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Fire Fighter Equipment Operational Environment: Evaluation of Thermal Conditions

FINAL REPORT BY:

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FOREWORD

The goal of this study was to review the available literature to develop a quantitative description of the thermal conditions firefighters and their equipment are exposed to in a structural fire environment. The thermal exposure from the modern fire environment was characterized through the review of fire research studies and fire-ground incidents that provided insight and data to develop a range of quantification. This information was compared with existing standards for firefighting protective equipment to generate a sense of the gap between known information and the need for improved understanding. The comparison of fire conditions with the thermal performance requirements of firefighter protective gear and equipment demonstrates that a fire in a compartment can generate conditions that can fail the equipment that a firefighter wears or uses.

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

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Keywords: fire environment, fire fighter equipment, personal protective equipment, PPE, fire fighter ensemble, thermal exposure, NFPA 1971, NFPA 1981, NFPA 1801, NFPA 1961, NFPA 1964

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Fire Fighter Equipment Operational Environment (FFEOE): Evaluation of Thermal Conditions

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Prepared for the NFPA Fire Protection Research Foundation

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August 10, 2017

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List of Acronyms

AFG	Assistance to Firefighters Grant program
DHS	U.S Department of Homeland Security
FEMA	Federal Emergency Management Agency
HRR	Heat release rate
IDLH	Immediately dangerous to life or health
IAFC	International Association of Fire Chiefs
IAFF	International Association of Fire Fighters
IFSI	Illinois Fire Service Institute
IFSTA	International Fire Service Training Association
MFRI	Maryland Fire and Rescue Institute
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
PPE	Personal Protective Equipment
SFPE	Society of Fire Protection Engineers
UL FSRI	UL Firefighter Safety Research Institute
USFA	United States Fire Administration

Abstract

The goal of this study was to review the available literature to develop a quantitative description of the thermal conditions firefighters and their equipment are exposed to in a structural fire environment. The thermal exposure from the modern fire environment was characterized through the review of fire research studies and fire-ground incidents that provided insight and data to develop a range of quantification. This information was compared with existing standards for firefighting protective equipment to generate a sense of the gap between known information and the need for improved understanding. The comparison of fire conditions with the thermal performance requirements of firefighter protective gear and equipment demonstrates that a fire in a compartment can generate conditions that can fail the equipment that a firefighter wears or uses.

The review pointed out the following:

1. The accepted pairing of gas temperature ranges with a corresponding range of heat fluxes does not reflect all compartment fire conditions. There are cases in which the heat flux exceeds the hazard level of the surrounding gas temperature.

2. Thermal conditions can change within seconds. Experimental conditions and incidents were identified in which firefighters would be operating in thermal conditions that were safe for operation based on the temperature and heat flux, but then due to a change in the environment the firefighters would be exposed to conditions that could exceed the protective capabilities of their PPE.

3. Gas velocity is not explicitly considered within the thermal performance requirements. Clothing and equipment tested with a hot air circulating (convection) oven are exposed to gas velocities that measure approximately 1.5 m/s (3 mph). In contrast, the convected hot gas flows within a structure fire could range from 2.3 m/s (5 mph) to 7.0 m/s (15 mph). In cases where the firefighter or equipment would be located in the exhaust portion of a flow path, while operating above the level of the fire, the hot gas velocity could be even higher. This increased hot gas velocity would serve to increase the convective heat transfer rate to the equipment and the firefighter, thereby reducing the safe operating time within the structure.

4. Based on the limited data available, it appears currently available protective clothing enables firefighters to routinely operate in conditions above and beyond the "routine" conditions measured in the fire-ground exposure studies conducted during the 1970s.

The fire service and fire standards communities could benefit from an improved understanding of:

- real world fire-ground conditions, including temperatures, heat flux, pressure, and chemical exposures;
- the impact of convection on the thermal resistance capabilities of firefighting PPE and equipment; and
- the benefits of balancing the thermal exposures (thermal performance requirements) across different components of firefighter protective clothing and safety equipment.

Because it is unlikely due to trade offs in weight, breathe-ability, usability, cost, etc., that fireproof PPE and equipment will ever be a reality, fire officers and fire chiefs need to consider the capabilities of the protection that their firefighters have when determining fire attack strategies and tactics to ensure that the PPE and equipment is kept within its design operating environment, and that the safety buffer it provides is maintained.

Section 1

Introduction

Over the past 50 years, changes in construction materials, construction methods, insulation, and furnishings have changed the means and the speed of fire growth within a structure. Both experiments and Line of Duty Death (LODD) investigations have demonstrated the importance of understanding of how ventilation affects fire behavior. Fires in today's fire environment, fueled predominantly by synthetic materials, commonly become ventilation-limited. How, where, and when a fire receives oxygen greatly impacts the fire dynamics and the resulting thermal environment inside the structure.

During the same 50 year period, the tactics firefighters use on the fire ground have also changed. This change occurred largely due to the improvements in protective equipment and clothing firefighters rely on to enter high temperature atmospheres considered immediately dangerous to life or health (IDLH). Just as the use of synthetic materials has overtaken the use of natural materials such as cotton, wool, or wood in homes, the same trend is true for firefighter protective clothing and equipment. In the past firefighting coats were wool lined and had an outer layer of cotton canvas or a layer of rubber. Firefighters protected their feet and legs with long rubber boots. Hoses used to be cotton jacketed with rubber liners. Today the firefighter has the most advanced protective ensemble and the widest range of tools and equipment for fighting fire than ever before. The synthetic materials currently used in the firefighting gear have improved performance over the natural materials in many ways.

However, in the aftermath of firefighter LODDs and Line of Duty Injuries (LODIs), the question of the protective capabilities of firefighter protective clothing and safety equipment arises. Although the firefighter protective clothing and safety equipment has been improving over the years, how do these improvements align with the changes in the firefighters' work place? In other words, have the hazards of the structural fire increased? If so, are the current thermal performance standards for firefighter protective clothing and safety equipment appropriate for the current operational environment?

This study will serve as a step in addressing the question of how well we understand the thermal conditions in the firefighters' operational environment. The study is composed of the four tasks listed below:

1. Literature Review and Defining the Operational Environment. Provide a comprehensive review of available literature related to thermal conditions in the firefighter operational environment. Determine extent of the operational environment on a structure fire incident, including location

and exposures. Possible locations to consider include rooms, hallways, stairwells, and outside of structure.

2. Gap Analysis. Determine gaps in available information on thermal conditions in the operational environment.

3. Thermal Scenarios. Identify conceptual thermal scenarios that can form the technical basis for test standards. These should include a quantitative description of the operational environment based on information from previous tasks.

4. Final Report. The final report should synthesize the information gathered in the completion of the previous tasks to develop a comprehensive description of the firefighter equipment operational environment based on the available information. The description of the operational environment should use terms that can be communicated to users (i.e., firefighters).

   The results from Tasks 1-3 are addressed in the sections below in this final report.

Section 2

Literature Review

There has been a significant amount of research conducted on the behavior of fire in compartments and, more recently, the spread of fire and fire gases through structures as it relates to firefighting. This literature review focuses on the studies that use furnishings one might find in a residential or "light hazard" occupancy. Other examples of "light hazard" occupancies include churches, hospitals, offices, and schools, to name a few [1]. The reason for the focus on "light hazard" occupancies, especially residential occupancies, is because the majority of firefighter LODDs typically occur in residential occupancies [2], [3], [4], [5], [6], [7].

During the past 10 years, an unprecedented amount of research and investigation has been conducted to examine the firefighters' work environment with the goal of improving firefighter safety and effectiveness. The majority of this research was funded by the Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA) Assistance to Firefighters Grant (AFG) program, the National Institute for Occupational Safety and Health (NIOSH), the National Institute of Standards and Technology (NIST), and the United States Fire Administration (USFA).

This literature review included four types of source materials:

1. Research papers on fire dynamics, firefighter protective equipment development, and firefighting tactics;
2. Near Miss Reports;
3. NIOSH LODD Reports; and
4. Research reports examining LODD incidents.

2.1 Fire Research

The fire research reports examined for this review were developed to understand fire dynamics within a compartment, the development of firefighter protective equipment, or the study of firefighting tactics. The focus of each report was to provide insight on the structural firefighting environment. The three paragraphs below give a sense of the evolution of funding sources for the research and how that changed the focus of the research over time.

The Federal Fire Prevention and Control Act of 1974 (Public Law 93-498) resulted in the creation of the Center for Fire Research at the National Bureau of Standards (NBS, now NIST) and the National Fire Prevention and Control Administration (NFPCA, now UFSA). The creation of these two government agencies and the funding that came with them resulted in studies focused on fire dynamics in a compartment, toxicity of fire gases, flammability of furniture (available at the time), plastics, fire detection, suppression and firefighting PPE. In addition, the Center for Fire Research had a well-funded fire research grants program. The high level of government interest and the amount of available funding resulted in contributions from industrial research partners and top-ranked engineering schools across the U.S. [8]. During this period there were also significant fire research efforts underway in Canada, Japan, Sweden, and the United Kingdom, to name a few.

The collective findings of these efforts were incorporated into the development of the SFPE Handbook of the Fire Protection Engineering [9] and additions to the National Fire Protection Association (NFPA) Fire Protection Handbook [10]. These major gains in fire knowledge in the 1970s, 1980s, and 1990s led to improvements in fire measurements and the development of quantitative methods of predicting or simulating fire behavior. The first text book on fire dynamics was authored by Dougal Drysdale and published in 1985 [11]. Needless to say the scope of the information contained in these books is beyond the scope of this review, but it is important to note that the fundamentals of fire behavior and analytical methods for the interaction between fire, buildings, and people are presented in the books.

FEMA supports and manages the AFG program. Since 2007, this program has been home to the the Fire Prevention and Safety Research and Development Grants. This program has generated a renewed interest in fire research aimed at supporting the needs of the fire service, including fire development in structures. The majority of the full-scale fire research in the 1970s through the 1990s was focused on the room of origin, or the room and a hallway. Few studies examined fire dynamics within a full scale structure. That changed in the 2000s. In the United States that change was due to the new funding available from FEMA. This funding drove a change in research perspective. The new perspective included "taking the science to the street". Prior to the AFG, research was done for the fire department, but AFG-funded research enabled the fire service to participate as a partner. Much of the research presented in the section below was funded by the U.S. government either through AFG grants or through federally supported programs at NIOSH, NIST, or USFA.

2.1.1 Fire Dynamics

This section examines research reports developed to better understand fire phenomena. They were not developed specifically for determining the firefighters operating environment. Reports referenced here were selected based on the use of realistic fuels as opposed to wood cribs or gas burners, and the suite of measurements that would provide insight into a range of firefighting thermal environments.

The thermal environment conditions a firefighter may be exposed to span a wide range of temperatures and heat flux. From a fire dynamics perspective, the energy generated by a fire in a room or compartment depends on many factors: type of fuel, amount of fuel, geometry and location of fuel, availability of oxygen, size and location of vents to provide exhaust and air intake, the size and shape of the compartment, and possibly wind. As a starting point, the baseline information on compartment fire behavior is examined.

Review of Thermal Measures

A number of terms are used to characterize or measure the thermal environment. A few of the terms; heat, temperature, heat release rate, heat flux, and their units of measure are reviewed below.

For thermal conditions, heat is a base measure. Heat is a form of energy characterized by the molecular activity within a material. Adding heat to a material increases the movement of the molecules within the material and results in an increase of temperature. Increased heat transfer can cause the bonds of the molecules to change or break, which results in chemical changes and changes of state of the material. Heat can be measured joules (J). One thousand joules equal a kilojoule (kJ). One kJ is approximately equal to 1 British Thermal Units (BTU). Units based off of joules are used in this review because most research results are presented these units.

Temperature is a measure of the heat (molecular activity) within a material. The two temperature scales most commonly used are Fahrenheit (°F) and Celsius (°C). The temperatures are reported in the units used in the report cited, or in both units. Lawson published a referenced list of temperatures that may be associated with fire growth conditions and relates specific human response to these thermal conditions, see Table 2.1 [12]. One of the key temperatures to keep in mind is that human skin will sustain a second-degree burn injury when it reaches a temperature of 55 °C (132 °F).

Heat release rate is the measure of the power of the fire. It is the rate at which energy is generated by the burning fuel. The unit commonly used are watts (W). A watt is equivalent to a joule per second. One thousand watts equals a kilowatt (KW). One million watts equals a megawatt (MW).

Heat flux is the rate of heat transferred per surface unit area. Heat flux can be measured in kilowatts per square meter (kW/m^2). In the case of a firefighter operating in a hot environment, the heat flux would be the amount of energy hitting the surface of the PPE or other equipment. The fire facts package revised in 2009 included a list of referenced heat flux values that is presented in Table 2.2 [12]. Key heat flux benchmarks include the baseline of 1 kW/m^2 for the sun on a clear day, and that 10 kW/m^2 causes a second degree burn to exposed skin in approximately 10 seconds. Some of the other heat flux references included in the table will show up as the research areas are reviewed in the following sections.

The Fire Protection Handbook has a chapter on the dynamics of compartment fire growth. It provides a qualitative description of a fire growing from an established flame to the transition to flashover [13]. The chapter presents and references the sources for several algebraic mathematical relationships to quantify various aspects of a compartment fire such as plume temperatures [14] and the minimum heat release rate required for flashover based on ventilation [15]. Most of these relationships do not account for time. The conditions are assumed to be quasi-steady or steady state. The triggering conditions for flashover are given as 600 °C (1,112 °F) upper layer temperature, and approximately 20 kW/m^2 radiant heat flux on un-ignited fuels in the room at the floor level or above. The change in conditions from pre-flashover to post flashover may occur within seconds.

These model conditions came from range of single compartment fire studies. One of the early compartment fire studies that used "modern" residential fuels was the The Home Fire Project sponsored initially by the National Science Foundation in 1972. This project was a joint effort between Harvard University and Factory Mutual Research Corporation. It included a range of studies including full-scale room fire experiments. Data from small bedroom flashover experiments con-

Temperature °C (°F)	Response
37.0 °C (98.6 °F)	Average normal human oral/body temperature [1]
38 °C (101 °F)	Typical body core temperature for a working fire fighter[2]
43 °C (109 °F)	Human body core temperature that may cause death [3]
44 °C (111 °F)	Human skin temperature when pain is felt [4]
48 °C (118 °F)	Human skin temperature causing a first degree burn injury [4]
54 °C (130 °F)	Hot water causes a scald burn injury with 30 s exposure [5]
55 °C (131 °F)	Human skin temperature with blistering and second degree burn injury [4]
62 °C (140 °F)	Temperature when burned human tissue becomes numb [4]
72 °C (162 °F)	Human skin temperature at which tissue is instantly destroyed [4]
100 °C (212 °F)	Temperature when water boils and produces steam [6]
250 °C (482 °F)	Temperature when charring of natural cotton begins [7]
>300 °C (>572 °F)	Modern synthetic protective clothing fabrics begin to char [7]
≥400 °C (≥752 °F)	Temperature of gases at the beginning of room flashover [8]
≈1000 °C (≈1832 °F)	Temperature inside a room undergoing flashover [8]

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Table 2.1: Temperatures commonly experienced during firefighting operations, and information on the associated human response to these temperatures. [12].

ducted in 1974 and 1975 demonstrated a transition to flashover in less than 7.25 minutes after ignition. Heat release rates of approximately 2 MW were generated, and fire gas velocities flowing out of the upper portion of the door exceeded 8 m/s (18 mph). Post-flashover, the peak hot gas layer temperatures in the room approached 1,000 °C (1,832 °F) Efforts to mathematically model fire growth were developed at the same time as the physical research was conducted [16].

Heat Flux Level kW/m^2	Response
≈1	A typical clear day solar flux on the earth's surface with direct solar radiation; a sun burn may occur in approximately 20 min to 30 min. [1]
2.5	Typical firefighter exposure and working environment [2] (About 2.5 times the solar flux).
4.5	Unprotected human skin will receive a second degree burn injury in about 30 s. [3] (About 4.5 times the solar flux)
6.4	Unprotected human skin has pain with 8 s exposure and blisters in 18 s with a second degree burn injury.[3] (About 6.4 times the solar flux)
10	Unprotected human skin will receive a second degree burn injury in about 10 s [3] (About 10 times the solar flux.)
13	Wood volatiles ignite with flame exposure.[4] (About 13 times the solar flux)
16	Unprotected human skin experiences sudden pain and blistering after 5 s exposure with second degree burn injury.[3] (About 16 times the solar flux)
20	Unprotected human skin will receive a second degree burn injury in less than 4 s [3]. This heat flux level represents the heat flux in a room at floor level at the beginning of flashover.[4] (About 20 times the solar flux)
80	Unprotected human skin will receive an instant second degree burn injury.[3] Flashover is established in a room.[4] (About 80 times the solar flux)
84	Heat flux level specified in the NFPA 1971 test for Thermal Protective Performance (TPP) to evaluate firefighters' thermal protective clothing.[3]
170	Maximum heat flux level measured by NIST with a post-flashover fire inside a burning room.[5] (About 170 times the solar flux)

References:
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Table 2.2
A list of heat flux levels commonly experienced during firefighting operations, and information on the human response to these heat flux levels. [12].

The study "Fire Development in Residential Basement Rooms" by Fang and Breese [17] also used residential furnishings and interior finish materials. Two different-size burn rooms were used in the study, one measuring 3.3 m (10.7 ft) x 3.3 m (10.7 ft), and the other 3.3 m (10.7 ft) x 4.9 m (16 ft). Both rooms had a ceiling height of 2.4 m (8 ft). Both of the rooms had a 0.76 m (30 in) wide by 2.03 m (80 in) high doorway opening located centrally in one of the 3.3 m (10.7 ft long walls) to serve as the single source of natural ventilation for the rooms. Some of the experiments were conducted with the doorway, closed and others were conducted with the doorway open. Interior finish materials included gypsum board, concrete block, exposed joists, and plywood paneling. The furnishings consisted of four upholstered furniture items weighing approximately 125 kg (275 lbs) total and five laminated wood items with a total mass of approximately 122 kg (268 lbs). For the upholstered furniture, more than 50% of the mass consisted of the wood frame and steel springs. The total amount of polyurethane foam in the furniture was approximately 15 kg (33 lbs).

The basement room experiments conducted with the doorway closed did not result in flashover. In the closed door tests, the peak temperatures in the gas layer ranged from 190 °C (374 °F) to 410 °C (770 °F), and the peak total heat flux measured on the ceiling ranged between 30 kW/m^2 to 40 kW/m^2 [17]. This provided the heat flux the ceiling was exposed to, not the direct exposure at lower elevations that a firefighter or their equipment would be exposed to.

The basement room experiments conducted with the open doorway transitioned to flashover within approximately two minutes after the ignition of paper on the sofa with an electric match. In the open door tests, the peak temperatures in the gas layer ranged from 950 °C (1740 °F) to 1,080 °C (1,976 °F). The total heat flux was measured on the ceiling, walls and floor. Over the course of the experiments, the peak total heat flux ranged between 90 kW/m^2 to 180 kW/m^2 at the ceiling, 120 kW/m^2 to 230 kW/m^2 at the walls, and 110 kW/m^2 to 160 kW/m^2 at the center of the floor. A radiant heat flux gauge, located 3.05 m (10 ft) outside of the room and 1.02 m (3.4 ft) above the floor, was exposed to the flames exiting the open doorway post-flashover and measured peaks of approximately 33 kW/m^2. The triggering conditions for flashover from these experiments are given as 706 $\pm$ 92 °C (1,303 $\pm$198°F) upper layer temperature, and approximately 20 kW/m^2 radiant heat flux at the floor [17].

In the late 1990s, eight compartment fire studies, in addition to the basement room study, were reviewed for the purpose of defining flashover for fire hazard calculations [18]. Most of studies were conducted in a single room arrangement. One of the larger test compartments had a floor area of 22.7 m^2 (244 ft^2). This analysis further supported conditions required for the onset of flashover as 600 °C (1,112 °F) upper layer temperature and approximately 20 kW/m^2 radiant heat flux at floor level. Experiments such as these formed the knowledge base for fire behavior in compartments.

In the 2000s, several large scale laboratory experiments were conducted at NIST as part of investigative studies examining fire growth rates with synthetic fuel packages. Three different types occupancies were represented: residential [19], office [20], and public assembly [21] scenarios. These three scenarios were chosen because of the difference in area of the test arrangements compared to the single compartment research experiments with relatively small floor areas and ceiling heights of 2.4 m (8 ft) or less. The smaller compartments were characteristic of those used to generate much of the compartment fire data cited in the literature from the 1970s through 1990s.

In the residential scenario the bedroom and living room were each 4.6 m (16 ft) by 3.6 m (12 ft). However, the total floor area of the apartment and adjoining corridor exceeded 72 m^2 (775 ft^2).

The office scenario was a large open room with a floor area of over 50 m^2 (550 ft^2) and a ceiling height of 3.4 m (11.2 ft). One end wall of the compartment was open to the laboratory to simulate the space being a portion of a much larger open plan office arrangement.

The public assembly space was also a large single room with a floor area of more than 75.5 m^2 (810 ft^2) and a ceiling height of 3.8 m (12.5 ft). One significant difference between this large compartment and the office scenario was the only ventilation opening was a single doorway 0.91 m (3 ft) wide and 2.0 m (6.6 ft) high located in the wall opposite the origin of the fire. The specific experiments are summarized below.

Residential Apartment

This experiment was the baseline experiment conducted as part of a series to study the impact of wind on structure fires [19]. This experiment was conducted without wind. All of the thermal and velocity conditions were generated by the fire and the available ventilation to the apartment. A plan view of the apartment and the instrument locations are shown in Figure 2.1. The fire was ignited in the bedroom in the rear of the structure with the door to the apartment open to the corridor, allowing the fire gases to flow through the apartment and into the corridor, which had an opening at one end. As the fire developed, it became ventilation limited. The fire in the bedroom reached a fully developed ventilation limited steady state. Then the bedroom window was vented, and thermal hazard increased all along the flow path from the bedroom to the exhaust vent in the corridor.

After the window was vented, additional oxygen was supplied to the fire, and the heat release rate increased from approximately 1.5 MW to 14 MW in less than 60 s. The heat release rate held steady between 12 MW and 13 MW for almost 180 s, until suppression was started. Along with the increase in heat release rate, the temperatures, heat flux, and gas velocities increased all along the exhaust portion of the flow path from the bedroom to the exhaust vent in the corridor.

Figures 2.2 and 2.3 show the measurements from the thermocouple arrays located in the centers of the bed room, the hallway, the living room, and the northern section of the corridor. In other words, the thermocouple arrays are positioned along the exhaust portion of the flow path from the bedroom through the vent at the north end of the corridor. In each array, a thermocouple was located 0.03 m (1 in), below the ceiling followed by thermocouples installed at approximately 0.3 m (1 ft) intervals until they were 2.13 m (7 ft) below the ceiling or 0.3 m (1 ft) above the floor.

During the first 200 s, the data shows a temperature gradient in the bedroom ranging from 700 °C (1,290 °F) near the ceiling to 100 °C (212 °F) at 0.3 m (1 ft) above the floor. As the window began to fail, the temperatures near the ceiling cooled by almost 100 °C (212 °F), while the rest of the thermal layer increased in temperature. Within seconds of the manual venting of the window at 248 seconds, the room went from a thermally stratified environment to a post-flashover (thermally well mixed) environment in which temperatures at all elevations in the room were similar and in excess of 600 °C (1,100 °F). This post-flashover condition continued until the fire was suppressed. The measurements from the thermocouple array in the hall followed a similar trend to the bedroom data until the target room doorway began to burn. The burning of the door and the change in ventilation and flow due to the resulting opening between the target room and the hall corresponded with the steady increase in temperatures starting at 350 seconds. As the door to the closed target room burned away, the oxygen flowed out of the "closed" room and burned, driving the conditions in the living room through flashover with temperatures from the ceiling down to the floor becoming nearly equal at at temperatures of approximately 600 °C (1,112 °F). This area also remained well mixed thermally post flashover until suppression.

The living room thermocouple array was in center of the room, in the flow path from the bedroom to the vent in the corridor. Similar to the bedroom and the hall, the timing and the trends were consistent, except the peak temperatures were lower and the temperatures at the different

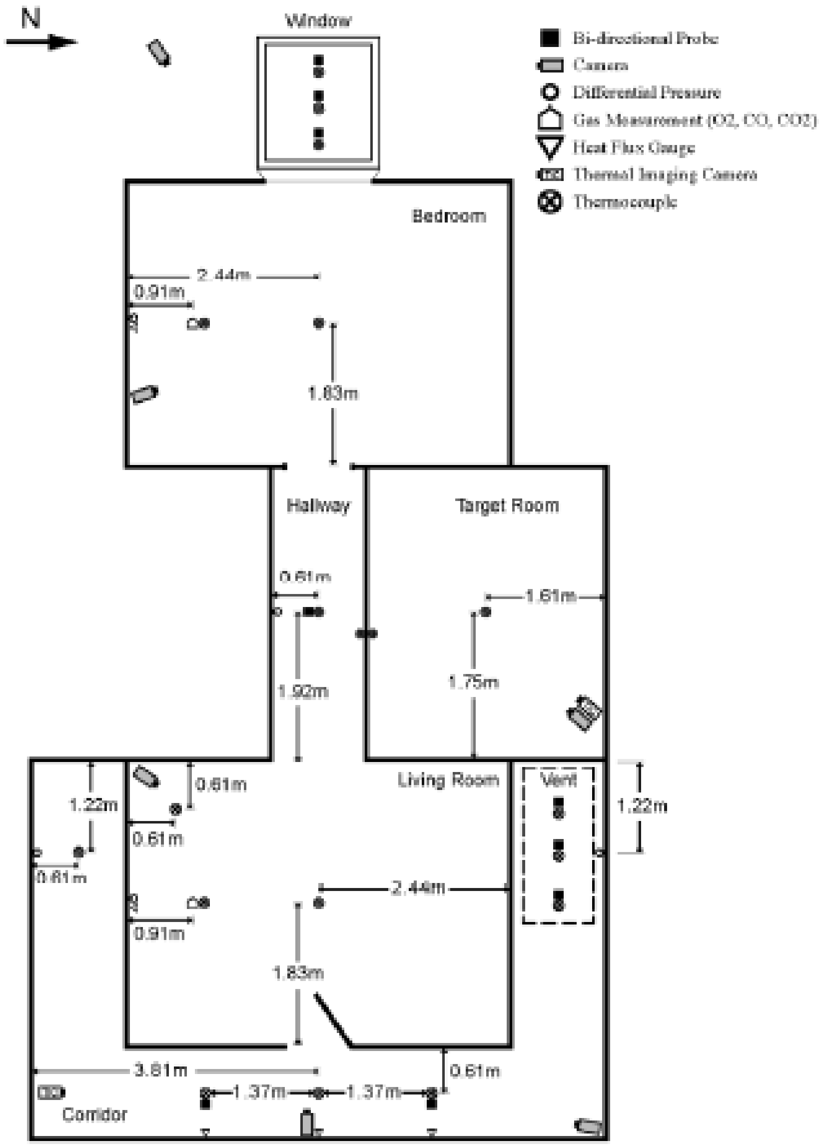


Figure 2.1: Residential apartment arrangement and instrument locations.

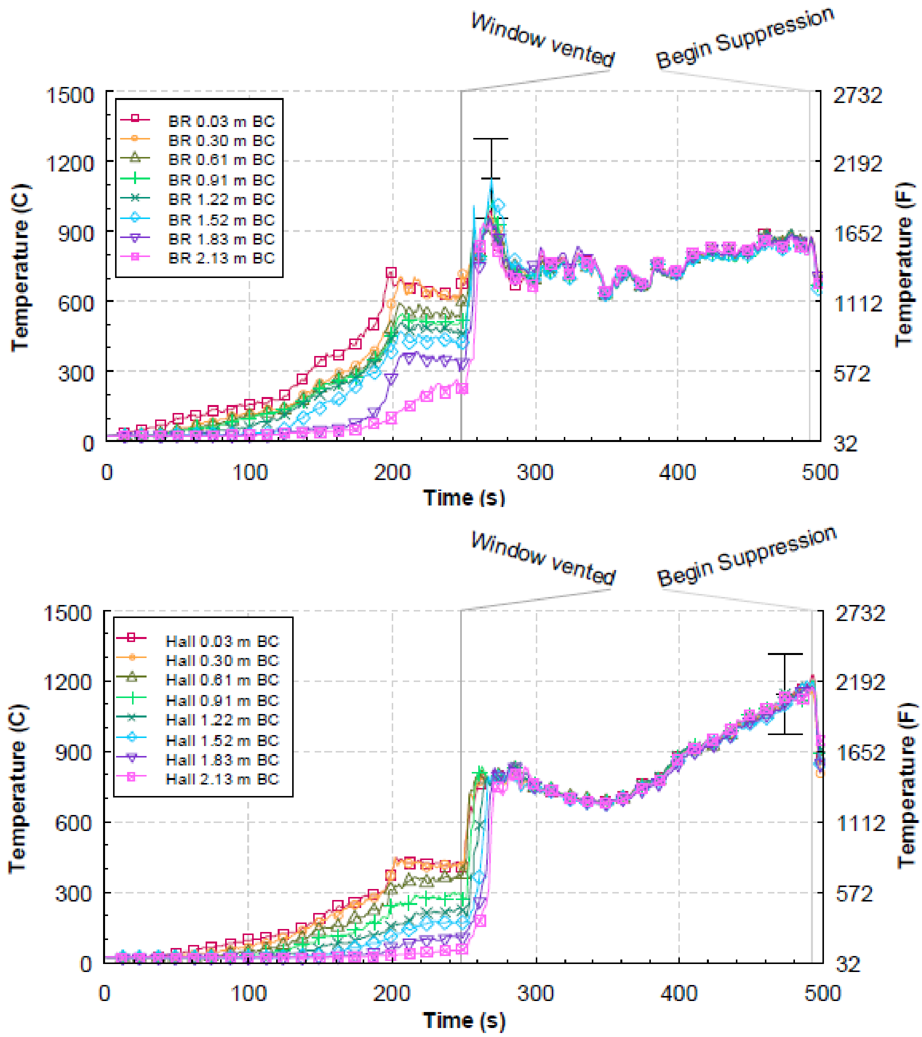


Figure 2.2: Residential apartment experiment temperature plots for the bedroom (i.e the room of origin) and hall position. BC in the legend stands for Below Ceiling.

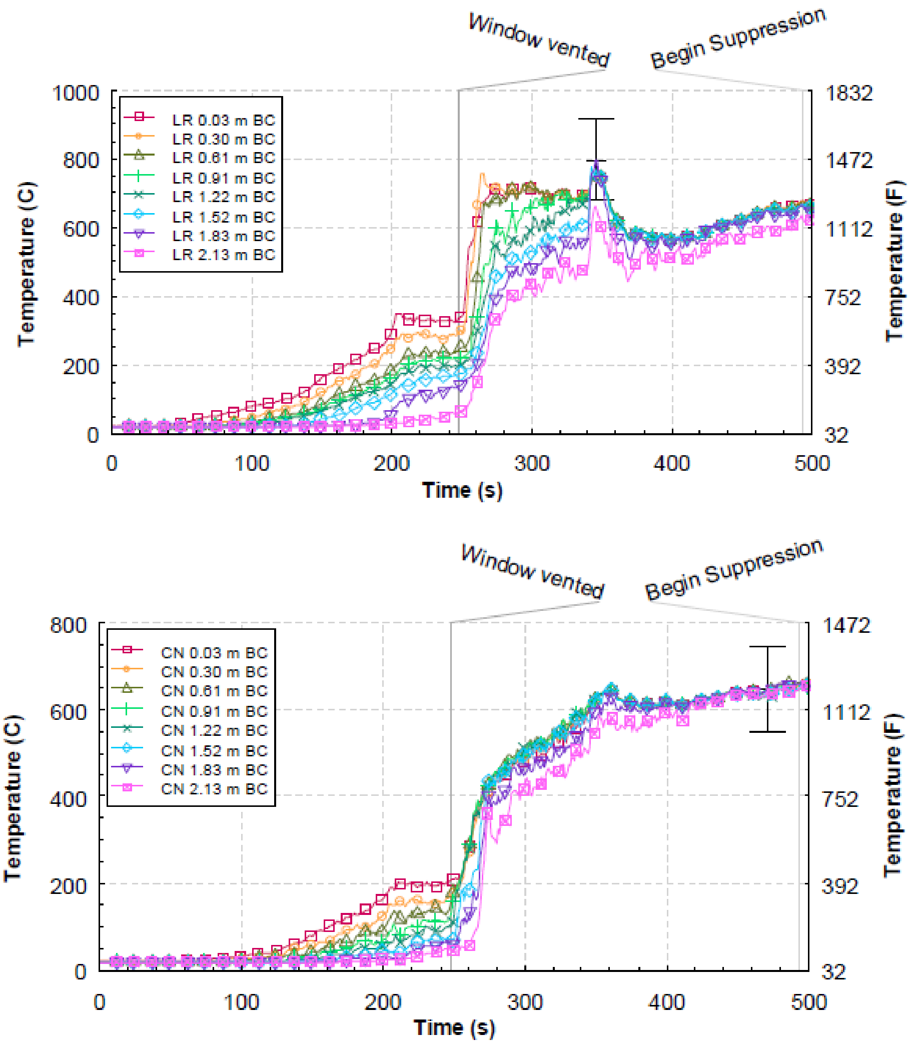


Figure 2.3: Residential apartment experiment temperature plots for the living room, and corridor north position. BC in the legend stands for Below Ceiling.

elevations in the room did not converge as well as in the other two spaces, which is consistent with a pre-flashover condition. Prior to the window being vented, peak temperatures near the ceiling were approximately 350 °C (660 °F). From a position of 0.9 m (3 ft) above the floor, the peak temperatures were about 170 °C (340 °F). After the window was vented, the temperatures in the center of the living room increased to approximately 700 °C (1,300 °F) near the ceiling and approximately 450 °C (850 °F) 0.3 m (1 ft) above the floor. As the door to the closed room located adjacent to the hallway burned away, oxygen flowed out of that room and burned, causing a sharp increase in the temperatures in the living room. This resulted in a well mixed thermal layer from the ceiling down to the floor with temperatures of approximately 600 °C (1,112 °F) or higher.

Before the window was vented, the peak temperatures in the north portion of the corridor ranged from approximately 200 °C (400 °F) near the ceiling to less than 100 °C (200 °F) at heights of 0.9 m (3 ft) above the floor and below. With 30 seconds after the window was vented, the temperatures had increased to more than 400 °C (750 °F) from the ceiling down to the floor level. As the fire continued to burn, the uniform temperature in the corridor exceeded 600 °C (1,100 °F), temperatures consistent with a post-flashover fire environment.

The heat flux gauges were installed at five different locations in the experimental structure, as shown in Figure 2.1. The gauges were positioned in the center of the south wall of the bedroom and the living room, and at the three positions (north, center, and south) along the east wall of the corridor. All of the heat flux gauges were installed 0.9 m (3 ft) above the floor, a position chosen to be representative of the height of a crawling firefighter's head. The time history from all five heat flux gauges is given in Figure 2.4. The heat flux in the bedroom increased to almost 30 kW/m^2 prior to the window failure. After the window vented, the heat flux measurement in the bedroom doubled within 30 seconds. The measured heat fluxes in the hall, living room, the center position of the corridor and the north position of the corridor increased in a similar manner and reached approximately 30 kW/m^2 less than 60 seconds after the window was vented. The heat flux measurement in the south corridor position was not in the flow path and remained at a lower values throughout the test. This is consistent with the temperature measurements from the same position.

A key reason why this specific experiment was chosen out of the many of fire studies that NIST has conducted was to show the velocities that accompanied the thermal changes that were generated by the change in ventilating the fire room. The velocities presented in Figure 2.5 were measured in the hallway in the exhaust portion of the flow path between the fire room and the open doorway in the living room leading to the corridor, and in the north position in the corridor in the exhaust flow path between the open doorway from the living room and the open ceiling vent at the end of the corridor. Prior to the change in ventilation and flashover in the bedroom, the peak velocity in the hallway was approximately 3 m/s (7 mph) in the ceiling jet at a position 0.3 m (1 ft) below the ceiling, flowing from the bedroom to the living room. At locations 1.2 m (4 ft) and 0.3 m (1 ft) above the floor, the velocities were less than 1 m/s (2 mph) flowing in the direction from the living room to the bedroom.

Pre-flashover, the hallway served as a component of a bi-directional flow path with exhaust leaving the bedroom and cooler air entering the bedroom. Once the ventilation changed due to the glass being removed from the window, the post-flashover flow in the hallway became a uni-directional exhaust flow of hot fire gases. The peak post-flashover hallway velocity of 6 m/s (13 mph) occurred at 1.2 m (4 ft) above the floor. The post-flashover velocities at the measurement positions near the ceiling and the floor were similar to each other, averaging approximately 4 m/s (9 mph). These velocities coincided with hallway temperatures in excess of 600 °C (1,100 °F).

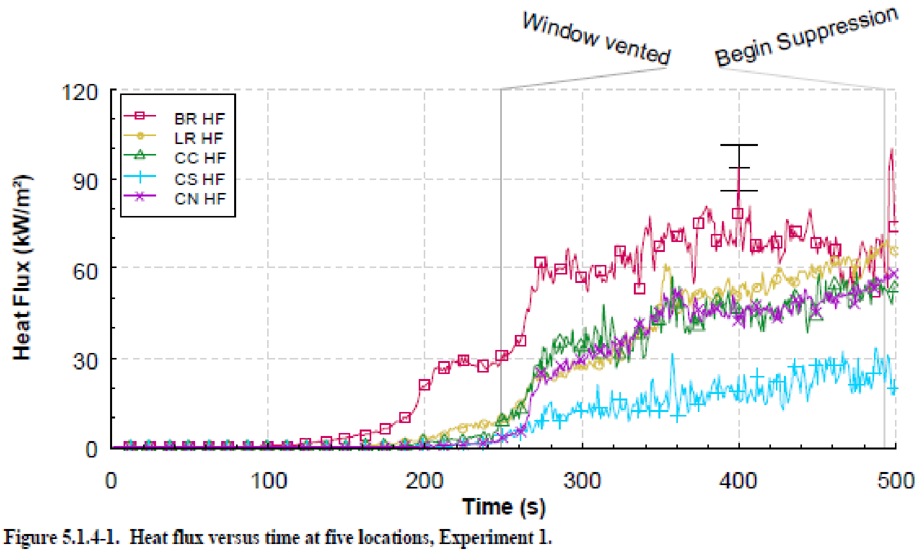


Figure 2.4: Residential apartment experiment heat flux plots, with heat flux measurements located 0.9 m (3 ft) above the floor along the apartment flow path.

The velocities at the north corridor array position are also shown in Figure 2.5. At this position, the positive direction is flow along the flow path from the bedroom to toward the north corridor vent. Prior to window failure, the ceiling jet/hot gas layer velocities reached a peak of approximately 0.6 m/s (1.4 mph) at 0.3 m (1 ft) below the ceiling. After the window vented, the velocities increased to a peak of approximately 4 m/s (9 mph) prior to suppression, at 1.22 m (4.0 ft) below the ceiling. Because the north corridor measurement position was in the direct flow path between the living room and the ceiling vent in the northwest section of the corridor, the peak velocities were approximately four times higher than the velocities at the south corridor position because the south corridor position was not in the flow path. In other words, the south position had a lower thermal exposure because it was not located between the fire and an exhaust vent. The post-flashover velocities measured at the bi-directional probes at 0.3 m (1.0 ft) below the ceiling and 2.13 m (7.0 ft) below the ceiling leveled off around 3.0 m/s (6.7 mph). These were uni-direction exhaust gas flows.

Figure 2.6 shows infrared images from a thermal imager of the flow of heat moving out of the living room doorway and into the corridor before and after the bedroom window was vented. Prior to the window being vented, the operating conditions in the corridor below the hot gas layer were less then 100 °C (200 °F) at heights of 0.9 m (3 ft) above the floor and with a heat flux of less than 5 kW/m^2 and a velocity of less than 0.5 m/s (1.0 mph). After the window was vented, the thermal exposure due to the hot gas flow increased to more than 600 °C (1,100 °F) with a heat flux of 30 kW/m^2 and velocities on the order of 3.0 m/s (6.7 mph).

Although this experiment did not demonstrate a range of temperatures or heat fluxes that were different from previous compartment fires, the documentation of the rapid change in fire conditions remote from the fire compartment based on the opening of a vent was new. Firefighters must be aware of the flow of the fire gases downstream of the fire and understand the increased velocity

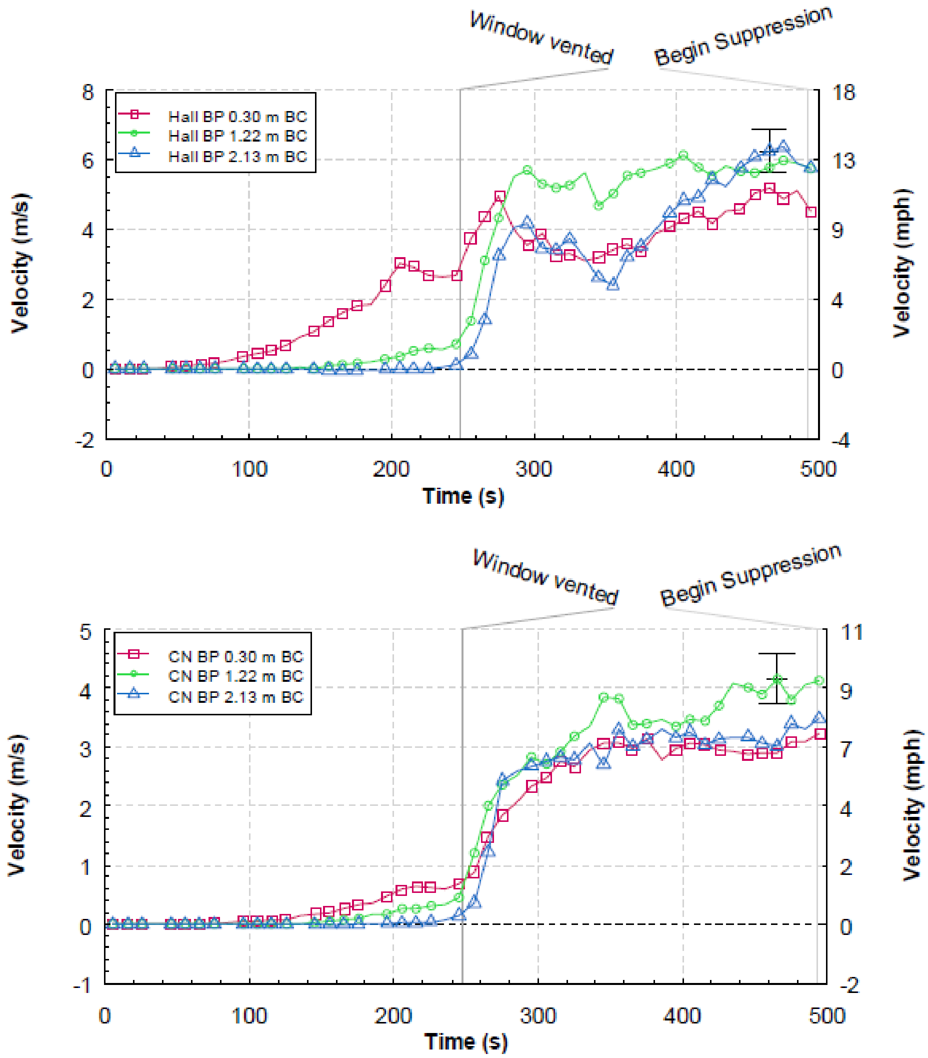


Figure 2.5: Residential apartment experiment gas velocity plots. The upper graph shows the gas velocity profile in the hallway between the bedroom and the living room, and lower graph shows the gas velocity profile in the corridor between the open apartment doorway and the ceiling vent.

and turbulence of the exhaust gases reduce the safe operational time.

Open Office

The experiment was conducted in a large compartment 7.0 m (23 ft) wide by 7.3 m (24 ft) deep enclosure with ceiling height of 3.4 m (11.2 ft). The compartment was enclosed with three walls, a ceiling, and a floor. The west side of the compartment remained open to simulate the compartment being open to a larger area. A suspended ceiling assembly was installed at 2.7 m (8.8 ft) above the floor. Four office workstations, each furnished with a desk, two office chairs, a computer, paper products, and waste containers were installed in the compartment. A heptane fueled pan burner was positioned between the east wall of the compartment and the workstations. The burner generated a heat release rate of 2 MW to simulate a fire from an adjacent room that was flashed over. This experiment was conducted as part of an investigation into the Cook County Administration Building fire [20]. The fuel load consisted of office furnishings similar to those that burned in the actual fire event. Figure 2.7 shows a plan view of the instrumented floorplan of the fire compartment.

Four thermocouple arrays were installed in the enclosure. Each array was located 2.44 m (4 ft) away from adjacent walls, as shown in Figure 2.7. Each array had thermocouples in contact with the ceiling tile, and 0.15 m (0.5 ft), 0.305 m (1 ft), 0.610 m (2 ft), 0.914 m (3 ft), 1.22 m (4 ft), 1.52 m (5 ft), 1.83 m (6 ft), 2.13 m (7 ft) and 2.44 m (8 ft) below the ceiling. The thermocouples were 0.51 mm (0.02 in) nominal diameter bare bead, Type K thermocouples.

Four heat flux gauges were installed in the enclosure on the north side of the workstations. The heat flux gauges were installed in pairs, with one heat flux gauge of each pair faced towards the ceiling and the other faced south at a workstation. The heat flux gauges were positioned approximately 1 m (3.3 ft) north of the northern edge of the workstations and 1 m (3.3 ft) above the floor. The heat flux gauges were centered on each of the northern workstations in the east-west plane. The heat flux gauges were water-cooled Gardon-type transducers. This arrangement provided a sense of the source of heat flux hitting the sensors, either from the hot gas layer or from the burning furnishings.

Figure 2.8 presents the temperature time histories from the vertical thermocouple arrays at the northeast (NE) and northwest (NW) positions, and the heat flux time histories at corresponding positions appear beneath them. The northwest positions are closer to the open wall of the compartment.

For the first 60 s after ignition, the majority of the heat release was provided by the heptane burner. As the furnishings began to burn, the heat release rate increased and reached a peak of approximately 17 MW. The ceiling tiles began to fall approximately 270 s after ignition, culminating in a partial collapse of the ceiling grid in the southwest corner of the enclosure approximately 305 s after ignition. This caused a significant reduction in the heat release rate because the ceiling tiles smothered some of the fire. The fallen ceiling tiles also began to burn and the heat release rate of the fire rebounded to reach approximately 19 MW before being suppressed.

The northeast thermocouple array was located closer to the heptane burner, hence the temperatures near the ceiling are higher. The hot gas layer thickness was similar to that of the northwest thermocouple array. The layer was less than 0.6 m (2 ft) until 100 s after ignition, and then the layer began to thicken. The temperatures continued to increase and the layer continued to thicken. By 220 s after ignition, the layer had dropped to 0.9 m (3 ft) below the ceiling. At approximately 270 s after ignition, the temperatures in the lower half of the room began to increase. This is

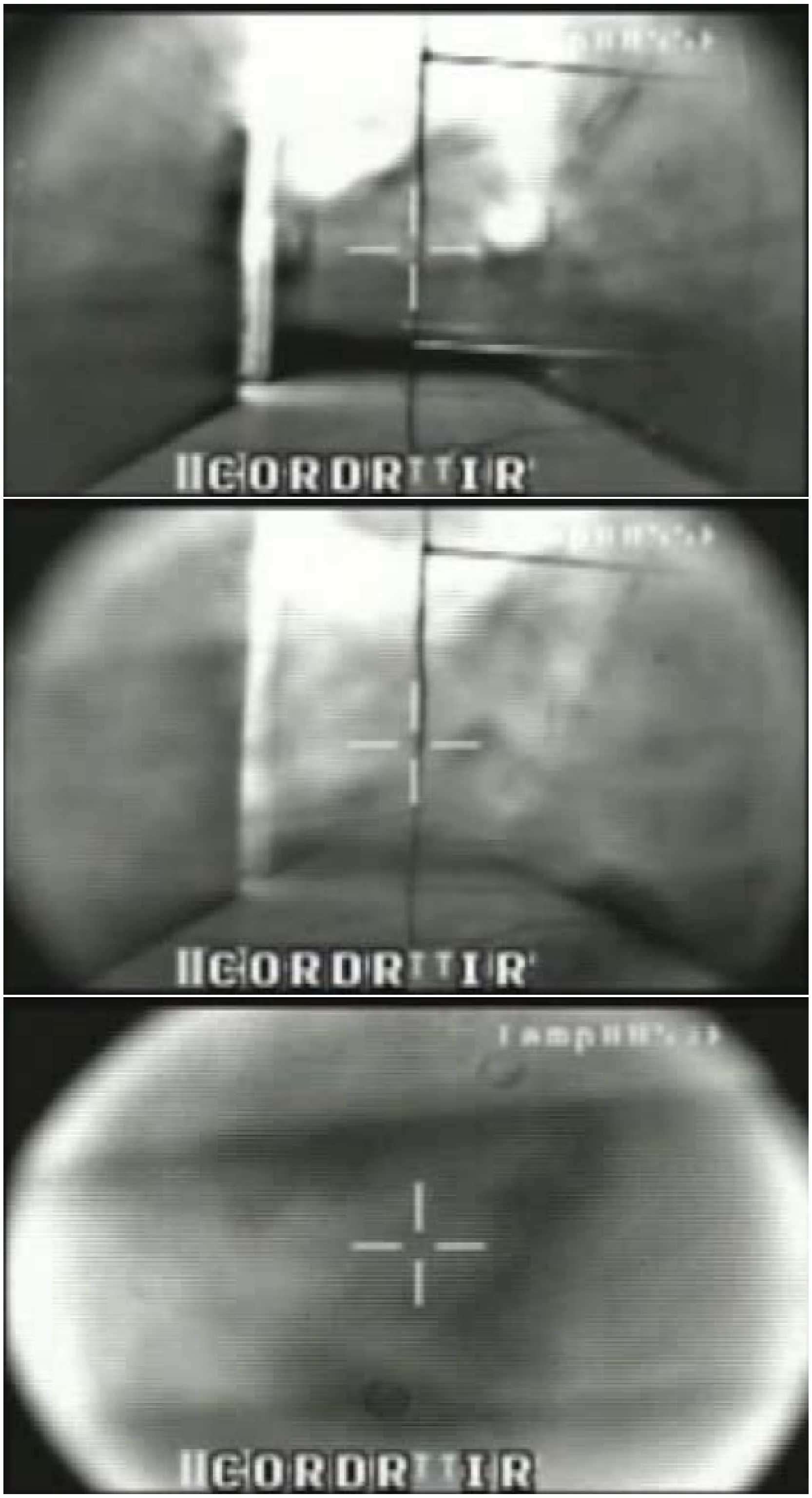


Figure 2.6: Residential apartment experiment hot gas flows into the corridor. The images show how the flow changed before the window was vented, just after the bedroom window was vented and 40 s after the window was vented.

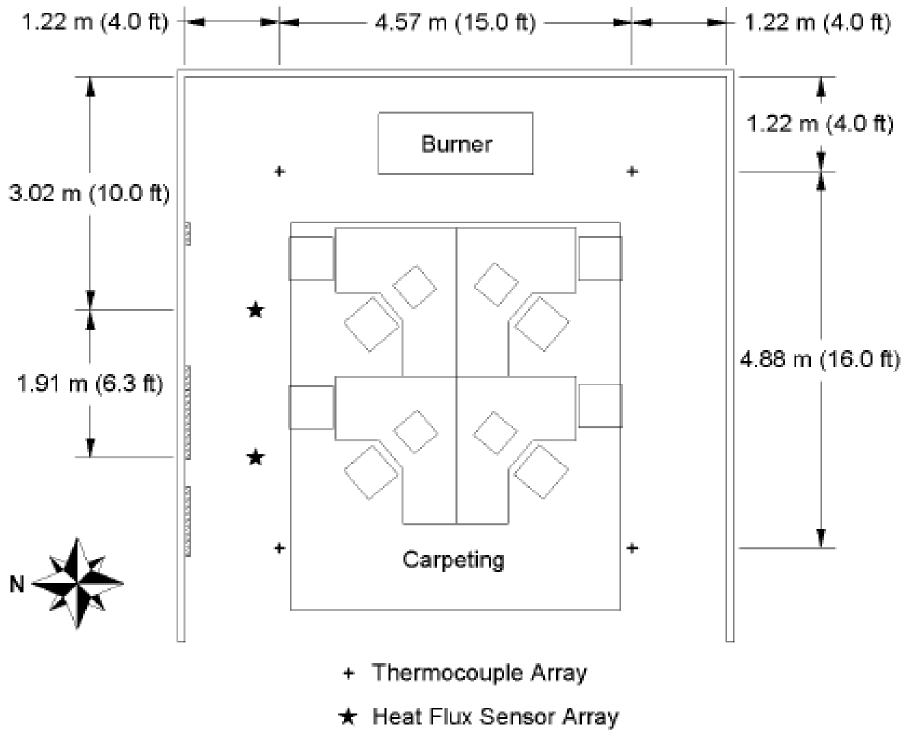


Figure 2.7: Open office plan arrangement and instrument locations.

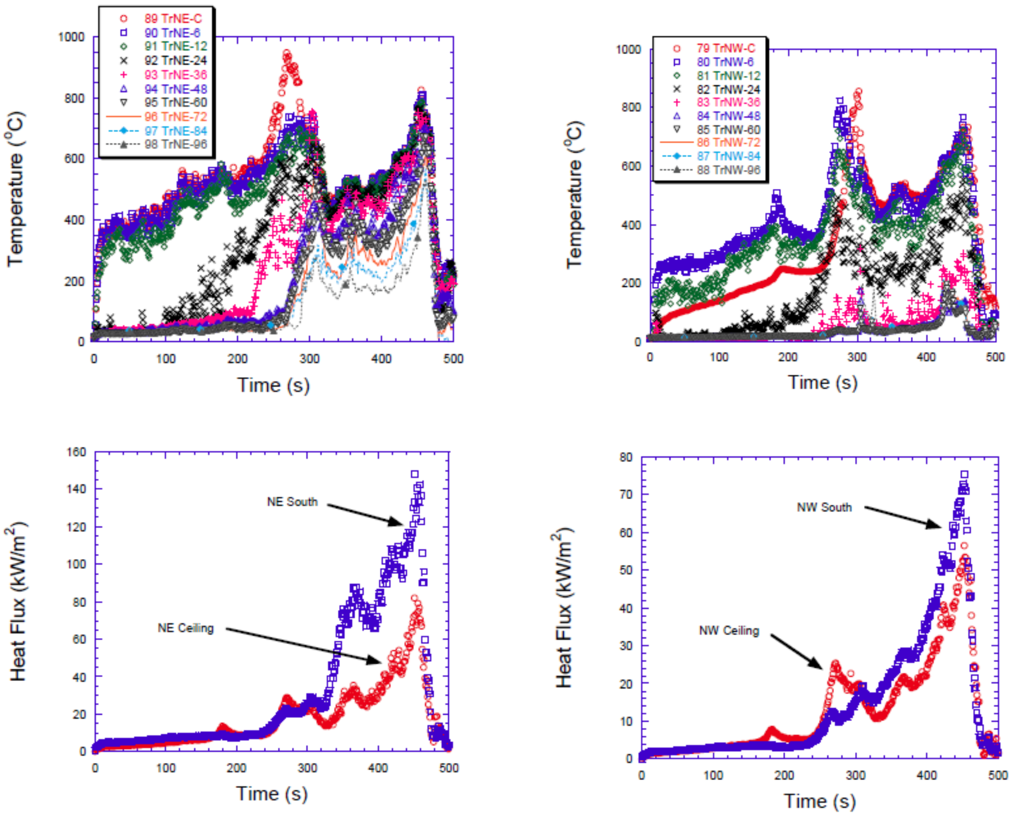


Figure 2.8: Open office temperature and heat flux plots. Temperature time histories from the vertical thermocouple arrays at northeast (NE) and northwest (NW) positions appear in the top row, with the heat flux time histories at corresponding positions beneath them in the bottom row. The NW positions are closer to the open wall of the compartment.

consistent with a well-mixed area of hot gas that could signify a flashover. However, due to the ceiling collapse, the nature of the fire changed and all of the temperatures cooled somewhat until approximately 450 s after ignition, when temperatures 1.83 m (6 ft) below the ceiling exceeded 600 °C (1,100 °F).

The northwest thermocouple array was located closer to the opening on the west side of the compartment. Here the temperatures show a steady ceiling jet of hot gas that is less that 0.6 m (2 ft) thick for the first 100 s. The smoke layer began to thicken as the temperatures 0.6 m (2 ft) below the ceiling increased. The sharp increase in temperature occurred at approximately 260 s, with the temperature near the ceiling representing flame impingement. Based on the data, it appeared that the thermocouples 0.92 m (3 ft) below the ceiling and lower were never fully enveloped by the hot gas layer. The temperatures near the floor increased when low level burning occurred with radiation heating of the thermocouple possibly affecting the temperature readings, too.

The northwest set of gauges was positioned farther away from the heptane burner and the areas of the most intense burning. Hence the peak heat flux values were approximately half of those from the northeast position heat flux gauges. Both graphs show the heat flux measured by the gauges that faced the workstations surpassed the heat flux values from the gauges that faced the ceiling once the workstations were fully involved with fire.

Of interest here is comparing the temperatures from the northwest thermocouple array positioned within 1.2 m (4 ft) above the floor, prior to the collapse of the ceiling at 305 s. The temperatures remained under 100 °C (212 °F) while the heat flux from the hot gas layer measured at 1 m (3.3 ft) above the floor exceeded 20 kW/m^2. The temperatures closer to the floor and closer to the open wall remained cooler as a result of fresh air being entrained to the fire deeper in the compartment. This is an example of a scenario in which the firefighter's exposure to gas temperatures (convective heat transfer) is within the normal range, while the heat flux exposure (radiant heat transfer) presents a higher level of hazard.

Public Occupancy

As part of the Station Nightclub fire investigation, two full scale experiments were conducted to examine the fire conditions in the portion of the nightclub that included the performance area and dance floor [21]. The dimensions of the test compartment were 10.8 m (35.4 ft) by 7.0 m (23 ft), and the ceiling height was 3.8 m (12.5 ft). A single opening, 0.9 m (3 ft) wide and 2.0 m (6.6 ft) high was located in the wall opposite the performance area. A plan view of the instrumented compartment is shown in Figure 2.9.

The fuels in the test compartment were limited to wall linings and carpeting in the performance area. The walls of the alcove and the raised floor area were covered with 5.2 mm thick plywood paneling. The plywood paneling extended 3.6 m (12 ft) from the raised floor along the rear wall of the test area. The rear wall was adjacent to the platform on the right as one stands on the platform facing the audience (stage-right). A non-fire retarded, ether-based, polyurethane foam was glued over the paneling in the alcove and along the walls on both sides of the alcove opening, and covered 2.4 m (8 ft) along the rear wall. The foam was also installed on the ceiling of the alcove.

For this review, the focus is on the data from the non-sprinklered experiment, specifically on the thermal conditions in the area of the main floor at the two thermocouple arrays at positions C and D. The thermocouples were located at elevations of 0.025 m (1 in), 0.30 m (1 ft), 0.61 m (2 ft), 0.91 m (3 ft), 1.22 m (4 ft), 1.52 m (5 ft), 1.83 m (6 ft), 2.13 m (7 ft), 2.44 m (8 ft), 2.74 m (9 ft),

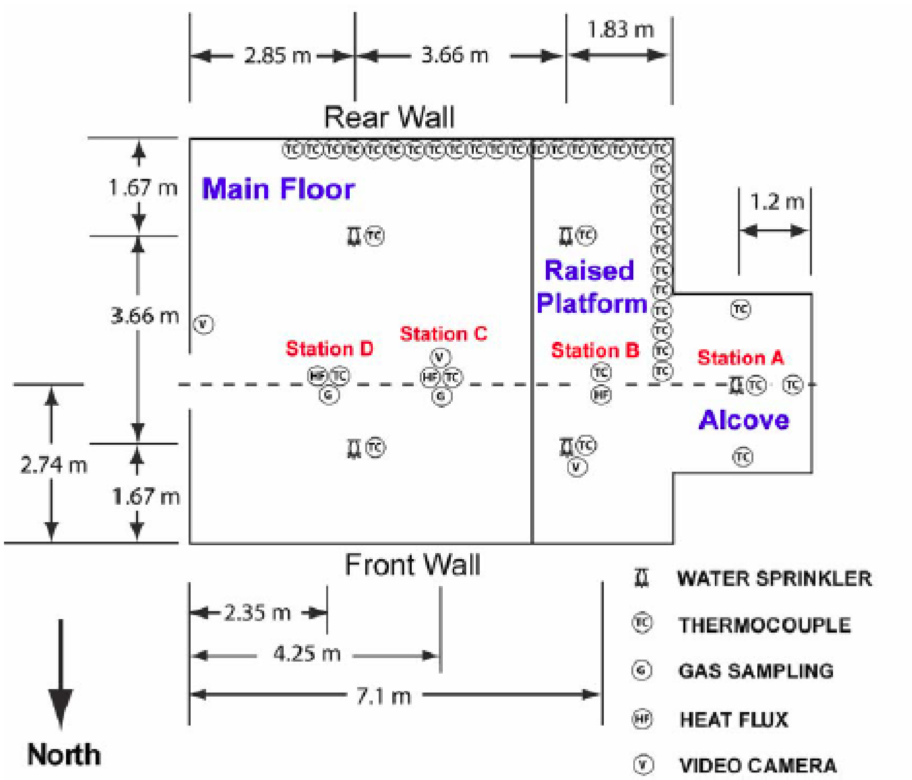


Figure 2.9: Public assembly occupancy plan view and instrumentation locations.

3.05 m (10 ft), 3.35 m (11 ft), and 3.66 m (12 ft) below the ceiling. The thermocouples were bare bead, Type K.

Three heat flux gauges were installed at positions C and D. One heat flux gauge was mounted on the ceiling looking toward the fire origin on the front corners of the alcove. Two additional total heat flux gauges were installed 1.5 m (5 ft) above the floor, or 2.3 m (7.5 ft) below the ceiling. One total heat flux gauge was installed to have an upward view of the hot gas layer, while the other gauge was aimed toward the alcove. The heat flux sensors were water-cooled Schmidt Boelter type transducers.

The temperature and heat flux time histories from positions C and D are shown in Figure 2.10. The thermocouple array at location C was installed 6.7 m (22 ft) away from the foam-covered back wall of the alcove. Within 70 s after ignition, peak temperatures of 800 °C (1,470 °F) were reached at the ceiling. The temperatures at 3.6 m (11.8 ft) below the ceiling did not begin to increase until 60 s after ignition. This was an indication of the time it took the lower interface of the hot gas layer to descend within 0.2 m (0.7 ft) above the floor. As the fire became ventilation limited, the temperatures reached steady values of approximately 100 °C (200 °F). The thermocouple location shown on the graph closest to the heat flux gauges 1.5 m (5 ft) location is 2.44 m (8 ft) below the ceiling thermocouple. At position C, this thermocouple measured approximately 350 °C (660 °F) during the post oxygen decay, steady ventilation limited period which began at approximately 120 s.

The thermocouple array at location D was installed 8.5 m (28 ft) from the foam-covered back wall of the alcove, an additional 1.8 m (6 ft) further away from the back wall of the alcove than the thermocouples at position C. Approximately 80 s after ignition, peak temperatures of 700 °C (1,300 °F) were recorded. The temperatures at 2.44 m (8 ft) below the ceiling did not begin to increase until approximately 70 s after ignition and reached a post oxygen decay stage steady value of approximately 350 °C (660 °F). These values where similar the values recorded in the same location at position C. Comparing the graphs provides the sense that the hot gas layer was stratified uniformly between the two positions.

Near the end of the fire's growth stage, the peak heat fluxes measured 1.5 m (5 ft) above the floor exceeded 50 kW/m^2 and 40 kW/m^2 at positions C and D, respectively. The total heat flux values during the ventilation limited period oscillated between 15 and 30 kW/m^2 at position C, and between 15 and 25 kW/m^2 at position D.

This experiment provided an example of a large compartment that underwent a rapid fire growth and then transitioned to a decay stage as a result of limited ventilation reducing the oxygen supply. The hot gas layer expanded from the ceiling to within a 0.61 m (2 ft) of the floor. Temperature and heat flux comparisons were only available at a level of 1.5 m (5 ft) above the floor. In this scenario, both the gas temperature and the heat flux exposure would present a high level of hazard to a firefighter.

2.1.2 Firefighter Protective Equipment Development

In 2006, NIST published the report "Thermal Environment for Electronic Equipment Used by Fire Responders", also known as NIST TN 1474 [22]. This report served as a starting point for this portion of the literature review, because NIST had examined studies from the 1970s through 2003. One objective of the report was to provide information to support thermal test criteria that could be used by the NFPA Technical Committee on Electronic Safety Equipment for Emergency Services.

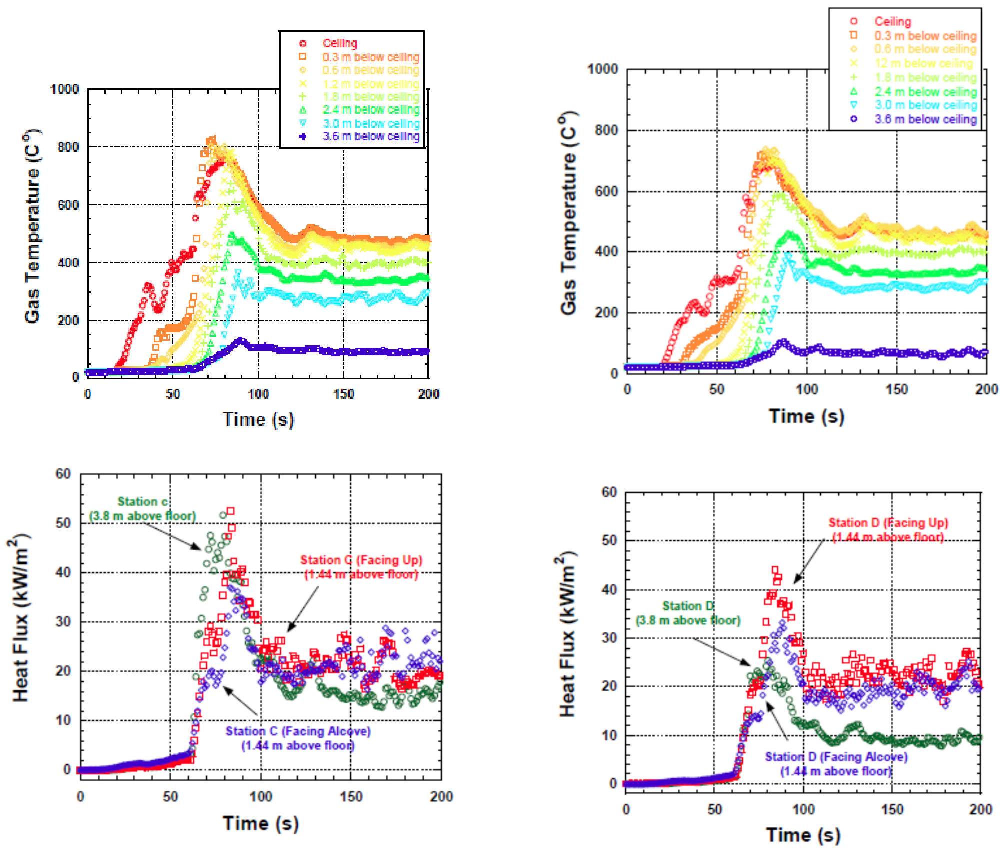


Figure 2.10: Public assembly occupancy temperature and heat flux plots. Temperature time histories from the vertical thermocouple arrays at positions C and D are presented in the top row, with the heat flux time histories at corresponding positions beneath them in the bottom row.

Thermal Class	Maximum Time (min)	Maximum Temperature (°C)/(°F)	Maximum Flux (kW/m^2)
I	25	100/212	1
II	15	160/320	2
III	5	260/500	10
IV	<1	>260/500	>10

Table 2.3: Recommendations for thermal classes for electronic safety equipment from NIST TN 1474 [22].

NIST TN 1474 included a review of six different efforts conducted to determine thermal categories that would be representative of different conditions on the fire ground. Some of the efforts had developed four categories and some other organizations had developed three categories. The dates of the final reports from the six efforts ranged from 1976 to 1995. It was noted that, "The researchers did not always specify what data were used to make their determinations." NIST synthesized the data from the six efforts, with selected NIST experimental data published from 1972 to 2003. In addition, a comparison was made with existing NFPA thermal test criteria for protective clothing, self-contained breathing apparatus, and PASS devices. The most current standard at the time of the study was 2002. The result of the NIST work was a recommendation for four thermal classes for electronic safety equipment as defined in Table 2.3. The NIST report also pointed out there may be conditions in which the temperature and heat flux ranges from different thermal classes may exist at the same time on the fire ground.

Project FIRES

One of the research programs examined in NIST TN 1474 was Project FIRES. FIRES was an acronym for Firefighters Integrated Response Equipment System. The overall objective of the project was to develop a protective ensemble for structural firefighters. In order to achieve this goal, the project needed to develop performance requirements and potential test methods for the prototype gear. Thermal performance was one of the key criteria. The thermal performance criteria used in Project FIRES are summarized in Table 2.4. These criteria were adopted by the NFPA and have been published and explained in the NFPA Fire Protection Handbook [23]. Class I was considered to be the thermal exposure a firefighter might receive during mop-up. Class II represented a small fire burning in a room. Class III is explained as a fire in a room in which more of the contents are involved in the fire. Finally, Class IV is a condition involving the ignition of the fire gases in the hot gas layer, flashover, or backdraft in a room or enclosed area. The chapter makes clear these thermal classifications do not cover all situations that may occur in structural firefighting, and that preheating of PPE will result in a reduction of the safe exposure time for a given thermal classification.

The source of data for Project FIRES came from two reports: "A Firefighter's Integrated Life Protection System" [25], and "Thermal Environment During Structural Firefighting" [26]. Both of these reports involved instrumenting firefighters and monitoring their working environment.

"A Firefighter's Integrated Life Protection System" was funded by FDNY and conducted by

Class	Air Temp °C	Radiant Flux, Watts/cm^2	Exposure Time
1	40 (104°F)	.050	30 MIN
2	95 (203°F)	.100	15 MIN
3	250 (482°F)	.175	5 MIN
4	815 (1500°F)	4.2	10 SEC

Table 2.4: Thermal classes for structural firefighting PPE [24]. In terms of kW/m^2, the classes range from 0.5 to 42. The radiant heat flux from the sun on a clear day (no clouds) is approximately 1.0 kW/m^2. This covers the radiant exposures to Classes 1 and 2. Class 3 has an upper limit of 1.75 kW/m^2 for 5 min. Class 4 was defined by the Harvard Study as 42 kW/m^2 for 10 s.

Grumman Aerospace Corporation. The thermal environment results were based on 63 exposures measured during 15 different fire events that occurred between August 1973 and January 1974. Seventeen of the exposures were measured during three fires set in a training building at the FDNY Welfare Island training school. Efforts were made to measure the temperature near the face height of the firefighter. Heat flux was measured with a sensor installed in the firefighters helmet. Although the firefighters carrying the instrumentation had SCBAs, it seems the firefighters fighting the fire did not.

The thermocouple was attached to an atmospheric sampling wand. The firefighter with the instrumentation would extend the "wand into the area a fireman was working, generally at the firefighters face level. Therefore, the samples were true measurements of the atmosphere that the firemen breathe in the course of their work" [25]. The air temperatures from the actual fire events typically ranged from 38 °C (100 °F) to 66 °C (150 °F). In one case, close to a fire set on Welfare Island, a maximum temperature exposure of 232 °C (450 °F) was measured. The exposure time was brief. Peak temperature exposures at the training school tended to be higher. Heat flux exposures were in the range of 0.32 kW/m^2 to 1.3 kW/m^2. These heat flux exposures occurred over periods of 7 to 10 minutes. The report noted that, "The fires observed during this program did not necessarily represent those involving extreme heat intensities" [25]. It is important to note that when these exposures were measured, the New York firefighters protective ensemble consisted of a leather helmet, a 3/4 length rubber coat with wool lining, work gloves, and rubber boots.

The study, "Thermal Environment During Structural Firefighting" was a joint venture between the Boston Fire Department and the Harvard School of Public Health [26]. The data was collected from 134 fire responses by members of Boston Fire Department's Rescue 1 and Rescue 2 companies that had volunteered to wear and operate instrumented turnout gear with them on structure fire calls. Volunteers were asked to only wear the instrumented gear to those fire incidents where significant heat was anticipated. Each volunteer was asked to log the approximate sequence of the exposure duration and was asked to rate the severity of the heat exposure based on a 1 to 10 scale with 10 being "nearly unbearable".

In order to maintain the firefighters' interest in the study, feedback was provided to them via a poster in the fire house showing the results of each thermal exposure. An example is shown

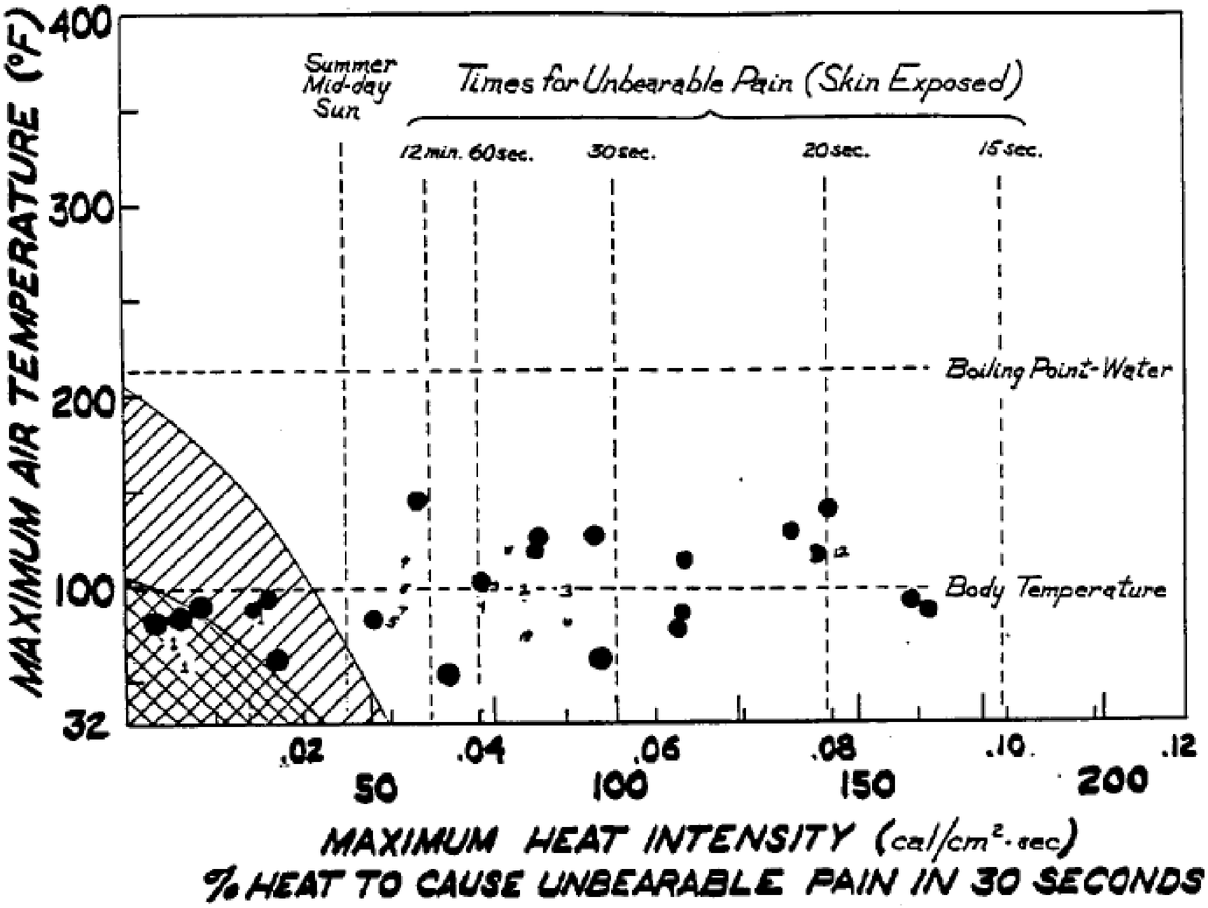


Figure 2.11: Wall chart for firefighter feedback on the thermal environment of firefighters [26].

in Figure 2.11. The poster also provided estimated tolerance times for "men working at various exposures without protective clothing".

The findings from the Boston Fire Department - Harvard Study were based on the data collected from the instrumented gear, and then frequency distributions of the results were developed from the data set. The median maximum temperature was found to be 33 °C (92 °F). It was determined that firefighters would be exposed to maximum temperatures in excess of 80 °C (176 °F) in only 1% of house fires. In terms of peak total heat flux, 5 kW/m^2 would be expected in approximately 10% of all structure fires. The highest level of heat flux observed in all of the incidents was 8.1 kW/m^2 [26]. Based on the radiant heat flux values observed, it was recommended that protective clothing be designed to withstand 10 kW/m^2 for up to 1 minute without damage to the gear [26]. It is important to note that when these exposures were measured, the Boston firefighters protective ensemble consisted of a leather helmet, a 3/4 length rubber coat with wool lining, work gloves, and rubber boots.

These data sets from Project FIRES provided information for the performance criteria and test methods of NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting [27].

NIST PPE Studies

As the NFPA standards developed, the thermal protective performance (TPP) test was adopted to provide a measure of the value of the material to protect firefighters from heat. The TPP test replaced the requirement for a minimum turnout gear thickness. The TPP test exposes a sample of turnout gear to a heat flux of 84 kW/m^2. The heat flux is generated by both convective and radiant sources. Each source provides 42 kW/m^2 of heat flux [27].

A study was conducted by a team led by Krasny at NBS to compare turnout gear exposures from a variety of room fire conditions to the theoretical level of protection provided by the TPP test [28]. The study indicated the TPP test provided a number of advantages over the thickness requirement. The room fire results showed post-flashover heat fluxes of as high as 170 kW/m^2 were measured. This would imply that firefighters would have 10 s or less to escape under most flashover conditions.

The study offered observations on factors other than heat conditions after flashover affecting the protective performance of turn out garments. Lengthy exposure to less than 20 kW/m^2 caused the inside of the gear to get hot before flashover. This situation also occurred even without flashover. Heat stored in the gear would continue to be delivered to the firefighter even after escape, unless the gear could be removed immediately. The presence of moisture in the gear could adversely affect protection because of the lower insulation value of wet rather than dry materials and possible steam formation [28].

The NIST team followed up with a study in which various types of turnout gear samples with TPPs ranging from 33 to 53 were exposed to fire conditions ranging from a steady state 300 kW gas burner to a furnished room fire that transitioned through flashover [29]. The rooms were 2.4 m (8 ft) wide by 3.6 m (12 ft) deep and 2.4 m (8 ft) high. The study showed the TPP rating provided a ranking consistent with the results of the furnished room fires that grew rapidly. Figure 2.12 shows the estimated time to pain and to 2nd degree burn injury for different turnout coat specimens exposed to six different room fire scenarios. The time between the onset of pain and the onset of the second degree burn is considered the time available for escape. The chart also shows the estimated times for unprotected skin, this condition is labeled "no specimen". The turnout gear offered the least amount of escape time when exposed to larger HRR and growing fires generated by the fires with upholstered furnishings.

NIST also conducted full-scale compartment fire experiments to evaluate the thermal behavior of firefighting turnout gear samples with phase change material (PCM) added, in a realistic fire fighting environment [30]. For the purposes of this review, the focus is on the structural firefighting protective clothing material without the PCM modifications. The fire compartment was 2.65 m (8.7 ft) wide, 3.86 m (12.6 ft) long and 2.63 m (8.63 ft) high. On the front wall of the compartment was an open doorway that measured 0.88 m (2.89 ft) wide by 2.02 m (6.63 ft) tall and a single double-pane window on the east wall that measured 0.46 m (1.5 ft) wide by 0.76 m (2.5 ft) tall. For the results shown here, the doorway was open and the lower half of the window was open at the time of ignition. The room was lined with gypsum wallboard, with foam padding and carpeting on the floor. Two upholstered chairs with polyurethane foam cushions were placed along the back wall of the compartment in opposite corners. The chair placed opposite the gear samples was the site of fire origin. The gear samples were installed on the front wall with the thermocouple and heat flux sensors positioned approximately 0.91 m (3 ft) above the floor. The chair was ignited and allowed to burn until the room transitioned through flashover.

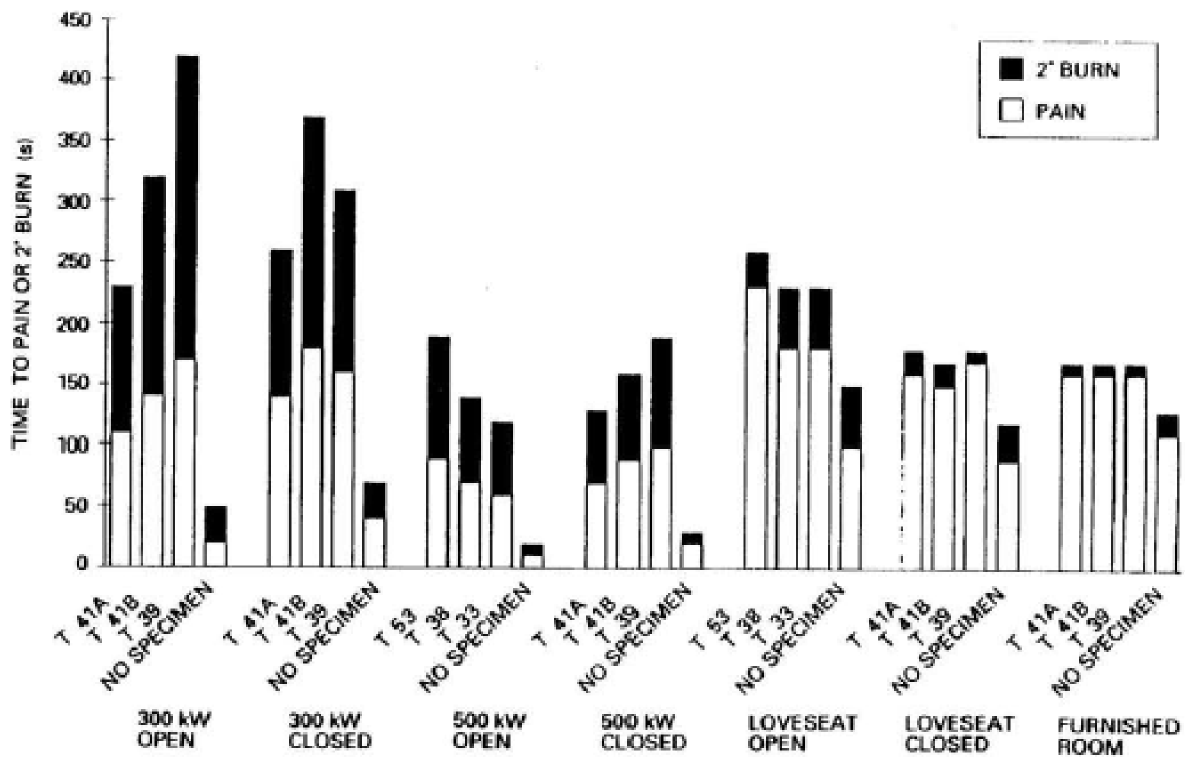


Figure 2.12: Estimated time to pain and 2nd degree burn injury for different turnout coat specimens exposed to six different room fire scenarios. The time between the onset of pain and the onset of the 2nd degree burn is considered the time available for escape [29].

Figure 2.13 contains three sets of data for comparison. The top graph shows the gas temperatures from the ceiling to the floor in front of the turnout gear sample mounted on the wall. The middle graph displays the data from the total heat flux and radiometer installed on the wall adjacent to the gear samples. The bottom graph displays the temperatures of the outer shell and the inside liner of the gear samples.

The gas temperatures in the top graph shows the steady development of the hot gas layer and rollover at approximately 190 s, leading to flashover at approximately 220 s. After flashover, the thermal conditions transitioned from a hot layer above a cold layer to a single well-mixed zone with temperatures effectively equal at all elevations, measuring approximately 800 °C (1,472 °F) from floor to ceiling. These conditions existed until a team of firefighters suppressed the fire at approximately 270 s.

The heat fluxes in the middle graph remained below 10 kW/m^2 (maximum of Thermal Class IV) until the hot gas layer came within 0.91 m (3 ft) above the floor. After rollover began, the total heat flux increased to a peak of 74 kW/m^2±6 kW/m^2 within approximately 30 s. The peak radiative heat flux measurement was 30 kW/m^2±2.5 kW/m^2. While radiative heat flux was determined to be the key hazard to the firefighters in the 1970s based on the FDNY and BFD studies, here we see that trapped firefighters could be exposed to an environment where the convective heat flux hazard of 44 kW/m^2 is higher than the radiant heat flux hazard of 30 kW/m^2.

The bottom graph compares the outer shell temperature with the temperature measured on the inside liner for the turnout gear sample. Until approximately 160 s, the outer shell temperature rose only approximately 10 °C (18 °F). After 160 s, the hot gas layer descended to the elevation of the thermocouple on the outer shell. This increased the total heat flux incident on the shell, and the outer shell temperature began to increase. In the 30 s between rollover and flashover, the outer shell temperature increased by approximately 650 °C (1,170 °F).

The temperature increase of the inside liner was negligible prior to rollover. The inside liner temperature also increased after rollover began. The inside liner temperature increased by approximately 60 °C (110 °F) before flashover at approximately 220 s. The inside liner temperature increased by 420 °C±65°C (760 °F±110 °F) within 10 s once flashover occurred. It is likely that the turnout gear sample burned through as flashover occurred.

Comparing the gas temperature and heat flux data to the thermal class values, Thermal Class I conditions were met for the first 160 s. Once the hot gas layer got within 0.91 m (3 ft) of the floor (heat flux sensor elevation), the temperature and the heat flux levels both increased to Thermal Class III prior to the occurrence of rollover at 190 s. Within another few seconds, prior to fully developed flashover, the conditions at the sample height exceeded the Thermal Class IV maximums of 260 °C (500 °F) and 10 kW/m^2. This demonstrates how fast the thermal conditions from a fire can overcome the thermal protective capabilities of protective clothing.

When the SCBA face piece was identified as the weak link in the firefighters' protective ensemble as a result of firefighter LODD incidents and reports, the fire service, fire equipment manufacturers, and researchers came together to examine the current conditions (circa 2010) and how to improve the equipment. The report, "Emergency First Responder Respirator Thermal Characteristics: Workshop Proceedings" provided a summary of SCBA facepiece related LODD incidents, current standards, current research activities, and recommendations for future research [31].

As a follow-up to the workshop, NIST conducted a study to better understand the level of thermal performance of the SCBA facepiece lens when exposed to radiant heat fluxes of 2 kW/m^2 to 15 kW/m^2 from a natural gas-fired radiant panel with the goal of developing an improved per-

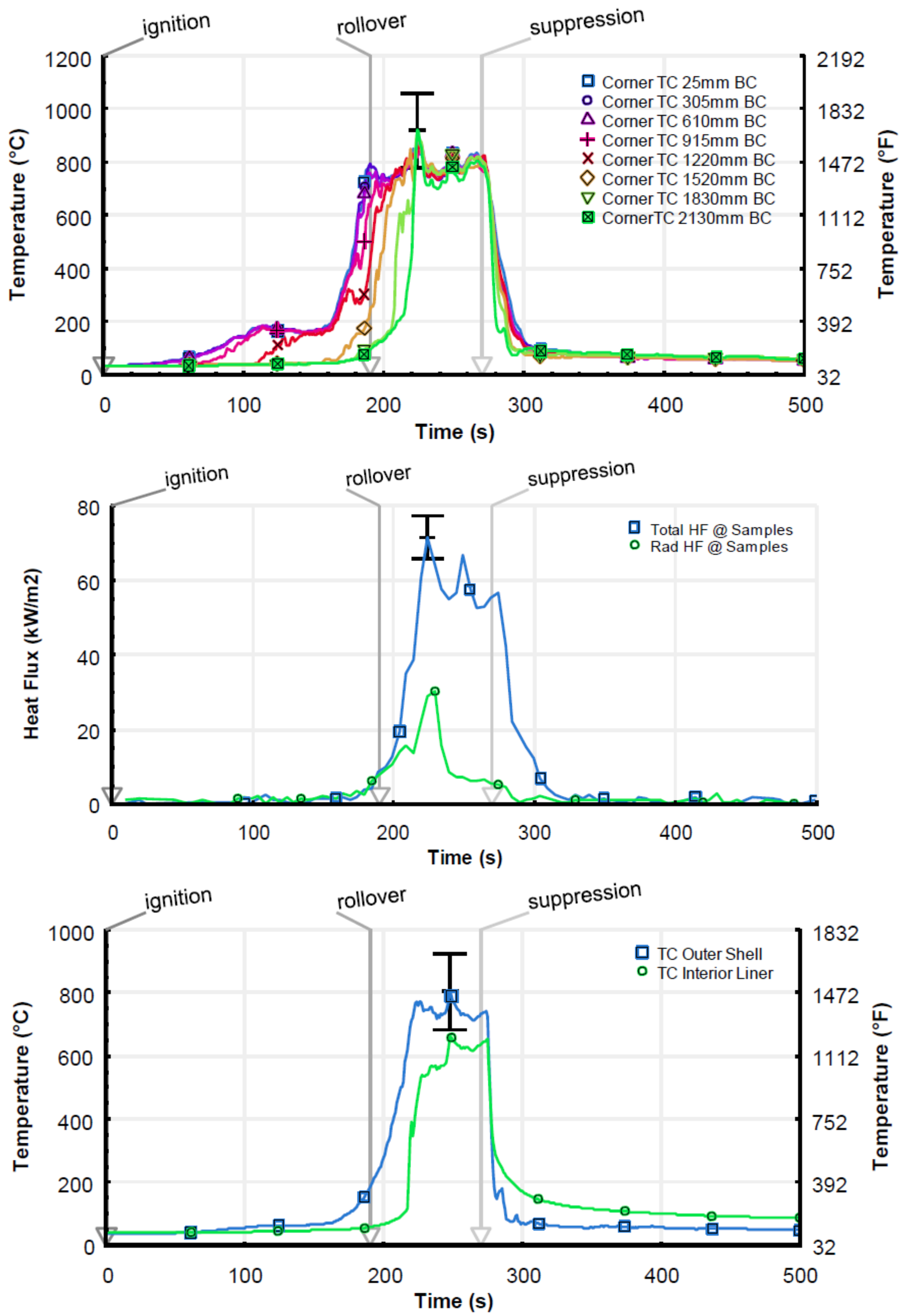


Figure 2.13: Thermal environment and turnout gear temperatures. The top graph shows the time history of the gas temperatures located in front of the turnout gear sample, the middle graph shows the time history of the total and radiative heat fluxes adjacent to the turnout gear sample, and the bottom graph shows the time history of the temperature of the outer shell and inner liner of the turnout gear. BC in the legend means below ceiling [30].

formance test method [32]. The maximum temperatures measured on the exterior of the lenses were approximately 290 °C (550 °F), while the maximum airway temperatures inside the face piece were approximately 55 °C (130 °F). Under these exposure conditions, the facepiece lenses sustained various degrees of thermal damage, ranging from no visible damage to the formation of crazing, bubbles, holes, and protuberant deformations. When exposed to 15 kW/m^2, the SCBA facepiece lenses reached the glass transition temperature of 140 °C (284 °F) in approximately 30 s and all tested SCBA lenses developed hole(s) after less than 300 s of exposure [32]. A new test method based on this research was adopted in the 2013 edition of NFPA 1981 [33].

IFSI Live-Fire Training Thermal Environment Study

It was noted in NIST TN 1474 that there may be conditions in which the temperature and heat flux ranges from different thermal classes may exist at the same time on the fire ground. This has been shown in some of the room-fire research experiments. This was recently demonstrated in a series of thermal exposure measurements conducted during 25 live-fire training evolutions at the Illinois Fire Service Institute (IFSI) [34]. The thermal exposures were examined via instrumentation installed in the training structure as well as heat flux and temperature instruments on a firefighters helmet. In the case of a "mild" training environment generated by a single wood-based fuel package in a compartment in a concrete training tower, firefighters' PPE was exposed to temperatures around 50 °C (120 °F) and heat fluxes around 1 kW/m^2. Under more severe training conditions that had multiple wood fuel packages burning in a compartment, firefighters' PPE was exposed to temperatures between 150 °C (300 °F) and 200 °C (390 °F) with heat fluxes between 3 kW/m^2 and 6 kW/m^2. In each of the training scenarios investigated, the heat flux data provided a more severe environment than the temperature data when interpreted using established thermal classes. This is evident in the temperature and heat flux exposure time in each thermal class shown in Table 2.5 and Table 2.6. The heat flux exposure times at Thermal Class III exceeded the temperature exposure times at Thermal Class III in each scenario. Time is a critical issue in determining the thermal insult to firefighting equipment and ultimately the firefighter.

2.1.3 Firefighting Tactics

Research topics covered by firefighting tactics have a broad range, but for purposes of this review the focus is on the operational environment for firefighting. Recent firefighting studies address the concepts of fuel-limited fires and ventilation-limited fires within a compartment or structure. One of the factors regarding the thermal environment firefighters may work in is time. It makes sense that the longer a firefighter is exposed to a hazard, the less time the firefighter may have to continue to operate. However, there is another time consideration: how long has the fire been burning, and what stage is the fire in?

Time to Flashover

The paper, "Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes", by Kerber, discusses many of the changes that have occurred on the fire ground [35]. These changes include home size, geometry, contents, construction materials, and

Exercise	Average ± StdDev (°C)	Maximum (°C)	NIST Thermal Class averages duration [mm:ss] (temperature ± StdDev [°C])			
			I	II	III	IV
1	119 ± 28	180	03:32 (90 ± 8)	05:41 (126 ± 19)	01:18 (167 ± 4)	00:00 (–)
2	113 ± 45	230	03:41 (68 ± 16)	03:37 (130 ± 17)	01:34 (181 ± 16)	00:00 (–)
3	115 ± 47	238	06:38 (69 ± 13)	04:36 (138 ± 17)	03:01 (180 ± 17)	00:00 (–)
4	92 ± 20	162	07:44 (84 ± 14)	02:33 (116 ± 12)	00:03 (161 ± 1)	00:00 (–)
5	59 ± 12	137	12:33 (53 ± 16)	00:14 (116 ± 11)	00:00 (–)	00:00 (–)

Table 2.5: Temperature data taken during firefighter training evolutions [34].

construction methods. As a result, the fire development in structures and the fire's response to traditional firefighting tactics has also changed.

Kerber conducted a series of compartment fire experiments to examine the difference in time to flashover between a room furnished with legacy fuels and a room furnished with modern fuels. Legacy fuels meant furnishings made from wood, steel and cotton. Modern fuels are characterized by polyurethane foam, polyester fiber and fabric, engineered wood, and plastics in many different forms. Each room was ignited by a small open flame from a candle on the sofa. The flashover times for the modern room averaged 235 s after ignition. Only two of the three legacy room fires resulted in flashover. The average flashover times for the two legacy rooms was 1,912 s after ignition. It took eight times longer for the cotton sofa to generate enough heat release rate to spread fire through out the room [35]. The driving difference in these experiments was the sofa with cushions made from polyurethane foam and polyester batting. These synthetic fuels can significantly change the thermal environment firefighters respond to. Keep in mind that the thermal environments measured with FDNY and Boston FD in the 1970s were most likely the result of burning legacy fuels.

Kerber and the UL Firefighter Safety Research Institute team began to build on this by conducting several research studies in structures built in their laboratory to resemble a single story and a two story home [36–38]. The results of the experiments demonstrated that ventilation limited fire conditions existed prior to fire department arrival and continued in the structures after venting, either horizontal or vertical, until suppression actions reduced the heat release rate of the fire. As the buildings were vented, oxygen entered the hot, fuel-rich, (ventilation limited) environment within the structure, which resulted in rapid (30 to 120 s) increases in heat and gas velocities within

Exercise	Average ± StdDev (kW/m^2)	Maximum (kW/m^2)	NIST Thermal Class averages duration [mm:ss] (heat flux ± StdDev [kW/m^2])			
			I	II	III	IV
1	2.4 ± 1.4	11.1	01:33 (0.6 ± 0.3)	02:50 (1.5 ± 0.3)	06:07 (3.2 ± 1.2)	00:01 (10.8 ± 0.3)
2	2.5 ± 1.7	10.0	00:31 (0.6 ± 0.5)	04:16 (1.5 ± 0.2)	04:05 (3.9 ± 1.6)	00:00 (–)
3	1.4 ± 1.3	12.7	05:28 (0.2 ± 0.7)	05:03 (1.5 ± 0.3)	03:43 (2.8 ± 0.9)	00:01 (12.7 ± 0.0)
4	1.0 ± 1.1	6.9	05:32 (0.2 ± 0.7)	03:10 (1.5 ± 0.3)	01:39 (2.8 ± 0.6)	00:00 (–)
5	1.0 ± 0.7	8.8	07:55 (0.5 ± 0.3)	03:43 (1.4 ± 0.3)	01:10 (2.9 ± 1.2)	00:00 (–)

Table 2.6: Heat flux data taken during firefighter training evolutions [34].

exhaust portion of the flow path. In other words, between the location of the fire and the exhaust vent. In these experiments, the temperature conditions ranged between ambient and those consistent with flames, as have been shown in previous studies. In these experiments the fire attack was started from the exterior of the structure.

UL FSRI Fire Attack Study

In 2016, another series of experiments was conducted by UL FSRI with the support of the DHS/FEMA Assistance to Firefighters Grant Research program. The goal of the study was to examine the impact of different fire attacks on a fire and in a bedroom(s), at the end of a hallway and understand the effect it would have on the fire environment and any persons in the structure [39]. Most of the experiments involved firefighters flowing water either before or shortly after they entered the structure. In three of the experiments, fires with different ventilation conditions were allowed to develop with the extinguishment portion of the experiment delayed to better understand the thermal conditions the fire would generate within the structure. The value of these experiments is that they provide temperature, heat flux, and velocity results along a hallway approximately 6 m (20 ft) long.

Figure 2.14 shows the floor plan of the test structure. The fires were either in Bedroom 1 or Bedroom 2 on the left side of the structure. The red circles indicate the measurement locations cited in Tables 2.7-2.9. Moving from the front door toward the bedrooms, the locations are start, middle, and end of hallway, respectively. This data will show the thermal conditions for firefighters if they approached the fire room and were not flowing water.

Table 2.7 provides the vertical temperature gradients along the hallway for a fire in Bedroom 1. The fire room is open to the hallway. The front door was opened approximately 8 minutes after the fire went ventilation-limited and darked down. The fire increased in heat release rate over time. The measurements provided were taken during a quasi-steady period 24 minutes after ignition. Most of the temperatures provided in the table are near the peak values for that location over the course of the experiment.

The start of hallway position is the farthest position from the fire room and the closest to the front door. The temperatures range from approximately 460 °C (860 °F) 7 ft above the floor to 40 °C (110 °F) 1 ft above the floor. The only heat flux gauge at this location is mounted in the floor and looking up to see the heat flux from above. These temperatures show just how different a firefighter's exposure would be depending on their position, such as lying on the ground, crawling, or standing. Referring back to the most recent thermal class table, the firefighter could transition through different thermal classes just by standing. Note that the heat flux on the floor would be Thermal Class II while the temperature 1 ft above the floor is Thermal Class I. Keep in mind this position is approximately 6 m (20 ft) away from the fire room.

Moving across Table 2.7 to the middle hallway position, we see the temperatures increased closer to the fire room. A crawling firefighter (3 ft above the floor) at this position would now be in a Thermal Class III condition due to temperature. Note that near the floor the 140 °C (280 °F) temperature would indicate Thermal Class II, while the heat flux would be a Thermal Class III.

The instrument position closest to the fire in Bedroom 1 is the end of hallway position. Temperatures from the ceiling down to the floor exceeded 540 °C (1,000 °F), or twice the maximum temperature allowed by Thermal Class IV. Three total heat flux gauges were installed at a position across the hall from the open door to the fire room 0.3 m (1 ft), 0.9 m (3 ft), and 1.5 m (5 ft) above

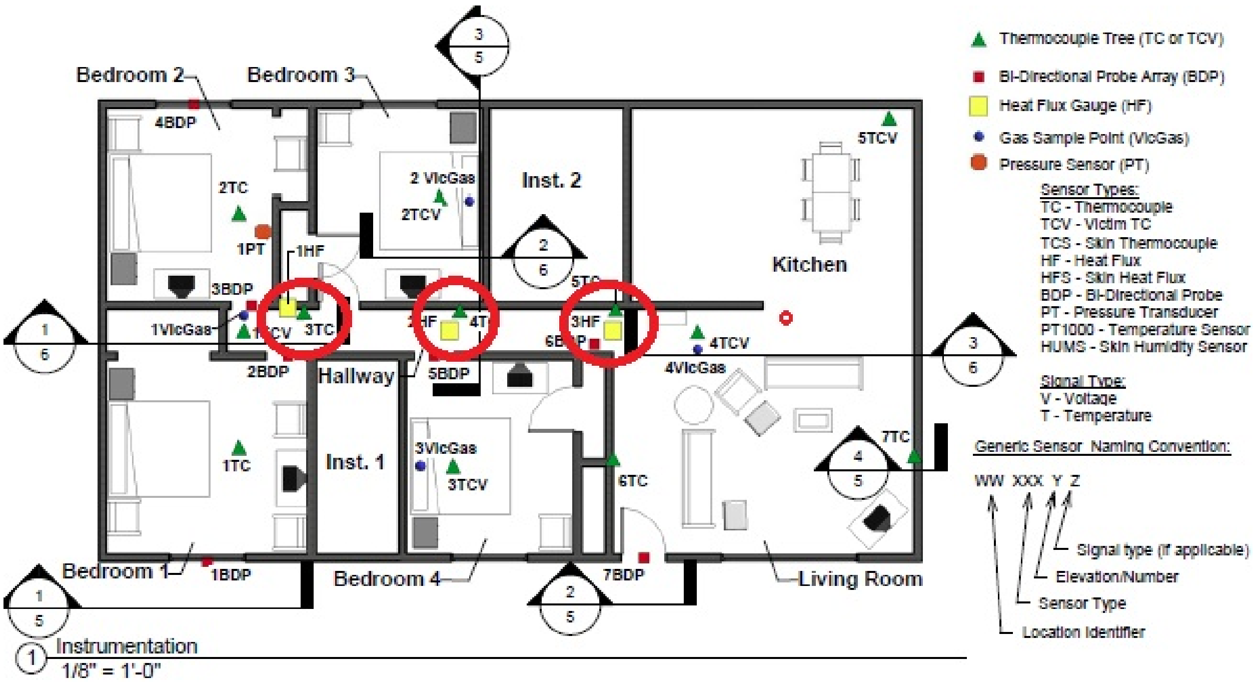


Figure 2.14: Floor plan with instrument locations for the UL FSRI fire attack study. The red circles indicate the measurement locations cited in Table 2.7. Moving from the front door toward the bedrooms, the locations are start, middle, and end of hallway, respectively. Fires were located in Bedroom 1 or Bedroom 1 and 2. [39].

the floor. All of the heat fluxes exceed the Thermal Class IV maximum of 10 kW/m^2.

Table 2.7: Thermal Measures along Hallway in UL FSRI Fire Attack Experiment, Bedroom 1 fire, closed window, and open front door. Measurements taken 24 min after ignition during quasi-steady post-flashover thermal conditions. Unit conversions rounded to the nearest 10.

Elevation	Start		Middle		End	
	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)
2.1 m (7 ft)	460/860	na	580/1,070	na	700/1,240	na
1.5 m (5 ft)	260/500	na	340/650	na	660/1,220	51
0.9 m (3 ft)	140/280	na	215/420	na	590/1,100	18
0.3 m (1 ft)	40/110	2	140/280	4	600/1,110	14

Table 2.8 provides data from similar measurement positions as Table 2.7. The difference is the ventilation. In this experiment, the Bedroom 1 window was opened prior to ignition, then the front door was opened approximately 7 minutes after ignition. With the door and window to the bedroom open, a flow path was created that allowed additional oxygen into the ventilation-limited fire room, and therefore the heat release rate was higher than the previous experiment. As a result, the only area of the hallway that was below 260 °C (500 °F) was at the start of the hallway at 3 ft above the floor or lower. Due to the hot gases near the ceiling, the heat flux at the floor level was approximately 3 kW/m^2 (Thermal Class III) while the temperature 1 ft above the floor at this location was only 40 °C (100 °F) (Thermal Class I). This indicates that the intake air flow from the

front door is drawn to the hallway and has not been significantly heated by the time it reaches this position.

Table 2.8: Thermal measures along hallway in UL FSRI fire attack experiment with a Bedroom 1 fire, open window, and open front door. Measurements taken 11 min, 45 s after ignition during peak post-flashover thermal conditions. Unit conversions rounded to the nearest 10.

Elevation	Start		Middle		End	
	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)
2.1 m (7 ft)	600/1,120	na	840/1,540	na	670/1,240	na
1.5 m (5 ft)	380/720	na	550/1,020	na	600/1,120	50
0.9 m (3 ft)	50/130	na	420/790	na	620/1,140	50
0.3 m (1 ft)	40/100	3	500/940	10	590/1,090	40

The last set of data presented from the UL FSRI fire attack study is shown in Table 2.9. The format of the table and and measurement positions are similar to the two previous tables. Again, the difference between the experiments is ventilation driven. In this last experiment, fire was started in both Bedroom 1 and 2. The windows in both bedrooms were open before ignition. The front door was opened approximately 5.5 minutes after ignition. Again, the energy produced by the fire increased, but a significant amount of the heat flowed out of the two open bedroom windows, which resulted in increased fresh air flow from the open front door into the hallway. This additional airflow provided Thermal Class III temperatures 0.9 m (3 ft) above the floor at the middle of the hallway position. There is a very steep temperature gradient at the start of the hallway position. At 1.5 m (5 ft) above the floor, the gas temperature is approximately 320 °C (600 °F). At the 0.9 m (3 ft) elevation, the gas temperature is only 40 °C (110 °F). The total heat flux at floor level at both the middle and start of hallway positions was approximately 1 kW/m^2. So, in the middle position the temperature exposure is at the upper bound of Thermal Class II low to the floor while the heat flux is representative of Thermal Class I.

Table 2.9: Thermal measures along hallway in UL FSRI fire attack experiment with a Bedroom 1 and 2 fire, open windows, and open front door. Measurements taken 10 min after ignition during quasi-steady post flashover thermal conditions, just prior to fire attack. Unit conversions rounded to the nearest 10.

Elevation	Start		Middle		End	
	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)	Temperature (°C)/(°F)	Heat Flux (kW/m^2)
2.1 m (7 ft)	520/970	na	640/1,180	na	730/1,350	na
1.5 m (5 ft)	320/600	na	430/800	na	690/1,280	54
0.9 m (3 ft)	40/110	na	170/340	na	540/1,000	28
0.3 m (1 ft)	30/80	1	150/310	1	530/990	18

IFSI, UL FSRI, NIOSH Study on Firefighters Thermal and Chemical Exposure in Residential Structure Fires

Another recent series of experiments was conducted by research teams from the Illinois Fire Service Institute (IFSI), UL FSRI, NIOSH, and Skidmore College. The goal of this study was to

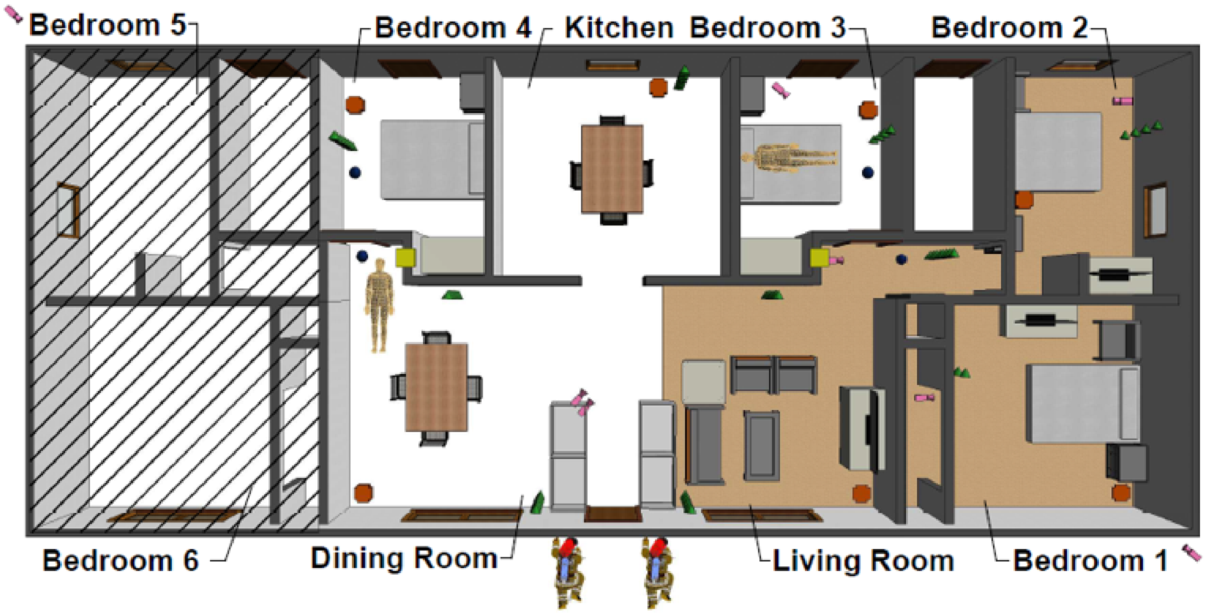


Figure 2.15: Floor plan with instrument locations for the IFSI, UL FSRI, NIOSH thermal response study. The room labels correspond with the measurement locations cited in Table 2.10. Fires were located in Bedrooms 1 and 2, or Bedrooms 5 and 6. [41].

investigate the effects of modern fire environments on the two most pressing concerns in the fire service today, cardiovascular and carcinogenic risks. A set of interim findings on the study was published in 2016 [40]. As part of the study, 12-person teams performed realistic firefighting tactics in residential fire environments that contained common building materials and furnishings. The fires were ignited in either Bedroom 1 and 2 or Bedroom 5 and 6. (see Figure 2.15). When ceiling temperatures in each fire room exceeded 600 °C (1,112 °F), fire dispatch was simulated and the firefighters started their response. The time of dispatch was between 4 and 5 minutes after ignition for each of the 12 experiments. When firefighters entered the structure, they entered through the front door to begin the tasks of either search or fire attack.

Specific to this thermal environment review one of the key areas of the IFSI study was the measurement of the production and transfer of heat through modern PPE and onto or into firefighters' bodies. The variables that impacted that heat transfer included tactical decisions (interior only vs. transitional attack) and operating location (interior fire suppression/search vs. exterior operations vs. interior overhaul). The overall results showed that: 1) temperatures inside the fire structure decreased after water was applied; 2) transitional attack resulted in faster water application; 3) local temperatures were higher for firefighters operating inside versus other positions (neck skin temperatures for inside attack firefighters were lower when exterior attack was used); and 4) higher body core temperatures were measured for the outside vent and overhaul positions. The paper, "Thermal Response to Firefighting Activities in Residential Structure Fires: Impact of Job Assignment and Suppression Tactic" has been accepted for publication in the journal *Ergonomics* [41]. The authors kindly shared some early data. The data is presented in Tables 2.10 and 2.11.

Table 2.10 provides temperature data for the dining room, living room, hallway, and (fire) bedrooms at three different elevations: 2.1 m (7 ft), 1.5 m (5 ft), and 0.9 m (3 ft) above the floor.

		Temperature when 'Inside Attack Reaches Hallway' (° F)							Heat Flux (kW/m^2)
Height	Tactic	LR Front	LR Rear	DR Front	DR Rear	Hallway	BR2/5	BR 1/6	
7 ft	Interior	547	472	490	442	1079	1371	1188	
	Transitional	317	325	289	279	411	676	645	
5 ft	Interior	465	323	409	395	968	1340	1187	19.3
	Transitional	226	226	256	238	276	641	350	5.2
3 ft	Interior	238	195	203	211	592	1203	1082	7.9
	Transitional	162	143	147	130	150	654	234	3.0

Table 2.10: Gas temperature and heat flux data measured at different locations in the test structure just prior to the flow of suppression water by interior attack team [41].

The temperatures were measured when the interior fire attack crew entered the hallway to attack the fires in the bedrooms. In the case of the transitional attacks, water was applied through the fire room windows prior to the interior crew reaching the hallway to complete the attack. The heat flux values presented in the far right column were measured in the hallway. The two heat flux elevations of 1.5 m (5 ft), and 0.9 m (3 ft) above the floor were intended to represent a firefighter in the standing or crawling positions, respectively. The temperatures were averaged over the six interior attacks and the six transitional attacks.

Examining the data from the interior attacks, the temperatures in the approach to the hallway 1.5 m (5 ft) above the floor were between 160 °C (320 °F) and 260 °C (500 °F) (Thermal Class III). The hallway and the bedroom temperatures exceeded 260 °C (500 °F), and the heat flux exceeded 10 kW/m^2. These values would place a firefighter in the hallway in a Thermal Class IV environment.

The transitional attack provided a Thermal Class II environment from the front door through the hallway position. However, the heat fluxes at the hallway position exceeded 2 kW/m^2, which is the upper bound for a Thermal Class II. This is another case in which the temperature and heat flux ranges that are paired in the Thermal Class definitions did not ocurr concurrently. It should be noted that no firefighters were burned during the experiments.

Another aspect of the IFSI study is based on the firefighters' task assignment. In these experiments, the attack crew entered first and as a result were exposed to the higher temperatures. The maximum temperature exposures (Thermal Class III, 160 °C (320 °F) to 259 °C (499 °F) were short, which then yielded overall average exposure temperatures in the Thermal Class I range (less than 100 °C (212 °F)).

Impact of Wind

Two studies were conducted to measure the impact of wind on the thermal environment within a fire apartment and public access areas connected to the apartment. One study was conducted within a laboratory to gain insight into the heat release rate of the apartment [19]. In this study, a three room apartment was attached to approximately 48 feet of public corridor. The other study was conducted in a high-rise apartment building where components of the flow path included the fire apartment, public corridor, and a stairwell [42]. Prior to the mitigation tactics, the wind-driven scenarios resulted in rapid increases in temperature, heat flux, and gas velocities along the exhaust portion of the flow path.

Helmet Temperature (°F)			
Measure	Job Assignment	Interior Attack	Transitional Attack
Maximum	Inside Attack	376	204
	Inside Search	146	130
Average	Inside Attack	136	108
	Inside Search	103	95
Ambient Temperature (°F)			
Average	Overhaul	77	80
	Outside	67	68

Table 2.11: Maximum and average temperatures from helmet-mounted sensors. The nozzleman on the attack team and the lead member of the search team wore the instrumented helmets [41].

The wind-driven laboratory study was conducted by and at NIST, with the support of the Fire Protection Research Foundation, DHS/FEMA, and the USFA. This series of fire experiments examined the impact of wind on fire spread through a multi-room apartment and examined the capabilities of wind-control devices (WCD) and externally applied water to mitigate the hazard.

The experiments exposed a public corridor area to a wind driven, post-flashover apartment fire. The door from the apartment to the corridor was open for each of the experiments, see Figure 2.1. The conditions in the corridor were of critical importance because that is the portion of the building firefighters would use to approach the fire apartment, or that occupants from an adjoining apartment would use to exit the building.

The fires were ignited in the bedroom of the apartment. Prior to the failure or venting of the bedroom window, which was on the upwind side of the experimental apartment, the heat release rate from the fire was on the order of 1 MW. Prior to implementing either of the mitigating tactics, the heat release rates from the post-flashover structure fire were typically between 15 MW and 20 MW. When the door from the apartment to the corridor was open, temperatures in the corridor area near the open doorway and 1.5 m (5 ft) below the ceiling, exceeded 600 °C (1,112 °F) for each of the experiments. The heat fluxes measured in the same location during the same experiments exceeded 70 kW/m^2. These extreme thermal conditions are more than twice the Thermal Class IV maximum temperature of 260 °C (500 °F) and more than seven times the Thermal Class IV maximum heat flux of 10 kW/m^2. These conditions were attained within 30 seconds of the wind impact. The report stated that the thermal conditions in the exhaust portion of the flow path in the public corridor, more than 24 feet downstream of the fire room doorway were not tenable, even for a firefighter in full protective gear [19].

The second wind-driven fire study was conducted by NIST, the Fire Department of the City of

New York (FDNY), and the Polytechnic Institute of New York University with the support of the DHS/FEMA Assistance to Firefighters Research and Development Grant Program and USFA, in a seven story building on Governors Island, New York. The measurement position in the stairwell on the fire floor was more than 70 feet from the fires started in the bedroom in the apartment.

Similar to the laboratory study, the high-rise experiments had a public corridor and stairwell area that was exposed to a wind driven, post-flashover apartment fire. The door from the apartment to the corridor was open for each of the experiments. Again, the conditions in the corridor and the stairwell were of critical importance because that is the portion of the building firefighters would use to approach the fire apartment or that occupants from adjoining apartments or adjacent floors would use to exit the building.

All of the experiments were ignited in furnished rooms of an apartment. Due to excess fuel (pyrolysis and smoke) generation, coupled with limited ventilation, the room of fire origin could not transition to flashover until windows self-vented and introduced additional fresh air with oxygen to burn, or air was introduced via the stairwell and corridor. This experiment was conducted with no externally applied wind. However, the vented bedroom (fire room of origin) created a flow path from the outside, through the fire apartment, into the corridor, and up the stairs to the open bulkhead on the roof. The temperatures and velocities in the corridors and in the stairwell increased, resulting in hazardous conditions for firefighters and untenable conditions for occupants on the fire floor and above in the stairwell. The temperatures 1.2 m (4 ft) above the floor, ranged from peaks of 400 °C (752 °F) (Thermal Class III) outside the door of the fire apartment to 200 °C (392 °F) (Thermal Class IV) inside the stairwell on the fire floor.

Adding an imposed wind of 9 m/s to 11 m/s (20 mph to 25 mph) to the open window of the bedroom (fire room of origin) combined with the same flow path as the experiment above increased the thermal hazard along the exhaust portion of the flow path. Temperatures over 400 °C (752 °F) (excess of Thermal Class IV) and velocities on the order of 10 m/s (22 mph) were measured in the corridor and stairwell above the fire floor. These extreme thermal conditions are not tenable, even for a firefighter in full protective gear. These experiments demonstrated the extreme thermal scenarios that can be generated by a room and contents fire, and how these conditions can be extended along a flow path within a real structure when wind and an open vent are present.

2.2 Near-Miss Reports

Near miss reports from http://www.firefighternearmiss.com/ were reviewed. "Near Miss" is an International Association of Fire Chiefs (IAFC)-managed program that collects and shares firefighter near-miss experiences. The reports are voluntarily submitted by members of the fire service that experienced or were involved with a close call or near-miss event.

The qualitative nature of the reports lacked sufficient data to aid in numerically defining a specific thermal environment. However, the reports provide a sense of the experiences where the thermal environment changed on the fire ground. Searching "structure fires" and "flashover" generated a list of incidents. The incidents which involved training fires were eliminated and the remaining reports were included in Table 2.12.

The common theme of the incidents is that conditions inside the structure changed from appropriate working conditions to untenable conditions requiring the firefighters to retreat or call for assistance. For this review, appropriate or tenable working conditions included mentions of visibility, well-defined smoke layers, and non-threatening perceptions of heat. Terms used to describe the untenable conditions typically began with a mention of a rapid change in conditions that resulted in a loss of visibility, compartments that rapidly filled with smoke and or flames, and the onset of threatening levels of heat.

Table 2.12: Flashover related near miss incidents. Training near misses were not included.

Date Published	Event Title	Conditions
12/30/10	Stove fire quickly grows with help from wind	Wind driven fire from rear impacted FF entering structure downwind.
01/10/11	Conditions change rapidly in house fire	Conditions went from light smoke with full visibility, to darkening down with increasing heat.
02/18/11	Crew trapped by rapidly changing conditions	Upstairs zero visibility conditions with low heat transitioned to rollover when kitchen downstairs flashed over.
05/30/11	Quick action by crew helps firefighter during bailout	Conditions went from almost clear to black and steamy instantly.
11/10/11	House fire intensifies after door opened	Initially FF opened front door with grey pressurized smoke coming out. This resulted in flames coming out three sides of the house prior to the arrival of the engine.
01/31/12	Proper PPE usage prevents tragedy	Fire self-vented out of window and FF was quickly engulfed in a firestorm.
02/09/12	Attic stairs trap FF in flashover	Firefighting inside house, then entered attic from interior stair. Suddenly the heat intensified and the attic flashed over. Windy day.
05/17/12	Firefighters burned worse than originally thought	Crew advancing upstairs encountered extreme heat and fire. All three FFs had 2nd degree burns.
06/29/12	Attic fire overcomes interior team	Attic was clear and the first and second floors clear of fire and with very little smoke, then FF in attic encoutered heavy smoke, heat and fire coming up attic stairway.
08/30/12	Windy conditions contribute to flashover	Fire burned through the roof, then wind pushed the heated gases down the vent hole that had been created when the interior crews pulled the ceiling.
02/15/13	Crew trapped by flashover	Crew experienced a flashover situation that occurred in a room just down the hallway. Three FF had heat damage to PPE.
04/11/13	High wind results in increased fire intensity	Flames slowly moving around FF head, FF felt a very sudden intense heat, FF face burning and radio damaged. 1st and 2nd degree burns to hand , 1st degree burns to ears.
05/03/13	Rapidly changing fire conditions endanger crew	Garden apartment, crew searching for fire on second floor while fire on first floor impacted crew with thick superheated black smoke and rapidly rising extreme temperatures.
05/08/13	Good SA anticipates imminent flashover	Instantly the smoke, heat, and energy overwhelmed us like a tidal wave. Felt the pressure wave of the smoke.
08/15/13	Fire reacts violently when ventilated	Inside smoke conditions were light, stairwell door was was opened, high heat but no visible fire upstairs. After 30 seconds a hostile fire event occurred.
10/03/13	Flashover leads to mayday	High heat conditions coming from the attic, followed by a backdraft that blew the ceiling out of the room and resulted in the room flashing over.
09/05/14	Uncoordinated ventilation leads to flashover	Once the door was open, arduous smoke conditions prevented making entry. Backdraft and flashover followed.
09/24/14	Separated crew member caught in flashover	Room flashed over, crew member inside for about 10 seconds prior to exit.
01/30/15	Firefighter injured during interior attack of hoarder home	FF crawled over a pile of collected items, entered hot gas layer, and was burned on face and ears.
02/22/16	Firefighters surrounded by fire creates mayday situation	Attack crew operating on fire upstairs overrun by fire coming up the stairs. Officer exited through fire and sustained burns.
04/08/16	Firefighters burned after being shoved into fire room	Small apartment with a fully involved room.
11/12/16	Crew advances into pre-flashover situation	Smoke was pushed to the floor and visibility was zero.

A few of the incidents indicate firefighters received 2nd degree burn injuries, indicating that the skin temperature reached at least 55 °C (132 °F). Other incidents mention heat-damaged PPE and one case of a damaged radio, but again, there is not enough data to develop any exposure correlations. The two main take-aways from these reports: 1) the speed of increase in temperature, and 2) the firefighters seemed to be positioned in the exhaust portion of the flow path within the structure. These trends are similar to the trends shown in the following sections reviewing the NIOSH LODD reports and computer simulations of LoDD/LODI fire incidents.

2.3 NIOSH LODD Reports

Prior On-Duty Injuries and Fatalities

There have been many previous fire incidents [43–57] in which changes in the flow paths are thought to have had an adverse impact on firefighter and occupant safety. Table 2.13 lists the NIOSH investigation reports from the past 15 years in which it could be determined that a flow path played a role in the related incident. This table lists the NIOSH report number, the outcome, and a brief description of the flow path details. These reports provided insight into the thermal environment scenarios that resulted in the loss of firefighters.

Based on a review of these incidents, it is clear that fires with rapidly developing or changing ventilation may lead to hot gas flows that are a significant thermal hazard to the fire service during a response. The development of (or changes to) a flow path could be caused by the failure of a component of the structure, such as a door, window, portion of a ceiling, wall, or floor. Environmental conditions such as wind can generate hazardous thermal conditions within a flow path. Uncoordinated ventilation procedures can also increase thermal hazards within a flow path. In each of these cases the firefighter(s) were located between the fire and the lower pressure (exhaust) vent, so the fire gases over took the firefighters' position.

This review demonstrates that firefighters caught in a flashover transition or in the exhaust portion of the flow path within a structure may not be a high frequency event, but it is a re-occurring and a high consequence event. In addition to having a NIOSH review report, a few select incidents had fire simulations conducted to provide insight into the fire dynamics of each event. These are presented in the following section.

2.4 Computer Simulations that Examined LODD/LODI Incidents

Since 1994, several firefighter LODD or LODI incidents have been simulated using what was the state of the art fire model at the time. These simulations are another means to provide insight about the thermal environment that existed during incidents in which firefighters were killed or injured. Table 2.14 lists 10 of the simulations completed and made publicly available.

Most of the incidents have a common theme: firefighters were in a position that was safe in terms of the exposure to thermal energy, and then there was a rapid change in the thermal environment typically due to a change in ventilation or a change in the firefighters' location. In some cases the change in ventilation was due to the failure of a barrier between the fire area and the adjacent space where the firefighters were operating. The barriers that failed ranged from gypsum board/walls or ceilings to steel-faced doors. In other instances it was the intentional or unintentional opening of doors or windows that generated the change in ventilation that resulted

Table 2.13: Flow path related LODD/LODI incidents.

NIOSH Report No.	No. of LODDs/LODIs	Flow Path Details
99-F01 [43]	3 LODDs	From apartment into hallway on 10th floor of high-rise apartment building.
99-F21 [44]	2 LODDs 2 LODIs	Basement to 1st floor.
F2000-04 [45]	3 LODDs 3 civilian deaths	1st floor to 2nd floor.
F2000-16 [46]	1 LODD 1 LODI 1 civilian death	2nd floor hallway through 2nd floor apartment.
F2000-23 [47]	1 LODD 2 LODIs	From ground level to 1st floor then to 2nd floor; flow exited through ceiling
F2000-43 [48]	1 serious LODI 2 other LODIs	1st floor to 2nd floor.
F2004-02 [49]	1 LODD	1st floor to basement.
F2005-02 [50]	1 LODD 4 LODIs	Rear to front of the building.
F2005-04 [51]	1 LODD 9 LODIs	Basement to 1st floor.
F2007-09 [52]	1 LODD 2 LODIs	3 story training burn, flow through all levels.
F2007-35 [53]	4 LODIs	1st floor to 2nd floor.
F2009-11 [54]	2 LODDs	Rear to front of the building.
F2011-13 [55]	2 LODDs	Lower level up stairs and through entry door and garage.
F2011-31 [56]	1 LODD	Fire extended from lower level apartment.
F2012-28 [57]	1 LODD 1 LODI	Attic fire extended into closed porch and then into 2nd floor.
F2013-02 [58]	1 LODD	Trapped in basement fire, SCBA degraded.
F2013-04 [59]	2 LODD 2 LODI	Flashover in assembly hall.
F2014-02 [60]	2 LODD	Fire extended from 1st to 2nd floor.
F2014-09 [61]	2 LODD 13 LODI	Wind driven fire, unrestricted flowpath.
F2014-14 [62]	1 LODD	Heavy smoke led to rapid fire growth.

in a rapid increase of the thermal energy the firefighters were operating in. Linking these to the NIOSH studies, we can determine that in 7 of the 10 incidents, the firefighters were exposed to thermal conditions that were able to transfer enough energy to the firefighters' facepieces to cause damage, indicating the facepieces had been heated to approximately 150 °C (300 °F) or more. Based on the NIST SCBA laboratory studies, the threshold heat flux exposure for this to occur would be 15 kW/m^2 (Thermal Class IV) for 30 s. If the heat flux were higher, the time to generate the thermal damage to the facepiece would be less.

Table 2.14: Computer simulations of LODD and LODI fire incidents.

Event Title	Conditions
62 Watts Street, NYC 1994 [63]	Opening door to fire apartment resulted in rapid and sustained fire development, 3 FFs killed.
Cherry Road, DC 1999 [64]	Ventilation-induced flashover in basement exposed FFs operating on the floor above to fire gases, 2 FFs killed, 3 FFs injured.
Keokuk, IA, 1999 [65]	Flashover on 1st floor rapidly spreads through the house from the rear to the front and up the stairs overtaking FFs, 3 FFs killed.
Restaurant, TX 2000 [66]	Partial roof collapse resulted in attic fire engulfing trapped FFs on the main level of the restaurant, 2 FFs killed.
Marsh Overlook, VA, 2007 [67]	Wind-driven fire, exterior fire had spread to the attic and then broke into the upper floor of the structure resulting in a rapid increase in heavy black smoke and heat, 1 FF killed.
Wind-driven fire, TX, 2009 [68]	Attic fire spread to first floor, rapid fire growth occurred after up-wind windows failed, 2 FFs killed.
Dowling Circle, MD, 2011 [69]	FF operating in a garden apartment above fire floor was overcome by a high rate of convective heat transfer. 1 FF killed.
Hillside house, CA, 2011 [70]	FFs located in the exhaust portion of the flow path between the fire on the lower level and the doors on the front of the structure were overcome by hot gases once the windows on the fire floor failed open, 2 FFs killed.
Attic fire, Chicago, IL, 2012 [71]	Attic fire spread down through an enclosed porch to the second floor of the structure. Failure of the door between the porch and the interior hallway exposed FFs to a blast of heat and smoke, 1 FF killed.
Wind-driven basement fire, MD, 2012 [72]	FFs opened and entered the exhaust portion of a hot gas flow from a wind driven fire on a level below them. The high velocity hot gas flow closed the front door, temporarily trapping the FFs, 7 FFs injured.

2.4.1 Cherry Road, DC 1999

In the Cherry Road fire simulation, after the basement sliding glass door was opened, leading to a ventilation induced flashover, the temperatures within the stairway exceeded 820 °C (1,500 °F) with a gas velocity of approximately 8 m/s (18 mph). The three firefighters badly burned in this fire were positioned on the upper level in the living room in front of the open doorway of the stairway to the basement. The temperatures in the hot gas flow in the upper half of the room remained at approximately 820 °C (1,500 °F) as it exited the basement stairs. In the lower half of the living room, the temperatures ranged from approximately 180 to 580 °C (350 to 1,080 °F), as shown in Figure 2.16. The report cited a range of temperatures and velocities at a height of 0.5 m (1.6 ft) above the floor between the basement stairway and the rear of the living room from 180 to 260 °C (350 to 500 °F) and 0 to 1.6 m/s (0 mph to 3.5 mph). This region was where the three firefighters were positioned. The simulation did not address heat flux, but the living room did not transition to flashover, and the carpeting in the living room did not exhibit evidence of burning or pyrolysis. This indicates the heat flux at the floor remained under 20 kW/m^2.

Based on the NIOSH report, Victim 1 died due to thermal injuries involving 60% of total body surface area and airways. Victim 2 died due to thermal injuries involving 90% of total body surface area and airways. It appeared both facepieces were thermally damaged and turnout gear had thermal damage. The thermal conditions near the floor in this incident would align with the temperature values that define Thermal Class III (260 °C (500 °F)). The peak heat flux value for Thermal Class III is given as 10 kW/m^2, with an exposure time of 5 minutes. The firefighter that survived, but was burned over 60% of his body, was exposed to these conditions for approximately 90 s. The fire was knocked down within 4 minutes of the flashover occurring in the basement. Therefore none of the victims were exposed to Thermal Class III conditions for 5 minutes, and none of the victims were protected from those thermal conditions for 5 minutes.

2.4.2 Keokuk, IA 1999

In 1999, a fire in Keokuk, IA killed three firefighters and three children. As noted in Table 2.14, flashover on the 1st floor rapidly spread through the house from the rear to the front and up the stairs. The FDS simulation of the fire shows the temperatures of the gases flowing up the stairs exceeded 600 °C (1,100 °F) (Thermal Class IV), as shown in Figure 2.17. Two of the firefighters were recovered from upstairs. One firefighter (Victim 1) was located at the top of the stairs, and another firefighter (Victim 3) was along the open stair toward the front bedroom. A third firefighter (Victim 2) was found in the front room on the ground floor. This room flashed-over. Flames from the front room were flowing into the open stairway. The NIOSH review of the fire reported that the causes of death for the victims as follows: Victim 1-Smoke inhalation (15% Carboxyhemoglobin level) and sudden exposure to intense heat, Victim 2-Smoke inhalation (25% Carboxyhemoglobin level) and sudden exposure to an extremely hot environment, and Victim 3-Sudden exposure to intense heat (1.0% Carboxyhemoglobin level). From the autopsy information, it would seem that Victim 3 was over come by heat alone prior to failure of his SCBA.

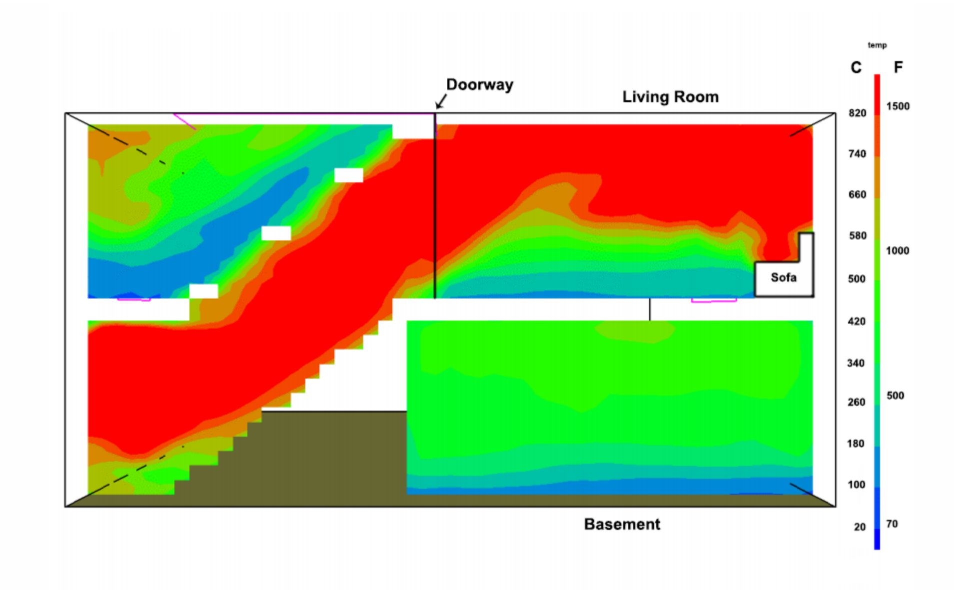


Figure 2.16: Gas flow temperature along the center line of the stairway from the Cherry Road fire. The basement has flashed-over and the exhaust flow was traveling through the open doorway at the top of the stairs into the living room and hitting the back wall. The three firefighters were positioned between the doorway and the sofa on the back wall [64].

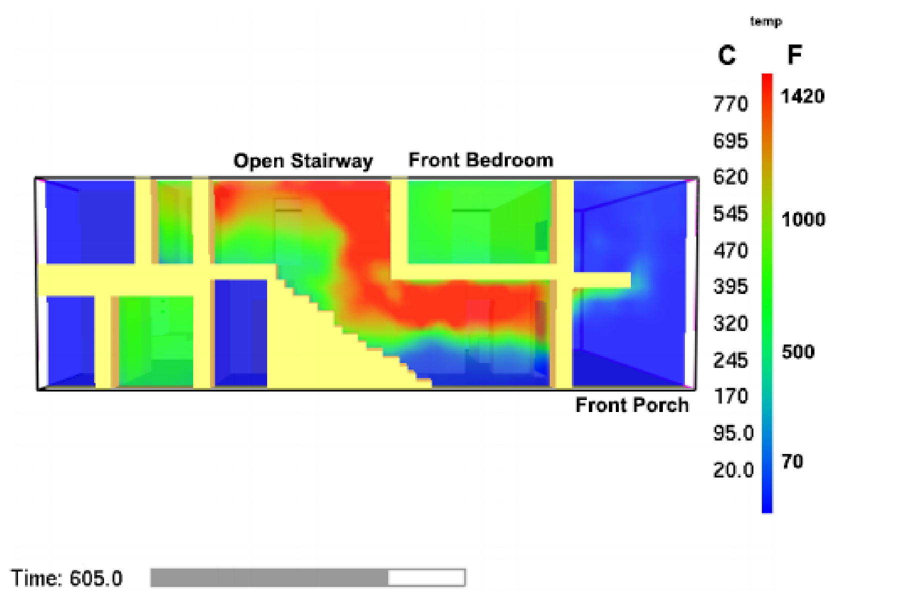


Figure 2.17: Gas flow temperatures along the center line of the stairway from the Keokuk, IA fire. The kitchen in the rear of the house had flashedover and fuel-rich fire gases flowed to the front of the house where they mixed with fresh air coming in the open front door. The living room in the front of the house also flashed-over and a significant portion of the excess fuel gases and flames flowed up the stairwell [65].

2.4.3 Wind-Driven Fire, TX 2009

A wind-driven fire in Texas resulted in the deaths of two firefighters caught in the convective exhaust flow. Once the windows on the rear of the house failed, the wind increased the burning rate of the fire. The two firefighters who died moved from the rear of the house to the front, but were unable to get to a safe area or out of the house.

Figure 2.18 shows two temperature profiles of a cross-section of the house from the den in the rear of the house (on the left side) to the front door via a hallway/foyer area [68]. The wind direction was generally from the rear of the house to the front. The temperatures in the upper image represent conditions just before the windows on the rear of the house failed open. At this point, the thermal conditions in the front hallway were roughly the same as the conditions at the time the firefighters made entry several minutes earlier. The cool flow in the lower layer is outside air moving from the front of the house toward the fire area in the rear.

The thermal and fire conditions change dramatically in the structure once the rear windows fail and the wind impacts the fire. The lower image in Figure 2.18 shows the thermal conditions in the front hallway after the rear glass fails. In seconds, the temperature in the lower layer transitions from near ambient air temperature to temperatures exceeding 100 °C (212 °F), and the hot gas layer moved closer to the floor. In addition, the gas flow direction close to the floor reversed. The flow out the front door was now all hot gas exhaust. The hot gas layer temperatures a few feet above the floor exceeded 200 °C (392 °F) (Thermal Class III). This increase in thermal conditions was felt by a crew operating in the front hallway. They were able to escape. As the firefighters exited the front of the house, they were observed to have helmets and portions of PPE on fire. This would indicate that the exiting firefighters may have been exposed to heat fluxes which resulted in the ignition of their PPE. As the fire continued to burn, the front widows vented and the temperatures in the house increased. The two victims were found in rooms in the front of the house.

According to the NIOSH report, the SCBA worn and used by both victims were too badly damaged by fire and heat exposure to be tested. Both SCBA facepiece lenses were melted with holes penetrating the lens material. The integrated PASS device on the SCBA used by Victim 1 was operational, but the PASS device on Victim 2 was not operational. The cause of death for Victim 1 was listed as thermal injuries. The cause of death for Victim 2 was listed as thermal injuries and smoke inhalation [54]. From NIST TN 1785, SCBA facepiece lenses exposed to 15 kW/m^2 had holes form between approximately 1.5 and 3.9 minutes. At the time when holes formed in the lenses, average lens temperature was approximately 270 °C (518 °F) regardless of exposure heat flux and facepiece model [32].

The Texas State Fire Marshal's Office, Firefighter Fatality Investigation Investigation Number FY 09-01 provided additional details on the condition of the victims' equipment. Helmets were charred and partially melted. Turnout coats and pants were heavily charred and damaged due to heat and flame exposure. Portions of the gear burned through to the thermal liner. The facepieces were not intact and not serviceable. There was heavy charring and melting of the entire SCBA unit. The cylinder showed severe thermal damage with charring to the cylinder shell. The back frame and harness assembly exhibited severe heat and thermal damage.

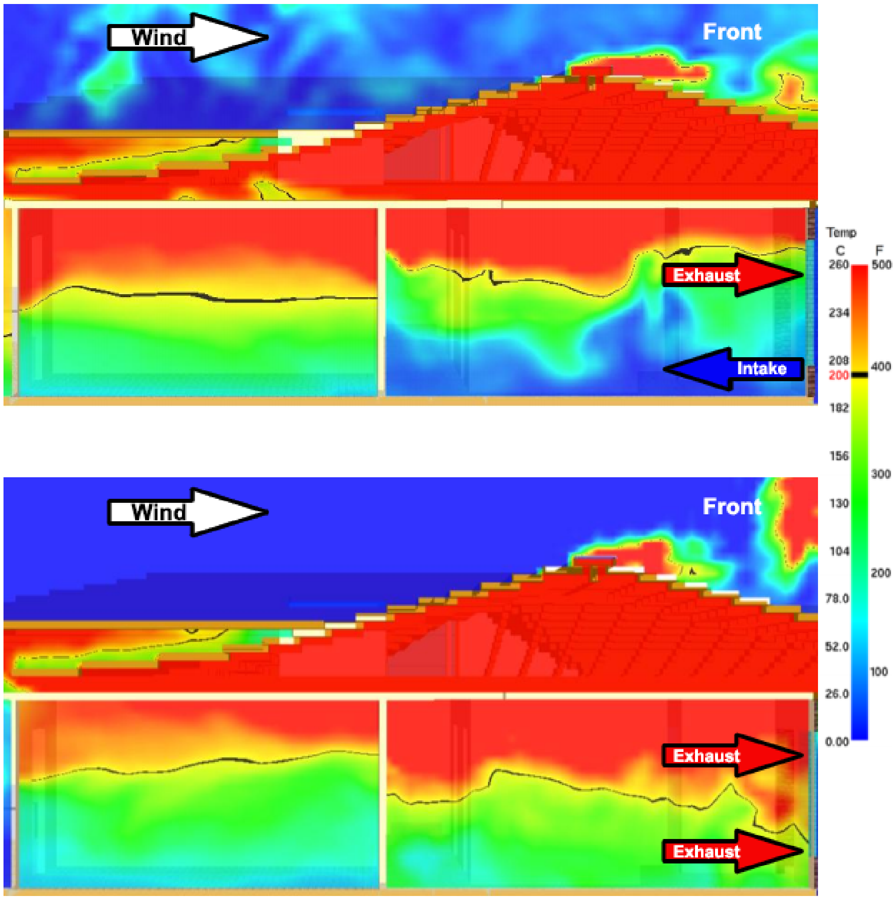


Figure 2.18: Gas flow temperature along the center line of the stairway from the of the front door and hallway from the Texas wind-driven fire. The upper image represents the gas temperatures and flow directions prior to the wind entering the structure from the rear. The front door is functioning as a bi-directional vent with hot gas flow out of the top and cool fresh air flow into the bottom. The lower image shows the conditions just after the rear windows failed and the pressure from the wind reversed the intake flow at the front door. The front door now functions as a uni-directional hot gas exhaust vent [68].

2.4.4 Hillside House, CA 2011

Two firefighters were positioned in the exhaust portion of the flow path between the fire on the lower level and the doors on the front of the structure. The firefighters were overcome by hot gases once the windows on the fire floor failed open. NIST TN 1856 documented the FDS simulation that was created for this incident [70]. Figure 2.19 shows cut-away views of the three floors of the structure, and the stairway that connects them. The fire started on the lower level near the windows on the rear (right side) of the house. The front door of the house was accessible via the stairs from the street level on the front (left side) of the house. The upper image in Figure 2.19 show the thermal conditions just prior to window failure.

The lower image in Figure 2.19 shows the conditions approximately 60 s after the rear lower level windows began to fail open. The simulation results indicated a high-hazard area in the stairwell near the laundry room landing area that exceeded the conditions of a Class III exposure (temperatures greater than 260 °C or 500 °F). The firefighters who died were located in the hallway near the landing on the middle floor level, shown in the circle.

The NIOSH report provided information from the medical examiner's report that both firefighters died from complications from thermal injuries. Victim 1 had 40 to 50% of his total body surface area burned and Victim 2 had 30 to 40% of his total body surface area burned. The burns to the bodies were in areas protected by their PPE coats and pants, even though the PPE seemed to be in good condition. The San Francisco Fire Department Safety Investigation Report included a thermal analysis of the PPE worn by the victims. It was estimated the victims' gear was exposed to peak temperatures between 290 to 400 °C (550 to 750 °F). This peak temperature exposure correlates with Thermal Class IV.

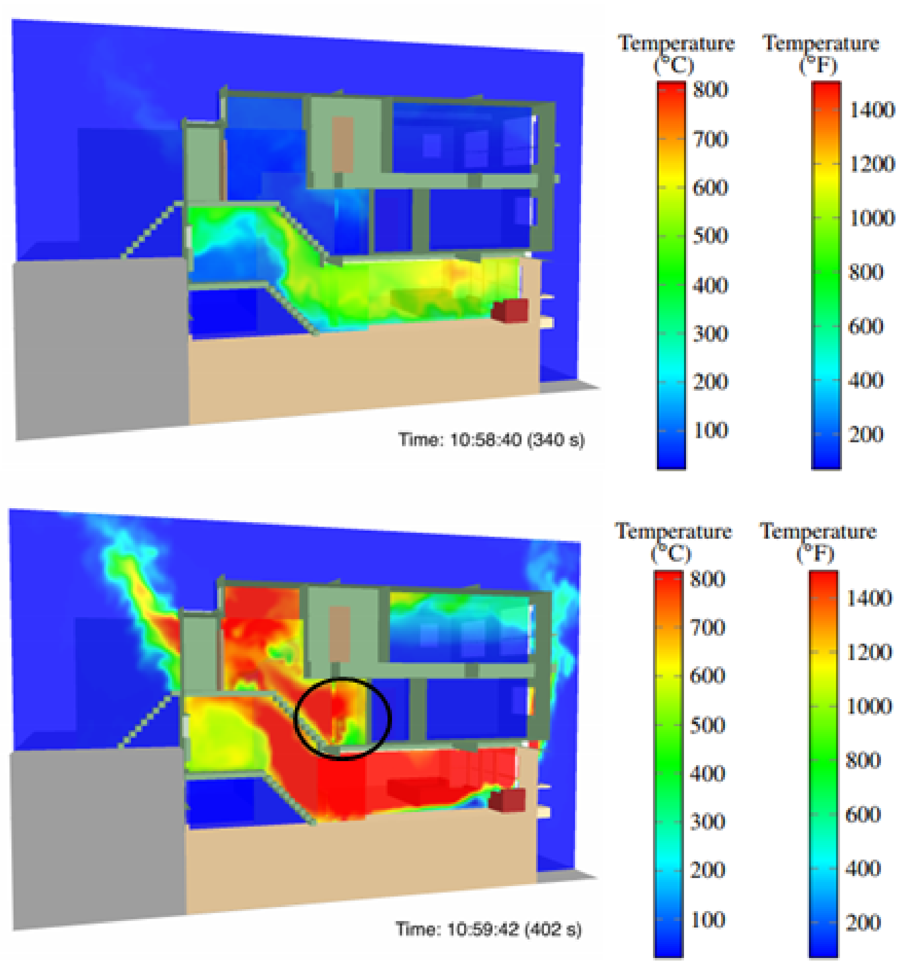


Figure 2.19: Gas flow temperatures along the center line of the stairs from the living room on the lower level (room of fire origin) up the stairs, and exhausting through the front door. The level that the firefighters were located on is circled. [70].

The LODD fire incidents, in this section, share several common issues, such as rapid fire development and increased thermal hazards as a result of the introduction of additional air into the fire compartment. The firefighters were all caught in the exhaust portion of the flow path, in some cases operating above the fire floor, or as the result of a pressure differential caused by pressure from the fire or wind. The thermal exposures the firefighters received were Thermal Class III or above. The speed with which the thermal conditions affected the firefighters must have been fast because several firefighters in the incidents did not move far from their locations prior to the change in conditions.

Section 3

Gap Analysis

In the previous section, research results, near miss reports, NIOSH LODD reports, and incident studies were examined. In this section, the current NFPA thermal performance standards for firefighter protective clothing and select equipment are examined and compared to the information from the literature review. Many NFPA standards include thermal performance requirements for firefighter equipment. NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting, will serve as a starting point to examine the thermal capabilities of fire fighting garments and turnout gear based on the performance standards they are tested to. NFPA 1801, NFPA 1961, and NFPA 1964, the standards for thermal imagers, fire hose, and nozzles, respectively, are also examined relative to thermal performance requirements.

3.1 Thermal Protective Performance

The scope of NFPA 1971 is to specify the minimum design, performance, testing, and certification requirements for structural fire fighting protective ensembles and ensemble elements that include coats, trousers, coveralls, helmets, gloves, footwear, and interface components. The purpose of the standard is to establish minimum levels of protection for fire fighting personnel assigned to fire department operations, including, but not limited to, structural fire fighting, proximity fire fighting, rescue, emergency medical, and other emergency first responder functions. To accomplish this, NFPA 1971 establishes the minimum requirements for structural fire fighting protective ensembles and ensemble elements designed to provide fire fighting personnel limited protection from thermal, physical, environmental, and blood-borne pathogen hazards encountered during structural fire fighting operations. For the needs of this review, only the thermal performance requirements and test methods for structural fire fighting protective ensembles are included.

3.1.1 Structural Fire Fighting Protective Ensemble Thermal Performance Tests and Requirements

NFPA 1971 requires the structural fire fighting protective ensemble components to undergo a variety of different tests. Depending on the component, multiple tests maybe required to ensure the thermal requirements of the standard are met. These tests include: Thermal Protective Performance (TPP), flame resistance, heat/thermal resistance, conductive heat resistance, radiative heat resistance, total heat loss, and thread melting. Each type of component,(garment, helmet, glove and interface garment) has different test methods and requirements. In this section, a brief summary of the key test methods and pass/fail criteria are provided. The purpose of this section is to consolidate and list the test conditions for consideration with conditions that could be generated by a fire. For complete details on each test method, please refer to NFPA 1971, Chapter 8, and also Appendix B.

A summary of thermal exposure conditions for the structural fire fighting protective ensemble appear in Table 3.1

Table 3.1: Summary of thermal performance test conditions from NFPA 1971, 2013 edition. These values relate to the exposure and capabilities of the materials, and do not directly represent the time when a burn injury would occur to the user.

PPE Component	Thermal Exposure	Time Exposed
Protective Coat and Pants	260 °C (500 °F)	5 minutes
	84 kW/m^2	17.5 s minimum for TPP of 35
	small open flame	12 to 15 seconds
Hood	260 °C (500 °F)	5 minutes
	84 kW/m^2	10 s minimum for TPP of 20
	small open flame	12 to 15 s
Boots	260 °C (500 °F)	5 minutes
	open pan flame	12 s
	10 kW/m^2	30 s
Gloves	260 °C (500 °F)	5 minutes
	small open flame	12 to 15 s
Helmet	260 °C (500 °F)	5 minutes
	10 kW/m^2	60 seconds
	small open flame	12 to 15 s
Flaps	260 °C (500 °F)	5 minutes
	84 kW/m^2	10 s minimum for TPP of 20

Thermal Protective Performance (TPP) Test

Protective garment elements, such as turnout coat and pants, are composed of an outer shell, moisture barrier, and thermal barrier. This composite system of materials is tested for thermal insulation capabilities with the TPP test. To pass the test, the turnout gear sample must have an average TPP of not less than 35. Helmet ear covers, hoods, and other interfaces must have an average TPP of at least 20.

The test uses an exposure heat flux of 84 kW/m^2 generated by gas burners (convective heat) and electric heaters (radiant heat). This heat flux is intended to be representative of the thermal energy present in a flashover. It should be noted that this is a harsh exposure and does not represent conditions in which firefighters are intended to work. It measures the ability of the composite to provide a few seconds of escape time from such an exposure. It should also be understood that although the heat flux used in this test is severe, this is a laboratory test, and firefighters can encounter conditions even more severe. Heat fluxes due to direct flame contact have been measured in the range of 60 to 170 kW/m^2 [28].

Flame Resistance Test

Helmets, gloves, garment outer shells, moisture barriers, thermal barriers, collar linings, winter liners where provided, drag rescue devices (DRDs), trim, lettering, and other materials used in garment construction including, but not limited to, padding, reinforcement, interfacing, binding, hanger loops, emblems, and patches are required to be individually tested for resistance to flame. Basically, the materials are exposed to an open, pre-mixed flame from a small laboratory burner (flame height approximately 50 mm (2 in) and a flame temperature of approximately 1,200 °C ±100 °C (2,192 °F ±180 °F). The item tested is exposed to the flame for approximately 12 to 15 s. After that exposure, garment materials cannot have a char length of more than 100 mm (4 in), cannot have an afterflame of more than 2.0 s, and no melting or dripping is allowed. Helmets have limits on the amount of distortion acceptable after exposure and are allowed up to 5 s for afterflame or glow. In one of the helmet flame resistance tests, the top of the helmet is exposed to a radiant heat flux of 10 kW/m^2 for 60 s before the flame is applied.

The flame resistance test for footwear is a different exposure. The footwear is exposed to the flame from a heptane-fueled pan fire (pan size 305 mm × 458 mm (12 in × 18 in)), for 12 s. The footwear is required not to have an afterflame of more than 5.0 s have no melting, dripping, or have burn-through to pass the test.

Although flame contact is a severe exposure, the time of that exposure is limited to 15 s or less. Is this exposure enough time for protecting a trapped firefighter?

Heat and Thermal Shrinkage Resistance Test

PPE components (i.e. helmets, gloves, interfaces and garment outer shells, moisture barriers, thermal barriers, collar linings, winter liners, drag rescue devices, trim, lettering) and other materials used in garment construction (i.e. padding, reinforcement, labels, interfacing, binding, hanger loops, emblems, or patches, and elastic and hook and pile fasteners that directly contact the wearer's body) are individually tested for resistance to heat. The materials cannot shrink more than 10.0% in any direction, and no melting, separation, or ignition is allowed. Basically, samples are placed inside an oven and exposed to 260 °C, +8/-0 °C (500 °F, +14/-0 °F) for 5 minutes +15/-0 s. The air velocity within the oven is less than 1.3 m/s (3 mph).

In the shrinkage tests, there is no flame exposure. What if the material shrinks and compresses the gear tightly to the body of a firefighter when exposed to flame for 15 s? How would that combination of exposures impact the safety of a firefighter?

Conductive and Compressive Heat Resistance (CCHR) Test

The garment composite from the shoulder areas and the knee areas are tested for resistance to heat transfer. Samples of 8 inch squares of the garment composite layers are conditioned for both wet and dry testing. Specimens are tested using an exposure temperature of 280 °C, +3/-0 °C (536 °F, +5/-0 °F). At time zero, the sensor and specimen are placed in direct contact with the exposure surface and under the appropriate pressure (2 psi ±0.2 psi for the shoulder or 8 psi ±0.8 psi for the knee). A determination is made if the time to second-degree burn is equal to or exceeds 25.0 s. Specimens showing a second-degree burn time equal to or greater than 25.0 s are considered as having passing performance. Specimens having a second-degree burn time less than 25.0 s fail.

While the gear must withstand 260 °C (500 °F) for 5 minutes, this test requires the PPE shoulder areas and knee areas provide at least 25 s of burn protection for the firefighter from direct contact with a surface at 280 °C (536 °F).

Thread Melting Test

All sewing thread utilized in the construction of garments, drag rescue devices, helmets, boots, and interface components (hoods and wristlets) is tested for resistance to melting and is required to not melt at or below 260 °C (500 °F).

Conductive Heat Resistance Tests (CHRT)

Gloves and footwear are required to pass different versions of the CHRT. CHRT1 represents a case where a firefighter is in contact with a hot surface with a temperature of 280 °C (536 °F), with pressure of 0.5 psi ±0.05 psi (glove palm and footwear upper material) or 2 psi ±0.2 psi (glove back). For the body of the glove and the upper material of the footwear, the heat transfer is slowed down so that a second-degree burn will not occur in less than 10.0 s, and will have a pain time of not less than 6.0 s.

CHRT2 applies to the sole of the footwear and represent a firefighter standing on a hot surface with a temperature of 260 °C (500 °F). The inside of the footwear is filled with 4.5 kg (10 lbs) of 10 mm diameter steel balls and placed on the hot plate for 20 minutes +15/-0 s. During that period, the temperature of the insole surface in contact with the foot cannot exceed 44 °C (111 °F) in order to pass the test.

Comparing the performance requirements from CHRT1 to those of the CCHR or TPP tests for the coat and pants would seem to indicate that a firefighter's hands or feet could be burned sooner than portions of his or her body covered with the garment under similar conditions.

Radiant Heat Resistance Test

The footwear is exposed to 10 kW/m^2 from a radiant panel for approximately 30 s. During the test period, the upper surface in contact with the skin can not exceed 44 °C (111 °F) in order to past the performance test.

Structural Fire Fighting Protective Ensemble Thermal Performance Tests and Requirements Summary

Based on the tests PPE must pass, the gear is intended to survive temperatures of at least 260 °C (500 °F) for 5 minutes (Thermal Class III). The tests in which portions of the ensemble are exposed to a radiant heat flux of 10 kW/m^2, are only required to provide protection for 10 to 60 s. Thermal Class III lists 5 minutes of protection or performance at 10 kW/m^2 for equipment. This brief overview shows that most of the structural ensemble is tested for protecting firefighters from short duration (25 s or less) exposures to flame and hot surfaces. Keep in mind second-degree burns to the skin can occur when the skin temperature reaches approximately 55 °C (131 °F).

3.1.2 Thermal Imagers Thermal Performance Tests and Requirements

NFPA 1801, Standard on Thermal Imagers for the Fire Service has two thermal performance tests, the heat resistance test (HRT) and the heat and flame test (HFT). These tests use thermal exposure conditions similar with tests conducted for PPE and SCBA.

During the HRT, thermal imagers are placed in a convection oven maintained at 260 °C (500 °F) for the duration of the test, 5 minutes +15/-0 s. After the specified thermal exposure, the thermal imager must be able to resolve frequencies to the index number 4 of the spatial resolution target and must not have any part of the thermal imager melt, drip, or ignite.

In the HFT, thermal imagers are exposed in a convection oven to 95 °C $\pm$2 °C (203 °F $\pm$5 °F) for approximately 15 minutes. At the completion of the 15-minute exposure, the oven door is opened, and the specimen mounted on the test fixture is moved out of the oven and into the center of the burner array. The product is then exposed to direct flame contact for 10 s. This exposure begins within 20 s of the product being removed from the test oven. Any afterflame of the test specimen exceeding 2.2 s, anything falling from the test specimen, and any test specimen falling from the mounted position is recorded and reported. Any occurrence of these conditions constitutes failing performance.

3.1.3 Nozzle Thermal Performance Tests and Requirements

NFPA 1964, Standard for Spray Nozzles, covers the requirements for new adjustable-pattern spray nozzles intended for general firefighting and other specific uses such as offshore platform fire fighting. For this review only thermal performance tests relating to the requirements for general fire fighting are cited.

The operational temperature range of the nozzles is defined by the following tests. The nozzle is required to be capable of operation after storage in high temperatures of 57 °C (135 °F) and after storage in low temperatures (with a dry nozzle) of -32 °C (-25 °F) for 24 hours. After the exposure, the nozzle must meet the operational control requirements and be free of any cracks or broken sections.

There is another thermal test for nozzles with nonmetallic components other than the rubber gaskets where a nozzle connects to a hose line. They are subjected to an air-oven aging test. The air-oven aging test exposes the nozzles to 70 °C (158 °F) for 180 days and then allows them to cool at least 24 hours in air at 23 °C (74 °F) at 50% relative humidity. After the oven exposure and cool down, the nozzles must meet the rough usage requirements of this standard and be free of cracking or crazing. For further details on these requirements and test, see NFPA 1964.

3.1.4 Fire Hose Thermal Performance Tests and Requirements

NFPA 1961, Standard on Fire Hose currently has two tests in which the hose is exposed to higher than ambient temperature conditions: 1) the test for heat resistance and 2) the oven aging test, which exposes the fire hose to temperatures of 70 °C (158 °F) for 96 hours.

The heat resistance test is intended to examine the ability of attack hose and supply hose to resist heat by conducting the test defined in ANSI/UL 19, Lined Fire Hose and Hose Assemblies, Heat-Resistance Test; FM Class Number 2111, Factory Mutual Approval Standard for Fire Hose, Heat Resistance Test; or equivalent.

The ANSI/UL 19-2013, heat-resistance test requires a coupled 457 mm (18 in) section of hose, filled with water, sealed and conditioned to 23 °C (73 °F). A solid steel block 63.5 by 38 by 203 mm (2.5 by 1.5 by 8 in) heated to 260 °C (500 °F) and placed on the hose sample for 60 seconds. After the hose has cooled, it is laid straight and subjected to the hydrostatic strength test. In other words, tested to three times the marked service pressure. It is important to note this test is conducted with a water-filled hose sample.

3.1.5 Gaps Between Standardized Tests vs Thermal Environments on the Fire Ground

Standardized tests used to examine thermal performance of firefighting PPE and equipment require a heat source that is repeatable and reliable. As a result, the heat source is typically an electric heater, a gas-fired panel, or a gas burner. The heat source is not a diffusion flame from a piece of furniture, structural members, or a room and contents fire. In fact, if you ask firefighters about fires, they will usually respond that every fire is different. Hence the thermal exposure conditions between a fire in a structure and a series of laboratory tests are likely to be and in some cases purposely designed to be very different. There seem to be gaps of different types that may require different approaches to solutions for bridging the gaps.

Nothing a firefighter wears or uses is fire proof. The data and standard requirements indicate flame temperatures can exceed 1,000 °C (1,832 °F), yet most of the PPE or gear is tested to 260 °C (500 °F) for 5 minutes. The peak heat flux exposures to firefighting coats and pants are 84 kW/m^2. This is a significant exposure, but the data shows heat flux values exceeding the TPP test by a factor of two can occur on the fire ground. Equipment such as fire hose and fire nozzles is currently not tested to the same extremes as PPE.

When PPE and gear are subjected to convective oven tests, the velocity of the hot gas is less than 1.4 m/s (3.1 mph). Data from fire experiments and fire simulations show that firefighters could be subjected to hot gas flows of at least two to three times the velocity used in the relevant standardized tests. This does not address conditions in which wind or elevation may further increase the velocity of the fire gases. The increased hot gas velocity reduces the firefighters safe operation time during a fire incident. In other words, it reduces the time the PPE can protect them or reduces the time their equipment will function as designed.

There may be several ways to address the gaps between the standardized tests for thermal performance and the thermal environments on the fire ground: education, improved knowledge through data, changes in tactics, and a better understanding of fire ground experience.

Education

If all users of firefighting PPE and equipment understand the thermal performance capabilities and limitations of the gear based on the standardized tests, then perhaps they could better prepare for and decide if the gear is suitable for a given fire situation. For example, only recently has a large portion of the fire service become aware that the SCBA lens is made of a thermoplastic which can degrade as a result of exposure to thermal radiation levels well below those associated with post-flashover conditions. The IAFC, International Association of Fire Fighters (IAFF), International Fire Service Training Association (IFSTA), NFPA, NIOSH, and many other organizations issued information on this topic to increase firefighter awareness. However, there is no easy metric to determine if all active firefighters, officers, and chiefs have received and understood that information. Other items such as the SCBA unit, thermal imager, portable radios, and remote speaker microphones, have all been associated with LODD incidents for a potential failure (or lack of understanding by the operator) due to thermal exposures on the fire ground. Are further alerts needed?

Perhaps there is a mis-understanding of the thermal failure temperature (for example, the melting point) or the loss of operation of various pieces of PPE or equipment used by firefighters. As a result, there may also be a misunderstanding of the thermal conditions in which a firefighter can safely operate. Ignition testing, melt testing, and operation testing on various pieces of PPE will define the thermal failure conditions and lead to a better understanding of the conditions for a safer firefighting environment. Although there are flame and heat resistance tests in NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting [27] and NFPA 1981, Standard on Open-Circuit Self Contained Breathing Apparatus for Fire and Emergency Services [33], these tests do not provide the engineering data needed to connect laboratory based research data with field data (thermally damaged equipment) from actual fire incidents. Therefore, they do not provide a thorough understanding of the impact of those conditions on the firefighter.

This review examined several incidents in which the capabilities of structural fire fighting PPE and equipment were overtaken by the thermal conditions of the fire environment. In these incidents, the operational safety of firefighters was compromised, in some cases resulted in a loss of life. There is a need to examine ways to enhance the understanding of thermal performance of structural fire fighting PPE and equipment in order to enhance protection for firefighters.

Perhaps the addition of a new requirement in NFPA 1001, Standard for Fire Fighter Professional Qualifications, for new firefighters to learn the capabilities of their PPE and equipment, based on NFPA standards, and also learn about the limitations of their PPE and equipment by comparing the gear capabilities to fire conditions and skin burn thresholds would reduce the current knowledge gap. The upcoming NFPA 1700, Guide for Structural Fire Fighting, may be another means of transferring the current knowledge about the capabilities and limitations of the PPE and equipment to current firefighters.

Data

There is a need for improved field data about current thermal conditions on the fire ground. The standards for firefighter PPE and equipment are based on limited sets of field experience data and on a series of research experiments in single rooms or compartments that do not completely reflect the exposures that may occur to a firefighter in a single family or multi-family dwelling unit. Additional research is needed to document the realistic thermal environment firefighters are currently exposed to. Given the changes on the fire ground and in firefighter protective equipment since the 1970s, it seems studies similar to those conducted in New York City and Boston must be conducted again. Advances in measurement technology and data communications would improve the quality, amount, and type of data collected. This is a crucial data set needed from both the fire training ground and actual incidents to quantify the thermal exposures firefighters encounter today, and to redefine the thermal classifications used by NFPA and other standards development organizations.

Improved understanding of the protective capabilities of firefighter PPE and equipment exposed to hot gas flows between 2.2 m/s (5 mph) and 9.0 m/s (20 mph) is critical because many of the LODDs and LODIs included hot gas velocities higher than the 1.3 m/s (3 mph) upper bound of current convective oven tests. Measurement of the heat transfer rate to equipment and through PPE under high convective flows is needed to assess the time component for future thermal classification, and to understand the protective capabilities of PPE and the operational capabilities of equipment under real-life fire conditions. Hot gas velocity is an important and largely undocumented component of the firefighter's thermal environment.

There is a need to understand the linkage between the human response, (such as pain or burn injuries), to the thermal environment and the capabilities of all firefighter gear.

3.1.6 Tactics

Data provided from recent and on-going research studies conducted by UL FSRI and the IFSI, and perhaps supported by the field studies conducted in New York City and Boston in the 1970s, indicates that if water was used to precondition the structural fire environment prior to and during firefighter entry or if the fire was attacked directly prior to entry, then the thermal exposure to the firefighter was reduced.

Another piece of information to consider. In November of 1950, a committee from the Fire Service Training Association (currently known as IFSTA) met with Chief Lloyd Layman in Parkersburg, WV. The outcome of that meeting was titled "Analysis of the Extinguishment of a Confined Structural Fire". As part of this analysis, the requirements to extinguish a fire that had flame production and major involvement of at least one room, or was a "smoldering fire" (ventilation-limited) were written down. The requirements included reducing the fire room temperature to 149 °C (300 °F) or less, before making entry to extinguish the fire [73]. The "Analysis of the Extinguishment of a Confined Structural Fire" was published in the IFSTA fire service training documents from 1957 through 1977. Bear in mind the firefighter protective clothing and some of the fire fighting equipment of the 1950s was not significantly different from the basic PPE that was being used by FDNY and the Boston FD in the 1970s (a leather helmet, a 3/4 length rubber coat with wool lining, work gloves, and rubber boots). Based on the data from the New York and Boston studies, the typical entry (exposure) temperatures were below 93 °C (200 °F) [25,26].

Is an exterior attack prior to making entry into the fire structure, or water flow while making entry, a tactical requirement needed to ensure the safety factor built into the PPE and equipment standards is maintained on the fire ground?

3.1.7 Fire Ground Experience

Fire ground experience is another type of data that seems to be missing when examining the standard test development needs for firefighting PPE and equipment. The literature review has several LODD reports and some near miss reports that provide information that show PPE and equipment were exposed to thermal conditions that exceeded the designed thermal capabilities. However, there are no data sets available to the fire service that show how many times a piece of PPE or equipment has failed to perform as expected, where no one was injured or killed. This type of crowd sourcing fire ground experience is needed to get a full understanding of where improvements to test standards are necessary. Conversely, it is just as important to understand the majority of fire ground experiences in which everything works. Again, collecting experience, and ideally collecting data from the fire ground is a keystone to closing the gaps between thermal performance test standards and the thermal exposure conditions on the fire ground. As "big data" measurement and collection systems evolve, perhaps firefighter equipment will record and transmit exposure data to enable insight into the thermal conditions of the firefighter equipment operational environment.

Section 4

Thermal Scenarios

Previous thermal classifications of the firefighters' thermal environment were developed from data that typically considered temperature only or temperature and heat flux pairs [22, 25, 74]. The challenge has been that the connection between gas temperature and radiant heat flux is a broad connection, not a narrow one. This means we do not have a one-to-one relationship between a given gas temperature and a given heat flux, because the temperature and heat flux can vary independently based on several parameters of the fire environment. This is also true for the relationship between gas temperature and the convective heat transfer rate. While it may be appropriate in some test methods to decouple the problem, there is a need for scenarios that account for the cumulative heat transfer rate vs safe operational time. Rapid growth rate fires or rapid changes in ventilation are not completely accounted for within the suite of tests currently used within the standards process.

Several fire ground scenarios can be considered to categorize the potential thermal hazard. For example, the location close to the origin of the fire or in the fire room, hallway approach to the fire room (horizontal exhaust vent), operating above the fire floor, or operating above the fire in a stairwell (vertical exhaust vent) have been shown as areas where fires have adversely thermally impacted firefighters. The fire environment depends on a number of variables such as the fuel (amount, type, geometry), the compartment (size, lining material), and available ventilation. That said, the range of conditions that could be potentially be generated in each of the scenarios is wide spread. The range of thermal condition extends from ambient conditions through post-flashover conditions. Rarely does the fire provide a steady state, thermal environment as the amount of fuel available for combustion varies, as does the oxygen available for combustion, throughout the course of the fire incident. So how do we move forward?

Figure 4.1 attempts to meld together the graphical representation of two of the thermal classification sets developed at NIST by Utech [74] and by Donnelly, et. al. [22]. In the figure, the three Utech thermal classifications of Routine, Ordinary and Emergency are shown in the bold color boxes. The lighter colored areas represent the four thermal classes NIST developed in 2006 based on a literature search that included the values from Utech. Keep in mind that of the four thermal classes from the NIST 2006 study have operational time limits for equipment. The time limits from Thermal Class I through Thermal Class IV are 25 minutes, 15 minutes, 5 minutes, and less than 1 minute, respectively. Overlaid on the graph of the thermal classes are symbols that represent selected data points from the literature review. Table 4.1 provides the legend for the symbols, the source of the data, the numerical values of the temperature, and the heat flux. The positioning of the symbols on Figure 4.1 demonstrate the distribution between the temperature and heat flux values. The symbols show the accepted pairing of gas temperature ranges with a corresponding range of heat fluxes does not reflect all fire conditions. There are cases in which the heat flux exceeds the hazard level of the surrounding gas temperature.

The graphic does not include the impact of velocity. Perhaps the next generation of Thermal Classes will be based on heat transfer rate and total heat transferred to determine safe operational time frames (for people and equipment), which is really what the time and temperature relationships were trying to accomplish.

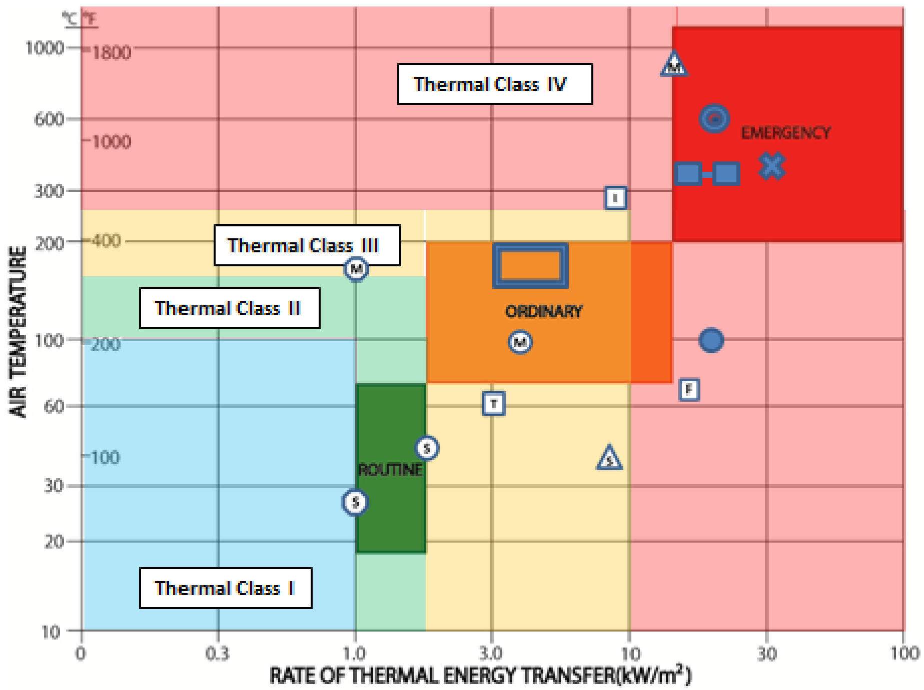


Figure 4.1: Thermal Class comparisons with temperature/heat flux data points from research studies included in this review.

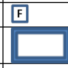
	Symbol	Temperatures ($^{\circ}C$ / $^{\circ}F$)	Heat Flux (kW/m^2)
Onset of Flashover		600 /1100	20
Residential Apartment		400/750	30
Open Office		100/212	20
Public Occupancy		350/660	15 to 25
Face Piece		25/77	15
IFSI Training		150/300 to 200/390	3 to 6
UL Fire Attack Bedroom 1 Window Closed Hallway Start		40/ 110	2
UL Fire Attack Bedroom 1 Window Closed Hallway Middle		140/280	4
UL Fire Attack Bedroom 1 Window Open Hallway Start		30/90	8
UL Fire Attack Bedroom 1 Window Open Hallway Middle		510/950	10
UL Fire Attack Bedroom 1&2 Windows Open Hallway Start		30/80	1
UL Fire Attack Bedroom 1&2 Windows Open Hallway Middle		160/320	1
IFSI Interior Attack		315/600	8
IFSI Transitional Attack		65/150	3

Table 4.1: Temperature and heat flux values from research studies included in this review.

Section 5

Future Research

A number of potential research efforts could improve the current understanding of the interaction of the broad spectrum of thermal conditions that can exist in the fire environment with the firefighters there to extinguish the fire and protect life.

1. Document current conditions on the fire ground by conducting the types of studies that were conducted with FDNY and Boston FD in the 1970s. This should involve a wider range of departments, varied weather conditions, and be conducted over a several year period in order collect adequate data.

2. Improved understanding of the impact of convective and radiative heat transfer on firefighter protective clothing and equipment.

3. Protective capabilities of firefighter protective clothing and equipment are not equal, in part because of the wide range of materials and composites used in the gear. Perhaps a new study of a systems-based approach to firefighting PPE and equipment is needed to examine the use and life-cycle of the gear. For example, we need a comprehensive look at materials used in PPE and equipment under a wider range of thermal conditions. Perhaps the chemicals emitted as PPE and equipment provide thermal protection should to be measured and considered in terms of potential carcinogenic exposures.

4. Improved understanding of the protective capabilities of fire fighter protective clothing and equipment under hot gas flows between 2.2 m/s (5 mph) and 9.0 m/s (20 mph). The improved knowledge of gas velocity would be required to develop the next generation of Thermal Classes based on heat transfer rates in order to develop an available safe operational time criteria for firefighter PPE and equipment.

5. Advance research on the human response to the thermal environment to better understand the ability to protect firefighters and civilians.

6. Develop research results and decision-making tools that would assist company officers and incident commanders in recognizing the potential for thermal conditions that would overcome the thermal capabilities of their crews' PPE and equipment. Thus enabling them to adjust tactics prior to committing to an interior attack.

Section 6

Summary

The goal of this study was to review the available literature to develop a quantitative description of the thermal conditions firefighters and their equipment are exposed to in a structural fire environment. The thermal exposure from the modern fire environment was characterized through the review of fire research studies and fire ground incidents that provided insight and data to develop a range of quantification. This information was compared with existing standards for firefighting PPE and equipment to generate a sense of the gap between known information and the need for improved understanding. The comparison of fire conditions with the thermal performance requirements of firefighter PPE and equipment demonstrates that a fire in a compartment can generate conditions that can fail the equipment that a firefighter wears or uses.

It is clear fire can generate thermal environments that can exceed the capabilities of the firefighter PPE and equipment that are available today. Since the 1970s, the NFPA, researchers, the fire service, and the manufacturers have been working together to improve and optimize the protective capabilities of the PPE and equipment. Optimization is a key word. Gear could be built to withstand higher heat transfer rates, but most solutions result in the addition of weight, reduced breathability, increased heat stress, some loss of functionality, and increased cost. Therefore, a fireproof suit with fireproof safety equipment is not likely to be available anytime soon. There is potential the solutions could be more harmful to firefighters than the current hazards present on most fire scenes, so a careful holistic analysis is needed prior to implementing changes to the standards.

The review pointed out that:

1. The accepted pairing of gas temperature ranges with a corresponding range of heat fluxes does not reflect all fire conditions. There are cases in which the heat flux exceeds the hazard level of the surrounding gas temperature and vice versa.

2. Thermal conditions can change within seconds. Experimental studies and incidents were identified in which firefighters would be in thermal conditions that were safe for operation based on the temperature and heat flux, but then due to a change in their environment, the firefighters would be exposed to conditions that could exceed the protective capabilities of the PPE and equipment.

3. Gas velocity is not explicitly considered within the thermal performance requirements. PPE and equipment tested with a hot air circulating (convection) oven are exposed to gas velocities

of approximately 1.3 m/s (3 mph). The convected hot gas flows within a structure fire could be in the range of 2.2 m/s (5 mph) and 9.0 m/s (20 mph). In cases where the firefighter would be located in the exhaust portion of a flow path, while operating above the level of the fire, the hot gas velocity could be higher. The increase in hot gas velocity would serve to increase the convective heat transfer rate to the PPE, the equipment, and the firefighter, thereby reducing the safe operating time within the structure.

4. Based on the limited data available, it appears the effectiveness of currently available protective clothing enables firefighters to routinely operate in conditions above and beyond the routine conditions measured in the fire ground exposure studies conducted during the 1970s.

The fire service and fire service standards communities could benefit from: 1) an improved understanding of real world fire ground conditions using modern sensor and data acquisition methods for monitoring the fire fighting environment; 2) an improved understanding of the impact of convection on the capabilities of PPE and equipment; and 3) an effort to harmonize or balance the thermal exposures across different components of firefighter protective clothing and safety equipment.

Fire officers and fire chiefs must consider the capabilities of the protection that their firefighters have when determining the strategies and tactics of a fire attack, to ensure the gear is kept within the design operating environment, and that the safety factor it provides is maintained in case of an emergency.

Section 7

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