the Interior tactic was used. Of particular note, there was only one instance where the peak temperature experienced by the attack firefighter was higher when utilising the Transitional tactic than when conducting the Interior tactic. This instance corresponded to the scenario where the firefighters' transition to the inside of the structure was delayed and the bedroom fire regrew. This was the only Transitional attack scenario where firefighters were exposed to conditions beyond NIST Class I (in this case, NIST Class III). On the other hand, when the Inside Attack teams utilised the Interior tactic, they were exposed to maximal conditions that would be categorised as Class II on one scenario and Class III conditions on the other five scenarios, with the highest exposure (256 °C) just below the Class IV cut-off (>260 °C). The maximum time over which Class III conditions were experienced by the attack firefighter was 26 s, well below the maximum recommended exposure time of 5 min. Comparing the local temperature measurements to the static temperatures provided in Table 3, it is apparent that the firefighters spent most of their time during the initial suppression efforts crawling into the structure. Had firefighters chosen to walk in, these local measurements would have been even more severe.

Temperature variations during inside activities fluctuated significantly as firefighters conducted their Inside operations, reaching a peak just prior to suppression of the fire by the attack team. Once water was applied to the fire and rooms were ventilated, ambient temperatures began to decline rapidly as seen in Figure 4. The average local ambient temperatures during Inside Attack (~50 °C) and Inside Search (~37 °C) operations were significantly higher than average temperatures experienced during Overhaul (~26 °C) and Outside operations (~20 °C), which varied little throughout operations. On average, conditions that firefighters conducting each of these latter two job assignments faced would be classified as NIST Class I.

These data provide the first quantitative measurement of the thermal conditions that firefighters face during a coordinated attack scenario when the suppression line advances in front of the other operating crews who are crawling in the structure. It should be noted that these fires were confined to room and contents scenarios that were relatively rapidly extinguished. Had the fire spread in to the walls of the structure, longer exposures would be expected. These findings, combined with those reported by Willi, Horn, and Madrzykowski (2016) for training scenarios, should be considered when developing laboratory based assessment of repeated exposures of firefighting

PPE to 'typical' fireground conditions or for characterising the physiological impact of new PPE interventions.

4.3. Skin temperatures

While the environmental temperatures at which firefighters operated varied greatly between the different job assignments, these same patterns did not universally translate to skin temperature changes. While maximum skin temperatures measured from Outside Command crews were significantly lower than the others, there was no statistically significant difference in skin temperatures between the Inside, Overhaul or Outside Vent crews. There are likely several reasons for this result. First, firefighters completing Inside, Overhaul or Outside Vent worked at or near maximal effort during their activities based on measured heart rates, resulting in significant metabolic heat generation. Secondly, the firefighting PPE insulated the firefighters from their surroundings and provided protection from the elevated ambient conditions on the Inside of the structure. For example, while search and attack firefighters experienced significantly different maximum and average local temperatures (Table 4), their skin temperatures under the PPE were similar. The average neck temperatures tended to be higher for the Attack firefighters compared to Search, but this did not achieve significance ($p = 0.080$). It is reasonable to assume that had the firefighters operated in the high ambient temperatures for a longer period of time, the heat may have transferred through the gear to a greater extent.

While no difference was detected in arm skin temperature by tactic, neck skin temperature was significantly lower for the Inside firefighters conducting a Transitional Attack versus an Interior Attack. The neck is provided relatively less protection by a knit hood compared with other parts of the body that are covered in bunker gear with three layers (shell, thermal layer, moisture barrier). The measured difference in neck skin temperature is relatively small (0.5 °C), but the physiological impact must be further investigated as these differences may affect the body's ability to dissipate heat from the core and/or may alter the absorptivity of the skin for specific chemical exposures. For example, Fent et al. (2014) found that neck skin is an important site of dermal exposures during firefighting. Our findings suggest that Transitional attack may reduce exposure to radiant and convected heat and potentially fire smoke, especially in the neck area for the inside firefighters.

4.4. Core temperatures

Core temperature did not change uniformly among firefighters. In some job assignments, core temperature rose quite rapidly, while those in other job assignments had more modest increases over the relatively short timeframes experienced in this study. While core temperature was expected to increase during Inside firefighting operations due to elevated ambient temperatures, significant elevations were also seen for Outside Vent and Overhaul operations due to heavy muscular work.

This is the first study to quantify core temperature increase during realistic fireground operations with realistic fuel, common residential construction and typical firefighting tactics. While measurements of heart rate have been documented from real fire suppression emergencies for a number of years (e.g. Smith et al. 2010; Sothmann et al. 1992), measuring core temperature is more challenging due to the logistics of instrumentations. In 2013, Horn et al. summarised the literature that had reported core temperature rise during live fire activities. While the scenarios and environments varied significantly among the studies reviewed, core temperature changes ranged from 0.3 to 1.4 °C with rate of rise varying from 0.010 to 0.100 °C/min. For Inside firefighting crews in this study, the core temperature change and rate of change was near the upper end of the ranges (1.04 °C and 0.095 °C/min) reported by Horn et al.

In 1987, Romet and Frim collected similar data from fire-fighting crews performing different job assignments during a live-fire training simulation (Romet and Frim 1987). The 'Inside' crew here can most closely be compared to the 'Lead Hand' in that data-set. In the Romet and Frim study, a 24 min firefighting/search and rescue activity resulted in an average increase in rectal (~core) temperature of 1.3 °C and mean skin temperature of 37.4 °C, which is similar to that measured in the current study (1.0 and 37.4 °C, respectively), but duration of activity was shorter in our scenarios than in the Romet and Frim study (11 vs. 24 min). The tasks conducted by the 'Crew Captain' and 'Exterior Firefighting' groups in Romet and Frim (1987) are similar to the 'Outside Command/Pump' operations in the current study, but Romet and Firm reported significantly lower core temperature increases (0.3 and 0.4 vs. 0.7 °C) and lower maximum skin temperatures (33.9 and 34.9 vs. 36.3 °C) for a similar duration of activity. The higher temperatures reported in the current study are likely attributable to the lighter firefighting PPE worn in the mid-1980s compared to heavier, more encapsulating NFPA 1971 compliant PPE from 2015.

Interestingly, the Overhaul and Outside Vent crews had the highest maximum core temperatures (38.9 and 38.6 °C, respectively). On average, core temperatures increased 1.7–1.8 °C over baseline during both of these activities. To our knowledge, there have been no other studies that have focused on the thermal strain induced by these common fireground assignments. These job assignments are often considered to be lower risk for heat stress because they do not occur in a superheated fire environment. However, strenuous activities and physiological burden imposed by the firefighting PPE results in increased core temperature. It is important to note that the period of time over which Outside Vent (average of 22 min) and Overhaul (average of 11 min outside and 17 min inside structure) crews operated were significantly longer than the Inside Attack and Inside Search crews (11 min). The overall rate of rise in core temperature of the Outside Vent crew (0.092 °C/min) was remarkably similar to that from the Inside crews (0.095 °C/min). This rate of rise was more modest for the Overhaul firefighters (0.063 °C/min) if averaged over the entire 28 min of activity. However, if we assume that the core temperature increase over the first 11 min is similar to the Outside Command/Pump firefighters (0.037 °C/min) who had comparable physical demands outside of the structure, then the rate of rise during the strenuous overhaul activities inside the structure (17 min) would be closer to 0.08 °C/min.

While significant attention has been paid to the need for appropriate PPE protection from fireground contaminants during overhaul operations (Bolstad-Johnson et al. 2000; Fent et al. 2014), it is also important for firefighters and fire officers to understand the thermal burden induced from wearing this level of protection during heavy muscular work like overhaul operations. As shown in Table 6, we measured core temperatures for Overhaul firefighters that increased to over 38.8 °C after operating through a single '30 min' SCBA cylinder of air. This activity began with firefighters in a rested state (core temperatures of approximately 37.0 °C) and followed approximately 11 min of relatively low intensity work of setting up RIT or pulling a backup line. Had the firefighters begun their overhaul activities after completing another strenuous assignment, as is common on the fireground, they could have accumulated a significantly higher level of thermal strain. For instance, if firefighters had just completed Inside operations or Outside Vent, their average starting core temperatures could be closer to 37.9 or 38.6 °C, respectively (Table 6). Thus, final core temperatures during overhaul could approach 39.7–40.4 °C. According to the American Conference of Governmental Industrial Hygienists (ACGIH 2016), a healthy, acclimatised, experienced worker's core temperature should not exceed 38.5 °C. In addition, a core temperature of 40 °C is the upper range of clinical heat exhaustion, and above 40 °C, heat stroke can occur. Common rehabilitation recommendations and protocols often call for implementation of rehab after completing work with two 30-min SCBA (NFPA 1584). However, our data suggest that it may be prudent to bring in additional manpower as rapidly as possible to relieve the crews performing suppression and ventilation operations or other strenuous activities while wearing full turnout gear. Furthermore, if crews are working through extended overhaul operations and using larger SCBA, formal rehab protocols with rest, hydration and active cooling (where appropriate) must be enforced.

While this study provides the most complete characterisation of the thermal conditions experienced by firefighters operating on a typical modern fireground, important limitations are noted. Although this study used a realistic, purpose-built structure, and measured thermal conditions and stress experienced by firefighters, we did not collect data on the vast array of structure fires to which firefighters might respond. Fires were limited to 'room and contents' and did not spread into the walls of the structure, which may have resulted in longer term operations. Following good firefighter training practices, participants were provided with the opportunity to conduct a quick walk through of the structure prior to igniting the fires. Therefore, firefighters may have completed the tasks more rapidly than if they had not been familiar with the layout.

5. Conclusions

When firefighters respond to modern residential structure fires, the thermal impacts – from the environment to the firefighters' core temperature – can be effected by both their job assignment and suppression tactic in many different ways. Firefighters performing different job assignments experienced different ambient conditions and had different thermal responses. Firefighters who performed the most strenuous work, had the highest skin and core temperatures, regardless of ambient conditions in which they were operating. Firefighting tactic has a significant effect on environmental conditions encountered by firefighters operating inside the structure. When performing Transitional attack, thermal conditions for the Attack firefighters were significantly reduced with no apparent detrimental effect on the environment inside the structure. A further benefit of lower ambient temperatures during Transitional attack was lower neck skin temperatures for the Attack firefighters. However, the reduced ambient and neck skin temperature for firefighters operating inside the structure did not translate to reductions in core body temperature during Transitional attack. Thus, it is important that firefighters wearing fully encapsulating PPE and working on the fireground be provided rest, recovery and rehab based on intensity and duration of work, regardless of tactic utilised or the apparent risk from their ambient conditions alone.

Disclosure statement

There are no conflicts of interest regarding this work.

Funding

This work was supported by the Department of Homeland Security Fire Prevention and Safety Grant [#EMW-2013-FP-00766].

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A.7 Paper VII: Contamination of Firefighter Personal Protective Equipment and Skin and the Effectiveness of Decontamination Procedures

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

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JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2017, VOL. 14, NO. 10, 801–814
https://doi.org/10.1080/15459624.2017.1334904

Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures

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ABSTRACT

Firefighters' skin may be exposed to chemicals via permeation/penetration of combustion byproducts through or around personal protective equipment (PPE) or from the cross-transfer of contaminants on PPE to the skin. Additionally, volatile contaminants can evaporate from PPE following a response and be inhaled by firefighters. Using polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) as respective markers for non-volatile and volatile substances, we investigated the contamination of firefighters' turnout gear and skin following controlled residential fire responses. Participants were grouped into three crews of twelve firefighters. Each crew was deployed to a fire scenario (one per day, four total) and then paired up to complete six fireground job assignments. Wipe sampling of the exterior of the turnout gear was conducted pre- and post-fire. Wipe samples were also collected from a subset of the gear after field decontamination. VOCs off-gassing from gear were also measured pre-fire, post-fire, and post-decon. Wipe sampling of the firefighters' hands and neck was conducted pre- and post-fire. Additional wipes were collected after cleaning neck skin. PAH levels on turnout gear increased after each response and were greatest for gear worn by firefighters assigned to fire attack and to search and rescue activities. Field decontamination using dish soap, water, and scrubbing was able to reduce PAH contamination on turnout jackets by a median of 85%. Off-gassing VOC levels increased post-fire and then decreased 17–36 min later regardless of whether field decontamination was performed. Median post-fire PAH levels on the neck were near or below the limit of detection ($<$ 24 micrograms per square meter [$\mu g/m^2$]) for all positions. For firefighters assigned to attack, search, and outside ventilation, the 75th percentile values on the neck were 152, 71.7, and 39.3 $\mu g/m^2$, respectively. Firefighters assigned to attack and search had higher post-fire median hand contamination (135 and 226 $\mu g/m^2$, respectively) than other positions ($<$ 10.5 $\mu g/m^2$). Cleansing wipes were able to reduce PAH contamination on neck skin by a median of 54%.

KEYWORDS
Contaminants; decontamination; evaporation; firefighters; PAHs; turnout gear

Introduction

The International Agency for Research on Cancer (IARC) classified occupational exposure as a firefighter as possibly carcinogenic to humans (Group 2B).[1] Since this determination was made in 2010, a number of epidemiology studies continue to find elevated risks of several cancers in firefighters. In the largest cohort mortality study to date (30,000 firefighters), Daniels et al.[2] found increased mortality and incidence risk for all cancers, mesothelioma, and cancers of the esophagus, intestine, lung, kidney, and oral cavity, as well as an elevated risk for prostate and bladder cancer among younger firefighters. In a follow-on study, Daniels et al.[3] found a dose-response relationship between fire-runs and leukemia mortality and fire-hours and lung cancer mortality and incidence. Other studies corroborate the elevated risk of a number of these cancers and provide evidence for the increased risk of other cancers, like melanoma and

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myeloma.[4–6] While chemical exposures encountered during firefighting are thought to contribute to the elevated risk of these cancers, the role that contamination on PPE and skin plays in this risk has not been well defined.

The materials found in modern buildings and furnishings are increasingly synthetic and can generate many toxic combustion byproducts when they burn.[7–9] Toxic substances identified in fire smoke include polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), hydrogen cyanide (HCN), and several other organic and inorganic compounds.[8,10–18] Many of these compounds are known or potential human carcinogens. A number of these compounds have been measured on firefighter PPE.[19–24] VOCs and HCN have also been measured off-gassing from turnout gear following use in live fires.[25,26] These contaminants, particularly the less volatile substances, could be transferred to fire department vehicles and firehouse living spaces.[27–29]

Skin exposure can occur during firefighting by way of permeation or penetration of contaminants through the hood, turnout jacket and trousers, in between interface regions of this ensemble (possibly aided by the bellows effect during firefighter movements), or through the cross-transfer of contaminants on gear to skin. Fent et al.[30] found significantly elevated levels of PAHs in skin wipes from firefighters' necks following controlled burns. In this and other studies, biomarkers of benzene and PAHs were identified post firefighting, even though SCBA were used, suggesting that dermal absorption contributed to firefighters' systemic levels.[30–33]

Differences in PPE and skin contamination by job assignment and firefighting tactic have not been well characterized. It is likely that exposures are not uniform among firefighting personnel. For example, the incident commander who is stationed outside is unlikely to have the same exposure as a firefighter who is operating on the interior of a smoke-filled room while advancing a charged hoseline or conducting search and rescue operations.

Laundering of firefighter turnout gear may not be routinely conducted following a fire response, but is more commonly performed only once or twice per year. In between launderings, toxic substances are likely to accumulate on the gear from each subsequent fire response and could transfer to the skin of firefighters. Likewise, field decontamination is rarely completed following a fire response. Field decontamination of firefighters' PPE is advocated by several firefighter support organizations.[34–36] Performing gross decontamination in the field following a fire event may remove a large quantity of hazardous substances from firefighters' PPE. A few departments have instituted new policies requiring field decontamination and even laundering of turnout gear following live-fire responses. Some departments now provide skin cleansing wipes for firefighters to use following a response.[34] However, we are unaware of any studies characterizing the effectiveness of field decontamination of firefighter PPE or skin cleaning measures. Efficacy data are needed to justify and support these efforts more broadly.

The purpose of this study was to characterize the contamination of a representative portion of firefighters' protective ensembles (turnout jackets and helmets) and skin (hand and neck skin) following structural firefighting activities involving realistic residential fires. Additionally, we aimed to investigate contamination levels on gear and skin by job assignment and firefighting tactic, as well as before and after decontamination measures. The effectiveness of skin wipes and three types of field decontamination methods were quantified. While contamination could consist of hundreds of compounds, for this article we focused primarily on PAH particulate (for surface and skin testing) and VOC and HCN gases and vapors (for off-gas testing).

Methods

Study population and controlled burns

This study was performed at the University of Illinois Fire Service Institute with collaboration from the National Institute for Occupational Safety and Health (NIOSH) and Underwriters Laboratories (UL) Firefighter Safety Research Institute (FSRI). IRB approval was obtained from both the University of Illinois at Urbana-Champaign and NIOSH. Forty-one firefighters (37 male, 4 female) participated in this study. All firefighters were required to wear their self-contained breathing apparatus (SCBA) and full PPE ensemble (including hood) prior to entering the burn structure. Use of SCBA outside the structure was at the discretion of the individual firefighter. Firefighters were instructed to use their own fire department protocols to determine if smoke exposure warranted SCBA usage. Each participant was provided brand new turnout jackets, trousers, hoods, and gloves at the beginning of the study. All PPE adhered to NFPA standards.

This study had a total of 12 scenarios (one per day and no more than four scenarios per person). For each scenario, a team of 12 firefighters completed a realistic firefighting response that involved a multiple-room fire (two separate bedrooms) in a 111 square meter (m^2) residential structure.[37] The bedrooms where the fires were ignited were fully furnished. Additional details on the structure are provided in the supplemental file.

Table 1. Deployment protocol, job assignments, and response times.

Apparatus	Job assignment (2 firefighters per assignment)	Specific tasks	Median time outside structure (min)	Median time inside structure (min)
Engine 1	Outside Command/Pump	Incident command and operate the pump	20	0
	Inside Attack	Pull primary attack line from engine and suppress all active fire	3	8
Truck 1	Inside Search	Forcible entry into the structure and then search for and rescue two victims (weighted manikins)	2	8
	Outside Vent	Deploy ladders to the structure and create openings at windows and roof (horizontal and vertical ventilation)	19	0
Engine 2	Overhaul/Backup	Pull a second attack line and support the first-in engine (from outside the structure) and then perform overhaul operations inside the structure after fire suppression	11	16
	Overhaul/RIT	Set up as a rapid intervention team (RIT) and then perform overhaul operations inside the building after fire suppression	11	17

The 12 firefighters on each team worked in pairs to perform six different job assignments (Table 1) that included operations ***inside*** the structure during active fire (fire attack and search & rescue), ***outside*** the structure during active fire (command, pump operator and outside ventilation), and ***overhaul*** operations after the fire had been suppressed (firefighters searched for smoldering items, removed drywall from walls/ceilings, and removed items from the structure). After ignition, the fires were allowed to grow until the rooms flashed over and became ventilation limited (typically 4–5 min) and then the firefighter participants were dispatched by apparatus in 1-min increments following the order in Table 1.

Thirty-one firefighters participated in a total of four scenarios, nine participated in two scenarios, and one withdrew from the study. For the firefighters who completed four scenarios, they were assigned to new job assignments upon completing the first two scenarios. The Inside Attack firefighters on each team used the following tactics: (a) traditional ***interior*** attack from the "unburned side" (advancement through the front door to extinguish the fire) and (b) ***transitional*** fire attack (water applied into the bedroom fires through an exterior window prior to advancing through the front door to extinguish the fire). These tactics were alternated so that each tactic was used during the first two scenarios and again for the last two scenarios. Once firefighters completed their primary assignments, they were released to the "PPE bay" approximately 40 m from the structure to doff their gear. After doffing their gear, the firefighters promptly entered the adjacent "biological collection bay" for skin wipe sampling. Investigators began sampling from the turnout gear after they had been removed. After sampling, the turnout gear was stored on hangers in the PPE bay until subsequent decontamination and/or use. Large fans were used to dry turnout gear that had undergone wet-soap decon.

Experimental procedure

Table 2 provides a summary of our sample collection and analysis methods. The main purpose of the sampling was to assess the contamination levels on firefighter PPE and skin after a structural firefighting response. Sampling was conducted pre-fire, post-fire, and post field decontamination of PPE and post skin cleaning. The following sections provide an abbreviated version of the methods. More details are provided in the supplemental file.

Wipe sampling of firefighter skin

After cleaning his/her skin using commercial cleansing wipes (Essendant baby wipes NICA630FW), one firefighter from each scenario was randomly selected for pre-fire sampling of his/her neck (*right side*) and hands. After firefighting, wipe samples were collected from all firefighters' hands and the *right side* of their necks. Investigators then used two cleansing wipes to clean the necks of firefighters assigned to Inside Attack, Inside Search, Outside Vent, or Overhaul (3–4 per scenario). A subsequent wipe sample was then collected from the *left side* of their necks. This was done to provide a comparison of neck exposures to PAHs before and after cleaning. A fresh pair of gloves were worn for each skin cleaning and sample collection procedure.

Dermal wipe sampling involved the use of cloth wipes (TX1009, Texwipe) and corn oil as a wetting agent, which is similar to the sample technique used by Väänänen et al.[38] Experiments were conducted prior to this study to determine the collection efficiency of using corn oil as a wetting agent. These experiments found >75% recovery of the majority of PAHs from glass slides at various spiking levels (i.e., 5, 50, and 200 micrograms [μg]) (unpublished data). Lesser collection efficiency can be expected from skin due to its absorptive nature. Thus, the actual

Table 2. Summary of sampling methods.

Sampling performed	Collection periods	Sample time (min)	n	Analytes	Method
Wipe sampling of exterior surface of turnout jackets	Pre-fire Post-fire Post-decon	NA NA NA	36 63 Dry-brush: 12 Air-based: 12 Wet-soap: 12	PAHs	Individually packaged wipes containing 0.45% isopropanol and benzalkonium chloride analyzed by HPLC/UV/FL (NIOSH Method 5506)[46]
Wipe sampling of hand and neck skin	Pre-fire Post-fire Post-skin cleaning	NA NA NA	Hands: 12 Neck: 12 Hands: 142 Neck: 142 Neck: 46	PAHs	Cloth wipes with corn oil analyzed by HPLC/UV/FL (NIOSH Method 5506)[46]
Offgas sampling of turnout jackets and trousers	Pre-fire Post-fire Post-decon	15 15 15	12 12 12	VOCs and HCN	Thermal desorption tube, 150 cc/min, analyzed by GC/MS and soda lime sorbent tube, 200 cc/min, analyzed by UV/VIS

VOCs = volatile organic compounds (i.e., benzene, toluene, ethylbenzene, xylenes, and styrene); GC/MS = gas chromatography/mass spectrometry; HCN = hydrogen cyanide; HPLC/UV/FL = high performance liquid chromatography with ultraviolet and fluorescence detection; UV/VIS = ultraviolet-visible spectroscopy.

dermal dose was likely higher than the reported measurements in this article.

Dermal exposure levels of PAHs were standardized by the surface area of the skin collection site. The surface area of both hands (0.11 m^2) was based on mean dermal exposure factor data for adult males.[39] The surface area of half of the neck (0.021 m^2) was determined based on data from Lund and Browder[40] showing the neck accounts for 2% of the total body surface area, which is 2.1 m^2 for adult males 30–39 years of age.[39]

Wipe sampling of firefighter PPE

Wipe samples from turnout jackets were collected before firefighting (n = 36, upper sleeve), after firefighting (n = 36, middle sleeve) and after each of three types of field decontamination methods (n = 36, lower sleeve), with a primary focus on gear worn by Inside Attack, Inside Search, and Overhaul/Backup firefighters. This sampling regimen assumed that PAH contamination was distributed equivalently across the sleeve. Wipe samples were also collected from turnout gear that had not been decontaminated after use by firefighters assigned to each of the six jobs after two scenarios (n = 18). Gear that had not been decontaminated after use in four scenarios and last assigned to Inside Attack, Inside Search, and Overhaul/Backup firefighters were also sampled (n = 9). In addition, wipe samples were collected from 4 helmets (new at the beginning of the study) after use in four scenarios by firefighters assigned to Inside Attack, Inside Search, Outside Vent and Outside Command/Pump. Helmets were assigned to the position rather than the individual firefighter and were not decontaminated. The wipe samples were collected inside 100 cm^2 templates affixed to the PPE. The wipes (Allegro® 1001) were designed to remove contaminants from PPE; however, the collection efficiency for PAHs is unknown.

Decontamination

Field decontamination was carried out after firefighters had doffed their gear and post-fire off-gas and surface sampling had taken place. For dry-brush decon, the investigator used an industrial scrub brush to scrape debris and contaminants from the gear. For air-based decon, an air jet provided by a modified electric leaf blower was directed over the entire surface of the turnout jackets and pants to remove contaminants. For wet-soap decon, the investigator prepared a 2 gallon (7.6 liter) pump sprayer filled with a mixture of water and ∼10 mL of Dawn® (Procter and Gamble) dish soap. The investigator pre-rinsed the gear with water, sprayed the gear with the soap mixture, scrubbed the gear with soap mixture using an industrial scrub brush, and then rinsed the gear with water until no more suds remained.

Off-gas sampling of firefighter turnout gear

Off-gas sampling preceded the wipe sampling of the turnout gear. Turnout jackets and trousers for each crew were split evenly by job assignment into two groups: decontaminated and non-decontaminated gear. Before and after each scenario, each group (consisting of 6 sets of gear) was hung on 1.8 m high bars inside one of two 7.1 cubic meter enclosures for testing the off-gassing of substances contaminating the gear. The enclosures were intended to represent the volume of a typical 6-seat apparatus cabin. The enclosures were lined in Tyvek (DuPont), located inside an open bay, sheltered from the sun, and kept at ambient temperature during the study, which ranged from 18–22°C.

Sampling for VOCs and HCN took place over 15 min, which was intended to be representative of the driving time for crews returning from the incident to the fire station. Afterward, half the gear was decontaminated in the field using dry brush, air-based, or wet-soap methods

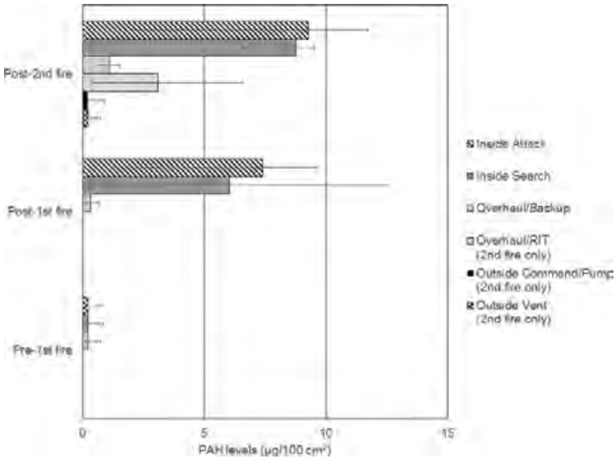

Figure 1. Median PAH levels on turnout jacket by job assignment and use in fires without field decontamination being performed (n = 3 for each observation, error bars represent minimum and maximum values).

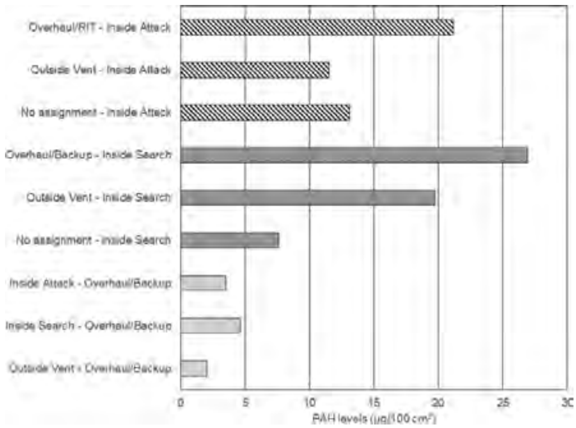

Figure 2. PAH levels on turnout jacket after use in four fires by job-assignment pairing (first assignment – last assignment).

(four scenarios each). Following field decontamination, all gear (decontaminated and non-decontaminated) were returned to their separate enclosures and tested again for off-gassing compounds.

Data analysis

Most of the descriptive comparisons for PPE surface and skin contamination were carried out using total PAHs, which was the sum of the 15 quantified PAHs. Zero was used for non-detectable concentrations in this summation. For PPE surface measurements, if all PAHs were non-detectable, the resultant zero value was imputed using the limit of detection for fluoranthene (0.2–0.3 µg/wipe) divided by the square root of 2.[41] On average, fluoranthene was the most abundant substance detected in the surface wipe samples. In presenting the levels of individual PAHs measured from turnout jackets and skin, non-detectable PAHs were assigned values by dividing the limits of detection by the square root of 2. The same imputation method was used for non-detectable VOCs off-gassing from turnout gear.

To quantify the effectiveness of the different types of decontamination methods, we calculated the percent change in PAH levels by decon type, restricting the analysis to gear that had detectable levels of PAHs post-fire. It was assumed that decontamination can only be assessed if the gear is truly contaminated. A Kruskal-Wallis test was used to test whether PAH levels remaining on turnout gear after decontamination were equivalent across the three decon-types. To quantify the effectiveness of skin cleaning using cleansing wipes, we calculated the percent change in PAH levels measured on the right neck (post-fire) vs. the left neck (post-cleaning), restricting the analysis to subjects with detectable levels of PAHs post-fire. In doing so, we assumed that (1) the PAH levels were evenly distributed across the entire neck and (2) that skin cleaning cannot be evaluated if the neck is not contaminated. A Wilcoxon signed-rank test was used to determine whether the change in PAH levels after decontamination procedures was significantly different from zero. This test was also used to assess whether PAH levels on hands were increasing on subsequent study days or differed between jobs, and whether PAH levels on turnout gear or skin differed by type of tactic. SAS 9.4 was used for carrying out the statistical analyses.

Results

Figure 1 provides a summary of the PAH contamination levels measured from non-decontaminated turnout jackets over the first two fires by job assignment. Measurements collected before the first fire (from new gear) are also provided for reference. As expected, the median PAH levels increased with successive use in fires. Samples from gear worn by firefighters assigned to Outside Command/Pump, Outside Vent, and Overhaul/RIT were only collected after the gear had been used in two fires.

Firefighters were assigned new jobs after the second fire. Figure 2 provides the PAH contamination levels measured from non-decontaminated turnout jackets after use in four fires by job-assignment pairings (first assignment – last assignment). Generally, higher contamination was found when the last job assignment was Inside Attack or Inside Search. For comparison, the PAH levels measured from helmets worn by firefighters assigned to Outside Command/Pump, Outside Vent, Inside Search, and Inside Attack (after use in 4 fires) were <0.2, 3.1, 54, and 78 micrograms per 100 square centimeters (μg/100 cm^2) of sampled surface. Helmet contamination appeared to follow a similar trend as the turnout jackets, whereby helmets worn by inside crews (Attack and Search) were much more contaminated than helmets worn by outside crews (Vent and Command/Pump).

We explored the contamination of turnout gear by type of tactic (interior attack vs. transitional attack). To account for the efficacy of the different decontamination methods and the effect of job assignment on contamination levels, our analysis was based on the percent change in the pre- to post-fire PAH levels on turnout gear worn by firefighters assigned to Inside Attack and Inside Search. According to this analysis, transitional attack resulted in similar changes in PAH contamination (median = 662%, range −35% to 6710%, n = 12) as interior attack (median = 1080%, range 136% to 8440%, n = 12) (Wilcoxon P = 0.48). This variability illustrates that the firefighters' movement and orientation during firefighting likely plays an important role in PPE contamination, possibly obscuring the effect of tactic.

Figure 3 provides a summary of the percent change in PAH levels from post-fire to post-decon by decon-type. The three decon-types differed significantly in their effectiveness (Kruskal-Wallis $P < 0.001$). Wet-soap decon was most effective in reducing PAH contamination, with a median reduction of 85%, compared to a reduction of 23% for dry brush decon and an increase of 0.5% for air-based decon. The latter finding is probably an artifact as it is unlikely that the contamination actually increased after air-based decon. In fact, if we restrict the analysis to turnout jackets worn by firefighters assigned to Inside Attack and Inside Search (and exclude the less

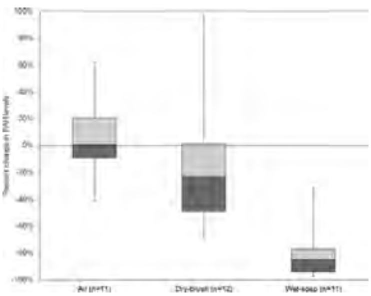

Figure 3. Box and whisker plots showing the percent difference in PAH levels measured on turnout jackets before and after decontamination. The minimum, 25th percentile, median, 75th percentile, and maximum values are provided. One sample each was excluded from air and wet-soap decon because post-fire levels were non-detectable.

contaminated Overhaul/Backup jackets), we find that the air-based decon provides a median change of −1.9% (interquartile range 12 to −30%).

Another way of testing the effectiveness of field decontamination is to compare decontaminated gear to non-decontaminated gear after both have been used in four fires. This comparison was conducted for each decon type by the firefighters' last job assignments (Inside Attack, Inside Search, and Overhaul/Backup). For example, decontaminated gear last assigned to Inside Attack was compared to non-decontaminated gear last assigned to Inside Attack. The job-assignment pairings were similar between the decontaminated and non-decontaminated groups (by design) and were unlikely to have biased the results. According to this analysis, gear that had undergone air-based, dry-brush, and wet-soap decon had 12–43%, 62–91%, and 90–95% lower contamination levels, respectively, than non-decontaminated gear ($n = 3$ pairs of comparisons for each decon type).

Figure 4 provides a summary of the VOCs and HCN concentrations measured off-gassing from decontaminated and non-decontaminated turnout gear. Horizontal lines are provided in the figure to denote the limits of detection. Median pre-fire levels were below the limits of detection for each analyte (and hence represent imputed values). As expected, the off-gas concentrations of these substances increased from pre-fire to post-fire and then decreased after that. The post-fire levels were well below applicable short-term exposure limits or ceiling limits; for example, the NIOSH recommended short-term exposure limit for benzene is 3,200 micrograms per cubic meter ($\mu g/m^3$), which is the lowest short-term exposure limit of all sampled compounds.[42] Post-decon levels from the decontaminated gear did not differ from the levels measured simultaneously from the non-decontaminated gear (Wilcoxon $P > 0.24$). This appeared to remain true when stratified by the different types of decontamination, although we had inadequate power to make statistical interpretations. Many of the compounds remained above the limits of detection during the post-decon testing period. For both the decontaminated and non-decontaminated gear, this testing took place an average of 24 min (ranging 17–36 min) after the culmination of the post-fire measurements.

Table 3 summarizes the PAH dermal exposure levels measured on the firefighters' hands and neck in micrograms per square meter ($\mu g/m^2$) of sampled skin. A large percentage of the measurements were non-detectable, particularly on the neck. Note that neck samples had a higher limit of detection than hand samples due to the smaller surface area of the neck being sampled. For all job assignments other than Outside Command/Pump,

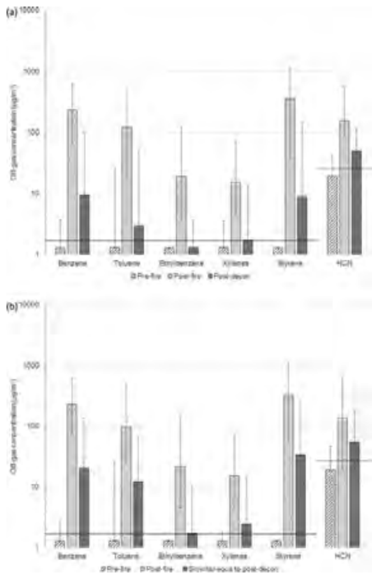

Figure 4. Median air concentrations of VOCs and HCN measured off-gassing from six sets of (a) *decontaminated* turnout gear during pre-fire, post-fire, and post-decon periods ($n = 12$ for each observation, except for the post-fire VOC observations in which $n = 10$ due to sample loss) and (b) *non-decontaminated* turnout gear during pre-fire, post-fire, and simultaneous to the post-decon periods ($n = 12$ for each observation). Horizontal lines represent the limits of detection for each analyte. Error bars represent the minimum and maximum values.

the median PAH levels increased on the hands from pre- to post-fire. The percentage of detectable levels on the neck increased after firefighting, but the median levels were below detection for all job assignments. After firefighting, PAHs were detected more frequently on hands (76%) than neck (41%). For firefighters assigned to Inside Attack and Inside Search, the median post-fire PAH levels on the hands were more than four times the levels on the neck. Inside Search firefighters had significantly higher post-fire hand exposures than Inside Attack firefighters (Wilcoxon $P = 0.0248$), even though both performed inside operations during active fire. The 75th percentile post-fire levels of PAHs on the neck and hands were higher for firefighters assigned to Inside Attack and Inside Search than other positions. Outside Vent was the only job where detectable levels from the neck were

Table 3. PAH levels measured on skin before and after firefighting.

Job assignment	Skin site	Period	n	No. of NDs	Median (μg/m²)[a]	Interquartile range (μg/m²)[a]
All	Hands	Pre-fire	12	9	< 4.5	< 4.5
		Post-fire	142	34	16.3	5.2–125
	Neck	Pre-fire	12	8	< 24	< 24–31.2
		Post-fire	142	84	< 24	< 24–38.1
Inside Attack	Hands	Post-fire	24	1	135	67–190
	Neck	Post-fire	24	12	< 32[b]	< 24–152
Inside Search	Hands	Post-fire	24	0	226	144–313
	Neck	Post-fire	24	12	< 27[b]	< 24–71.7
Overhaul/Backup	Hands	Post-fire	24	8	6.5	< 4.5–16.3
	Neck	Post-fire	24	17	< 24	< 24–31.4
Overhaul/RIT	Hands	Post-fire	24	4	8.4	6.1–30.8
	Neck	Post-fire	24	15	< 24	< 24–34.5
Outside Vent	Hands	Post-fire	24	4	10.5	6.2–23.4
	Neck	Post-fire	24	10	30.5	< 24–39.3
Outside Command/Pump	Hands	Post-fire	22	17	< 4.5	< 4.5
	Neck	Post-fire	22	18	< 24	< 24

[a]Values of < 4.5 and < 24 μg/m² were based on the lowest limit of detection for the measured PAHs (0.5 μg) divided by the surface area of the sampled skin site (0.11 m² for hands and 0.021 m² for neck).
[b]The median was somewhere between a non-detectable and a detectable measurement; therefore, a value of less than the detectable measurement is provided.

found in more than half the subjects (58%). For firefighters assigned to Outside Vent, the median post-fire PAH levels on the neck were three times the levels on the hands.

To test whether the accumulation of contaminants on PPE was contributing to skin contamination (i.e., cross-transfer to hands), we explored the levels of PAHs on the hands of firefighters over time. The analysis was restricted to firefighters who wore gear that was not being decontaminated ($n = 18$ firefighters). We compared post-fire PAH levels on hands measured in scenario 2 to scenario 1 and those measured in scenario 4 to scenario 3. The analysis was split this way because firefighters changed job assignments after the second scenario. According to this analysis, we found no evidence that PAH levels on hands were increasing with subsequent study day (Wilcoxon $P > 0.85$) despite an increase in contamination on PPE (see Figures 1 and 2).

To test whether the tactic employed had any effect on dermal exposure, we investigated the post-fire neck and hand contamination levels for firefighters assigned to Inside Attack and Inside Search by type of tactic (Table 4). According to this analysis, hand and neck exposures did not differ significantly (Wilcoxon $P = 0.37$ and 0.28, respectively) between interior and transitional attack.

For firefighters who used cleansing wipes to clean their neck skin post-firefighting, we found a 54% median reduction in PAH levels on the neck (Interquartile range = −18% to −100%), which was statistically significant (Wilcoxon $P = 0.0043$). Again, this analysis compared levels measured from the right neck (post-fire) to the left neck (post-cleaning) and was restricted only to the 22 firefighters who had detectable post-fire PAH levels on their right neck.

The composition of PAHs measured on turnout gear and skin may be of interest as certain types of PAHs are more hazardous than others. Figure 5 provides a summary of the individual PAHs measured from turnout gear and hands of firefighters assigned to Inside Search (a higher exposure group). Overall, fluoranthene was the most abundant species identified on turnout gear and skin (constituting >25% of the total PAHs). The IARC classifications are also given in this figure. Benzo[a]pyrene is the only species that is a known human carcinogen (1) and it accounted for 5% of the PAHs measured on hands and 8% of the PAHs measured on turnout gear. Several PAHs classified as probably (2A) or possibly (2B) carcinogenic were also detected and accounted for 26% of the total levels on skin and 37% of the total levels on turnout gear. Similar PAH composition was found on jackets and hands of firefighters assigned to Inside Attack.

Discussion

This is the first study to investigate both the contamination of firefighters' PPE and skin as well as the effectiveness of field decontamination of PPE and skin.

Table 4. Post-fire PAH levels measured on the skin of firefighters assigned to interior attack and search by tactic.

Skin site	Type of tactic	n	No. of NDs	Median (μg/m²)	Interquartile range (μg/m²)
Hands	Interior	24	0	180	129–276
	Transitional	24	1	144	114–257
Neck	Interior	24	11	36.2	< 24–113
	Transitional	24	13	< 24	< 24–49

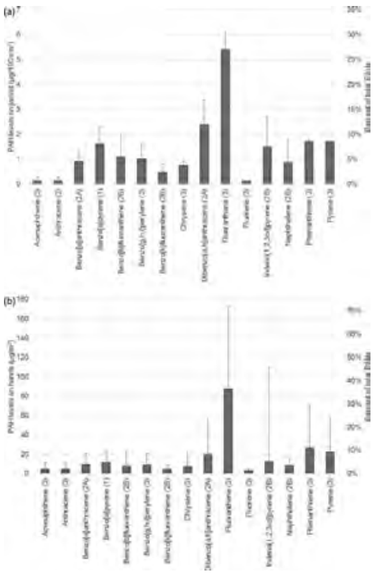

Figure 5. Median levels of specific PAHs measured on (a) *jackets* of firefighters assigned to Inside Search after use in four fires without any field decontamination (n = 3 jackets) and (b) *hands* of firefighters assigned to Inside Search after firefighting (n = 24). Also provided are the median percentage of total PAHs and IARC classification for each PAH species. Class 1 = carcinogenic to humans; 2A = probably carcinogenic to humans, 2B = possibly carcinogenic to humans, and 3 = not classifiable. Error bars represent the maximum levels measured.

This study was limited somewhat by sample size and the sensitivity of the sampling and analytical methods. In addition, the collection efficiency of the wipe sampling methods is unknown for the surfaces sampled in this study. Based on laboratory testing of these wipes (or similar wipes) at collecting PAHs from a non-porous surface, it is likely that a large percentage of PAH contamination on skin and turnout jackets (25% or more) may not have been collected. As such, our sampling results should be considered an underestimation of the actual surface loading. Despite these limitations, we were able to identify important contaminants on firefighter PPE and skin and quantify the change in contamination levels following decontamination measures. The data provide important scientific evidence of exposure risk from firefighting by job assignment and will support departments in developing and refining policies to clean their gear and skin following live-fire responses.

We found that PAH contamination on PPE increased with each use in a fire. For firefighters assigned to Inside Attack, Inside Search, and Overhaul/Backup, the median levels on jackets were 7.4, 6.0, and 0.31 µg/100 cm^2 after use in a single fire and 9.3, 8.8, and 1.1 µg/100 cm^2 after use in two fires (without any decontamination), corresponding to a 1.3–3.5 fold increase. Post-fire PAH contamination on turnout jackets assigned to Inside Attack and Inside Search for the last two scenarios ranged up to 21 and 27 µg/100 cm^2, respectively. Increasing accumulation of PAHs with each fire response has been shown in other studies as well.[24,26]

In two separate studies involving live fire training using particle boards as fuel, Kirk and Logan[13,26] measured deposition of PAHs onto turnout gear of 6.9–29 µg/100 cm^2 and deposition flux of 3.3–16 nanograms per square centimeter per minute ($ng/cm^2/min$). The firefighting activities in these studies were most similar to those performed by Inside Attack and Inside Search in our project. Taking the median time inside the structure for Inside Attack and Inside Search of 8 min, this level of flux would result in 2.6–13 µg/100 cm^2 of PAH contamination after each fire. Because of differences in fuels, it would not be surprising if deposition flux in our study differed from Kirk and Logan,[26] but our data suggest similar levels of flux. It should be noted, however, that Kirk and Logan[13,26] used fabric swatches attached to the gear to sample PAH deposition. This would likely result in a higher collection efficiency than could be expected from our sampling methodology. Our methodology was intended to collect substances that could easily transfer to skin, while methods that extract bulk materials may also measure substances embedded in the fabric.

The PPE wipes used in our study, containing 0.45% isopropanol and benzalkonium chloride, have not been tested for their collection efficiency of PAHs. Because benzalkonium chloride is a surfactant, these wipes may be more effective at removing lipid soluble PAHs than PPE wipes containing 70% isopropanol, which, according to our unpublished data, may provide <40% collection efficiency from non-porous surfaces. Additional studies are underway to test the collection efficiency of different types of sampling wipes (wetting agents) in comparison to PAHs measured on a filter substrate affixed to turnout gear. Of note, we would expect higher wipe-sampling collection efficiency from the helmets (non-porous material), but at the same time, contamination on the helmets may be more likely to transfer to the skin during handling.

As expected, VOC and HCN levels measured off-gassing from turnout gear increased from pre-fire to post-fire. Median post-fire VOC concentrations were highest for styrene (340 μg/m^3) and benzene (230 μg/m^3). In our previous study, we measured a median of 25 μg/m^3 of benzene and 85 μg/m^3 of styrene off-gassing from a single set of gear (inside a 0.18 m^3 enclosure).[25,26] Kirk and Logan[26] reported similar off-gas concentrations of benzene and styrene from a single set of gear as our previous study. Kirk and Logan[26] also measured HCN concentrations ranging from 630–1300 μg/m^3, which were well above the post-fire levels we found in this current study (< 26–620 μg/m^3). The higher HCN concentrations may be due to the fuel package being composed primarily of engineered wood products in the Kirk and Logan[26] study.

Our current study further differs from these previous studies in that six sets of turnout gear were placed inside an enclosure representative in volume to an apparatus cabin. Hence, the VOC air concentrations we measured could be expected if six firefighters were to wear or store their turnout gear inside an enclosed apparatus cabin during a 15-min ride back to their station, provided they embarked on this trip soon after completing overhaul. While the levels we measured are well below applicable short-term exposure limits or ceiling limits, these findings indicate that firefighters could inhale a number of chemicals in the period following a fire response. Although not a major focus of this study, semi-volatile compounds would evaporate much more slowly and could pose a longer-term inhalation hazard for firefighters.

While effective at removing PAH contamination, field decontamination had no apparent effect on the VOC concentrations as decontaminated gear provided similar off-gas levels as the gear that had not been decontaminated. Our results suggest that a large proportion of the VOCs evaporated naturally from PPE that was not decontaminated (but allowed to air out on a hanger) over the time it took to decontaminate the other half of gear. Although we lacked the power to test the changes in off-gas concentrations by type of decontamination, the primary purpose of field decontamination is not to remove VOCs, but rather to remove soot and other particulate from the gear. Because soot can be composed of semi-volatile compounds or act as a sorbent for other organic substances, field decontamination could conceivably help reduce the levels of off-gassing semi-volatile compounds, and this should be investigated in future studies.

If PAH contamination was not distributed similarly across the sleeve, the decontamination findings could be biased upward or downward. However, the pre- and post-decon wipe samples were consistently collected from abutting (middle and lower) sleeve locations to minimize this bias. Of the three types of field decontamination methods investigated in this study, the wet-soap decon method was clearly the most effective at removing surface contamination, providing a median reduction in PAH levels of 85%. Soot is generally composed of lipid soluble compounds like PAHs. Surfactants, like those in dish soap, are designed to surround lipid molecules and liberate them from surfaces so that water can then take them away. Future studies should investigate how water-only decon compares with wet-soap decon. Although the dry-brush method was not as effective as the wet-soap decon method, a median PAH reduction of 23% is certainly better than doing nothing. This method would be relatively easy to implement at any department and would not take PPE out of service while drying. The air-based decon method has similar advantages to the dry-brush method, but it was not as effective in removing PAHs (∼2% reduction). We suspect that the air-velocity was able to remove "loose" particulate, but could not overcome the surface tension of much of the "sticky" soot coating the turnout gear. Airflow across the surface of the turnout gear could also facilitate the evaporation of more volatile contaminants (e.g., naphthalene), however, many of these components would evaporate naturally in a well-ventilated space. An air-based system could be effective in certain firefighting situations (e.g., when ash or dust are abundant) and this should be investigated further.

After use in four fires, gear that had undergone post-firefighting decontamination had markedly lower levels of PAHs than gear that had not undergone decontamination, with the largest effect found for wet-soap decon. This further demonstrates that field decontamination could be used routinely to manage PPE contamination. However, laundering through commercial extractors that adhere to NFPA requirements[43] would likely provide the greatest cleaning efficacy; quantifying the efficacy of extractors is currently a topic of ongoing research. How repeated laundering compares with wet-soap decon in terms of material degradation and the effects on the protective properties of the turnout gear also requires further study. Our findings indicate that PAH contamination varies by job assignment, and so departments should consider prioritizing gear for laundering based on a firefighter's assignment during the response.

For nearly all positions, 50% or more of the post-fire PAH measurements from the neck were non-detectable (i.e., <24 μg/m^2). The one exception was for firefighters assigned to Outside Vent who had 14 of 24 detectable PAH measurements from the neck after firefighting with a median level of 30.5 μg/m^2. When PAHs were detected on the neck, firefighters assigned to Inside Attack and Inside Search had higher values than other positions as evidenced by their respective 75th percentiles (152 and 71.7 μg/m^2 compared to <40 μg/m^2 for all other positions). In a previous study, we measured PAH levels on firefighters' necks ranging from <57–187 μg/m^2 and only 33% of the measurements were non-detectable.[30] In our previous study, firefighters observed the growth of a fire (involving furniture) inside a two-room structure while standing, crouching, crawling, or performing other activities to simulate firefighting tasks. These firefighters were positioned a little higher in the target rooms and had a longer smoke exposure (∼10 min) that was not as operationally relevant as the scenarios conducted here. We also collected samples across the entire neck in our previous study rather than only half the neck, which could explain the higher frequency of detectable levels.

Contaminants measured on neck skin in both studies are likely penetrating or permeating the protective Nomex® hoods worn by firefighters or infiltrating around the hood/coat or the hood/SCBA interface and therefore may be directly affected by the duration of time spent in smoke. Firefighters assigned to Inside Attack and Inside Search in our current study were operating from the crawling position, low in the smoke layer for much of the response, which would lessen their exposures. Fires were also quickly suppressed (within a few minutes after entry). Firefighters assigned to other job assignments did not enter the structure at all or entered after the fire had been suppressed. Any firefighters not wearing hoods on the fireground may have been at risk for neck exposures. In reviewing video footage, we found that several of the Outside Vent firefighters did not wear their hoods while conducting exterior operations, which could explain the higher frequency of detectable PAHs on their necks. This illustrates the importance of wearing the Nomex hood when performing exterior operations (i.e., Outside Vent). The research and development of hoods that offer additional chemical protection may be warranted especially for use in interior operations (i.e., Attack and Search).

Nearly all (47 of 48) post-fire PAH measurements taken from the hands of firefighters assigned to Inside Attack and Inside Search were detectable, with interquartile ranges of 67–190 μg/m^2 for Inside Attack and 144–313 μg/m^2 for Inside Search. The respective median post-fire levels of PAHs on hand skin (135 and 226 μg/m^2) were higher than on neck skin (<32 and <27 μg/m^2). This contradicts our earlier study that found higher levels on the neck (median 52 and 63 μg/m^2) than the hands (median 16 and 24 μg/m^2).[30] For firefighters assigned to the other jobs, the median post-fire hand exposures (<4.5–10.5 μg/m^2) were similar to our earlier study. Our current findings corroborate the findings by Fernando et al. 2016[33] which found an increase in PAH and methoxyphenol contamination on firefighter skin after conducting training fires, with higher loading on the fingers than the other skin sites (back, forehead, wrist, and neck).

Hands may become contaminated during the doffing of gear. However, our analysis did not show an increasing trend in PAH levels on hands with each subsequent study day in firefighters who wore non-decontaminated gear even though the contamination levels on the jackets increased (see Figures 1 and 2). The gloves had a moisture barrier between the inner and outer materials, and as such, we do not believe the PAHs permeated the gloves. Penetration of contaminants around the gloves (likely facilitated by sweat or water on the fireground) is another possible mechanism. Inside Search firefighters in our study likely spent more time crawling than any other job assignment and as such, their gloves would have contacted contaminants and water that collected on the floor. This could explain why they had significantly higher post-fire hand exposures than the Inside Attack firefighters, even though both performed inside operations during active fire.

While this paper does not report biomarker levels of PAHs, PAHs were measured on skin and have been shown to readily absorb through skin.[44,45] Thus, it is likely that firefighters in this study, especially the interior crews, had biological uptake of PAHs. Biological absorption will be thoroughly evaluated in future manuscripts.

When executed successfully, transitional attack will knock down or substantially retard the fire from the exterior of the structure (through a window or other opening). When firefighters then enter the structure to perform final suppression and search and rescue operations, their smoke exposures should theoretically be less than if interior attack were performed. However, we did not find statistically significant differences in PPE or skin exposures by tactic for firefighters assigned to Inside Attack and Inside Search; although, median exposures were generally lower for transitional attack. Several factors can influence the magnitude of exposures during transitional attack, including exposure to smoke while outside the structure and regrowth of the fire while inside the structure. These factors may have contributed to the overall variability in PPE and skin contamination during transitional attack, thereby reducing our power to detect statistical differences. Further investigation into how tactics affect personal exposures is warranted.

One possible way of mitigating dermal contamination is by using cleansing wipes after firefighting. The median reduction in PAH levels on neck skin after using commercial cleansing wipes (i.e., baby wipes) was 54%. It is important to note that this analysis assumed equal distribution of PAHs across the neck skin. If the left side of the neck was biased to have higher exposures than the right side, our stated efficacy would be underestimated. If the opposite were to have occurred, then our stated efficacy would be overestimated. Also, by excluding firefighters who had non-detectable levels on their neck post fire, we may have introduced some bias toward higher efficacy. Despite the inherent limitations of this field experiment, we provide the first ever evidence that cleansing wipes can be effective at reducing PAH contamination from skin. Not all cleansing wipes may have equal efficacy and further investigation is warranted. The data show that some level of contamination is likely to remain on the skin after using these wipes. As such, showering, hand washing or other means of more thorough cleaning of the skin should be conducted as soon as feasible following any exposure on the fireground.

Conclusions

Personal protective equipment, neck skin, and hand skin became contaminated with PAHs during firefighting. The magnitude of contamination varied by job assignment. Firefighters assigned to Inside Attack and Inside Search generally had the most contamination on their turnout gear and skin following each response, and their hand skin was more contaminated than their neck skin. Inside Search firefighters had significantly more PAH exposure to their hands than the Inside Attack firefighters, possibly because Inside Search firefighters spent much of their time crawling on contaminated floors. Outside Vent crews had the highest frequency of detectable PAHs on their necks and this contamination was higher than the levels measured on their hands. This finding was likely due to the inconsistent use of hoods by the Outside Vent crews.

Contamination on turnout gear increased with each fire response if not decontaminated. Three types of field decontamination methods were evaluated and wet-soap decon was found to be the most effective at removing PAH contamination from turnout gear. Commercial cleansing wipes also showed some benefit at removing PAH contamination from neck skin. While turnout gear became contaminated with VOCs, off-gas levels were low (below short-term exposure limits) and a large proportion evaporated within 24 min. Overall, this study provides a greater understanding of the exposure pathways associated with firefighting and the measures that can be implemented to reduce these exposures.

Acknowledgments

This was a collaborative project that could not have been completed without the help from several people. We thank Matthew Dahm for conducting the surface wipe sampling, Donald Booher for performing the off-gas sampling, Kenneth Sparks for preparing and maintaining our sampling equipment, and Bureau Veritas North America for analyzing the surface and skin wipe samples. We also thank Globe Manufacturing for providing turnout gear for this study. Most of all, we thank the firefighters for participating in this study. Participants were compensated up to $599 to participate in this study. This study was approved by the Institutional Review Boards at NIOSH and the University of Illinois. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of NIOSH. Mention of any company or product does not constitute endorsement by NIOSH.

Funding

This study was funded through a U.S. Department of Homeland Security, Assistance to Firefighters Grant (EMW-2013-FP-00766). This project was also made possible through a partnership with the CDC Foundation.

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Printed by Media-Tryck, Lund 2020 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY

ISBN 978-91-7895-555-8
ISSN 1402-3504
ISRN LUTVDG/TVBB--1064—SE
Report 1065
Fire Safety Engineering
Lund University