Residential Structure Fire Intervention and Victim Tenability

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1 Abstract

Twelve full scale fire experiments were conducted in a 111 m^2 structure constructed to be representative of a single family dwelling constructed in the late 20th century. The structure was instrumented with temperature measurements in each room and gas concentration measurements in the hallway between the two fire rooms; the two uninvolved, closed bedrooms; and the dining room. Two 61 kg (135 lb.) firefighter training mannequins were placed in the dining room and the closed bedroom closest to the fire rooms in order to simulate occupants who were trapped within the structure. 6 groups of firefighters, recruited from fire departments throughout the country, participated in two experiments each. Each group included an attack team and a search team, each of which consisted of two firefighters. The attack team executed either a transitional attack or an interior attack, and the search team searched for the simulated trapped occupants in a pattern starting away from the fire.

The results showed that there was a large variation in the times it took the 6 groups to complete various fireground tasks. The coefficient of variation of the groups' times to execute various fireground actions ranged from 20% to 95% of the average times. This emphasized the importance of training to develop proficiency in tasks such as hose advancement, forcible entry, and search techniques, as well as coordination between companies on the fireground to minimize miscommunication and improve efficiency.

Gas concentration and temperature measurements were analyzed using a fractional effective dose (FED) approach. The results indicated that a closed bedroom door was effective at isolating the contents of the room from toxic products of combustion. The FEDs within the two closed bedrooms were found to be significantly lower than locations just outside of the closed door. Occupants trapped in the closed bedrooms would likely have been tenable well into the experiment. The most severe toxic and thermal exposures that were measured were in the hallway outside of the two fire rooms. This was the only location within the structure where incapacitation due to thermal insult occurred prior to incapacitation due to toxic gas exposure. This is consistent with fire victim data where occupants found close to the origin of the fire typically sustain severe thermal injuries, but have relatively low carboxyhemoglobin levels. The thermal

exposure in other areas of the structure decreased as distance from the fire room increased, particularly in isolated areas.

Water application by the fire attack teams was associated with a rapid drop in temperatures throughout the structure, followed shortly afterward by a decrease in the FED rate. There was no significant difference between the magnitude of the temperature decrease or the time until the inflection point in the FED curve between transitional attack and interior attack. For the transitional attack scenarios, water was applied to the fire significantly earlier in the experimental timeline than in the interior attack scenarios, while in the interior attack scenarios, the attack team made entry to the structure significantly sooner than in the interior attack scenarios. In one of the transitional attack experiments, the exterior water application was not sustained for a sufficient amount of time, allowing for regrowth of the fire, resulting in temperature rebound in areas close to the seat of the fire and a substantially longer time until the FED rate began to decrease. Similarly, for the interior attack scenarios, significant improvements within the structure were not noted until the attack team able to direct water directly onto the burning contents in the bedrooms. For both attack methods, significant improvements in interior conditions were observed following effective water application, while ineffective water application reduced or delayed the positive effects.

The time from search team entry to removal of the dining room victim ranged from 20 seconds to 158 seconds. As the removal time for the victim increased, the toxic exposure to the victim increased, despite the decreasing FED rate due to suppression. This observation is consistent with the nature of the governing equations, as the FED will always increase until concentrations return to ambient. The search crews in these experiments were directed to search in a pattern away from the fire, although some fire service literature dictates that the search should begin close to the seat of the fire to find the victims that are most threatened. In these experiments, a victim located at the hallway would indeed have been more threatened at the time that the search crew reached and located them, but the victim would also have been less likely to be tenable compared to the same victim located in the dining room. This dining room victim, while exposed to a high dose of toxic gases, received a significantly less severe thermal insult than an occupant located in the hallway next to the post-flashover bedroom fires. The victim tenability analysis highlighted the guidance of fire service literature, that the search should attempt to focus on the victims that are most threatened, although showed that threatened victims are not always closest to the seat of the fire. Additionally, the results emphasized the need for rapid removal of occupants to limit toxic exposures. The results of the 12 experiments conducted indicated that a successful fire attack in terms of maximizing the probability of occupant tenability involves the coordination of suppression and ventilation tactics to promptly and effectively deliver water to the fire and reduce the thermal and toxic insult to potential occupants with rapid identification and removal of the occupants.

2 Introduction

A primary goal of firefighting is to extinguish fire to protect life and property. While this basic goal may seem obvious and straightforward to a civilian, the tactics used by the fire department to accomplish this goal may vary considerably. Based on an accumulating body of evidence, many fire departments are emphasizing applying water to the fire as soon as possible to improve conditions inside the structure [1]. Such an approach is often called a “transitional” attack in which firefighters apply water through a window in order to initially suppress the fire before they enter the building to completely extinguish the fire and ensure there is no further fire growth. This approach contrasts with the “interior attack” method that many departments have been taught, which is that it is best to initially enter the house through the front door with a charged hose line. In theory, the goal of this “interior” fire attack is to find the seat of the fire and extinguish it as soon as possible to protect potential victims. To date, there is limited research that has considered the effect of different firefighting tactics on potential occupant survivability.

Occupant tenability, which is related to the survivability of occupants in the fire environment, is a primary concern for any firefighting operation. Occupant tenability was estimated seperately for two routes of exposure, temperature and gas concentration, using the fractional effective dose methodology from the SFPE Handbook [2]. The method used to consider the time-dependent exposure of an occupant to toxic products of combustion is defined in Equation 1. FED relates to the probability of the conditions being non-tenable for a certain percent of the population through a lognormal distribution. For reference, FED = 0.3 is the criterion used to determine the time of incapacitation for susceptible individuals (young children, elderly, and/or unhealthy occupants) and corresponds to untenability for 11% of the population, and FED = 1.0 is the value at which 50% of the population would experience untenable conditions. Untenability as a result of exposure to products of combustion is considered the point where the occupant would no longer be able to affect their own rescue.

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

In Equation 1, (FED_{CO}) and (FED_{HCN}) are the fractional doses for carbon monoxide (CO) and hydrogen cyanide (HCN), respectively. These terms are the fraction of an incapacitating dose at a discrete time step, Δt. A study conducted by Fent et al. [3] examined the fireground exposure of firefighters to various chemicals, including HCN. The study found that the interior and exterior crews (attack and outside vent) were exposed to immediately dangerous to life and health (IDLH) concentrations of HCN. Although HCN was not measured in these experiments, it is reasonable to assume that it would contribute to the toxic exposure of victims trapped in the structure. CO is often considered to be the most important asphyxiant gas that trapped occupants will encounter [2]. The expression for FED_{CO} is shown in Equation 2, where ϕ is the CO concentration in parts per million and Δt is the time step, V is the volume of air breathed each minute, in liters, and D is the exposure dose, in percent COHb, required for incapacitation. ISO 13571 [4] lists the uncertainty assocaited with the calculated FED_{CO} as 20%.

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

Values of V and D vary depending on the level of work being conducted by the subject. The default case is often taken to be light work, which corresponds to D = 30% COHb and V = 25 L/min. The uptake rate of CO and other products of combustion can vary considerably with V, and is dependent on a number of factors, including hyperventilation due to CO_2. This increase in respiration rate due to CO_2 inhalation is accounted for in Equation 1 by the hyperventilation factor, v_{CO_2}.This factor is defined in Equation 3, where ϕ_{CO_2} is the mole fraction of CO_2. ISO 13571 [4] lists the uncertainty associated with the calculated v_{CO_2} as 35%.

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

There is no FED criteria to conclusively predict lethality, as the pathology of toxic inhalation becomes complicated in the period between incapacitation and death. The incapacitating and lethal effects of CO inhalation are related to the carboxyhemoglobin (COHb) level, in the blood stream. Carboxyhemoglobin is formed when CO bonds with hemoglobin. Since hemoglobin has a higher affinity for CO than for oxygen (O_2), high COHb levels have an asphyxiating effect on vital organs, notably the brain. Incapacitating levels of COHb in the bloodstream are between 30% and 40% for the majority of the population, although susceptible populations may experience loss of consciousness at levels as low as 5%. Death is predicted at COHb levels of 50-70%. Autopsy data indicates that survival is rare among fire victims with COHb levels between 50% and 60%, with 50% COHb typically taken as the median lethal dose. Incapacitating levels of COHb are commonly found in surviving fire victims [2]. Active subjects are more severely affected by COHb concentrations than sleeping subjects. Often, relatively minor increases in actrivity can result in the loss of consciousness to a previously sedentary subject.

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

The FED_{temp} tenability limit is commonly taken as the expected onset of second degree burns. FED_{temp} is composed of two components: a convective component and a radiative component, as shown in Equation 4, where t_{conv} is the time (minutes) to incapacitation due to convective heat transfer and t_{rad} is the time (minutes) to incapacitation due to radiant heat transfer. Since t_{rad} is a function of the heat flux from the gas layer, which was not measured, the radiative contribution was not considered in these experiments. Rather, the FED_{temp} was calculated by considering the convective contribution, shown in Equation 5, at an elevation of 0.9 m above the floor, representative of a relative worst case scenario of a person crawling on the floor.

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

$$FED_{conv} = 4.1x10^8 T^{-3.61} \tag{5}$$

This paper will focus on occupant survivability and the interaction between firefighter suppression (transitional attack and direct interior attack) and search and rescue tactics on occupant survivability. This will be done by utilizing building temperature and gas concentration measurements that were placed close to two simulated occupants.

3 Methods

3.1 Subjects

subjects were recruited through a nationwide multimedia effort, along with a focus on a statewide network of firefighters who teach and train at the Illinois Fire Service Institute (IFSI). Forty (n=40) firefighters (36 men, 4 women) from departments in Illinois, Georgia, Indiana, Ohio, South Dakota and Wisconsin participated in this study. On average, firefighters were 37.6±8.9 years old, 1.80±0.08 m tall, weighed 89.8±14.5 kg and had an average body mass index of 27.6±3.4 kg/m^2 [5].

All subjects were required to have completed a medical evaluation consistent with National Fire Protection Association (NFPA) 1582 [6] in the past 12 months. An emphasis was placed on recruiting experienced firefighters who had up-to-date training, could complete the assigned tasks as directed, and were familiar with live-fire policies and procedures. Throughout the study protocol, all firefighters were required to wear their self-contained breathing apparatus (SCBA) prior to entering the structure. The research team supplied all personal protective equipment (PPE) for the subjects to enhance standardization and to ensure that all protective equipment adhered to NFPA standards.

3.2 Study Design

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

Trials differed only in the tactics used by the fire attack team: (a) traditional interior attack from the “unburned side” (advancement through the front door to extinguish the fire) and (b) transitional attack (water applied into the bedroom fires through an exterior window prior to advancing through the front door to extinguish the fire). The firefighters performed the same role using both tactics.

In each scenario, the attack crew of two firefighters approached the fireground at the time of dispatch, proceeded to the attack pumper, and deployed the hoseline. The attack team was directed to execute either a transitional attack or an interior attack. For the interior attack scenarios, the attack crew deployed their line to the front door of the structure, donned their SCBA, and made entry after the search crew had simulated forcing entry. In the transitional attack scenarios, the crews positioned their hoseline so that they could apply water to the bedroom on the A-side (front) of the structure. Once applying water to this window, the crews maneuvered their line to the second window, applied water to that window, before repositioning their line to the front door to make entry. The duration of flow in each window varied between groups, and the average values are presented in Table 4.

The search team was delayed by 60 s following dispatch, to simulate companies arriving at different times. Upon arrival on the scene, the search crew donned their SCBA masks and simulated forcing entry on a training prop before entering the structure. The search crew of two firefighters were instructed to search the structure beginning in the half of the house opposite the fire room. As the crews searched, they found the first simulated occupant, located in the corner of the dining room, propped against the far bedroom door. Once they removed this occupant, they continued their search pattern through the far closed bedroom, the kitchen, and the living room, before reaching the closed bedroom closer to the fire bedrooms, where the second simulated occupant was located.

3.3 Study Protocol

To ensure the fires conducted as reliably as possible, a structure was designed and built to have all of the interior finishes and features of a single family dwelling and identical furnishings were used in each fire. To ensure safety, specialized safety systems and hardened construction were employed. A residential architectural company designed the house to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings. The home had an approximate floor area of 111 m^2, with 8 total rooms, including 4 bedrooms and 1 bathroom (closed off during trials). Interior finishes in the burn rooms were protected by 15.9 mm Type X gypsum board on the ceiling and 12.7 mm gypsum board on the walls. To maximize the use of the structure and minimize time between trials, the house was mirrored so that there were 2 bedrooms on each side where the fires were ignited. During each trial a temporary wall was constructed at the end of the hallway to isolate 2 bedrooms so that they could be repaired and readied for the next trial. The left and right layouts are shown in Figure 1. Furniture was acquired from a single source such that each room was furnished identically (same item, manufacturer, make model and layout of all furnishings) for all 12 trials. The bedrooms, where the fires were ignited, were furnished with a double bed (covered with a foam mattress topper, comforter and pillow), stuffed chair, side table, lamp, dresser and flat screen television. The floors were covered with

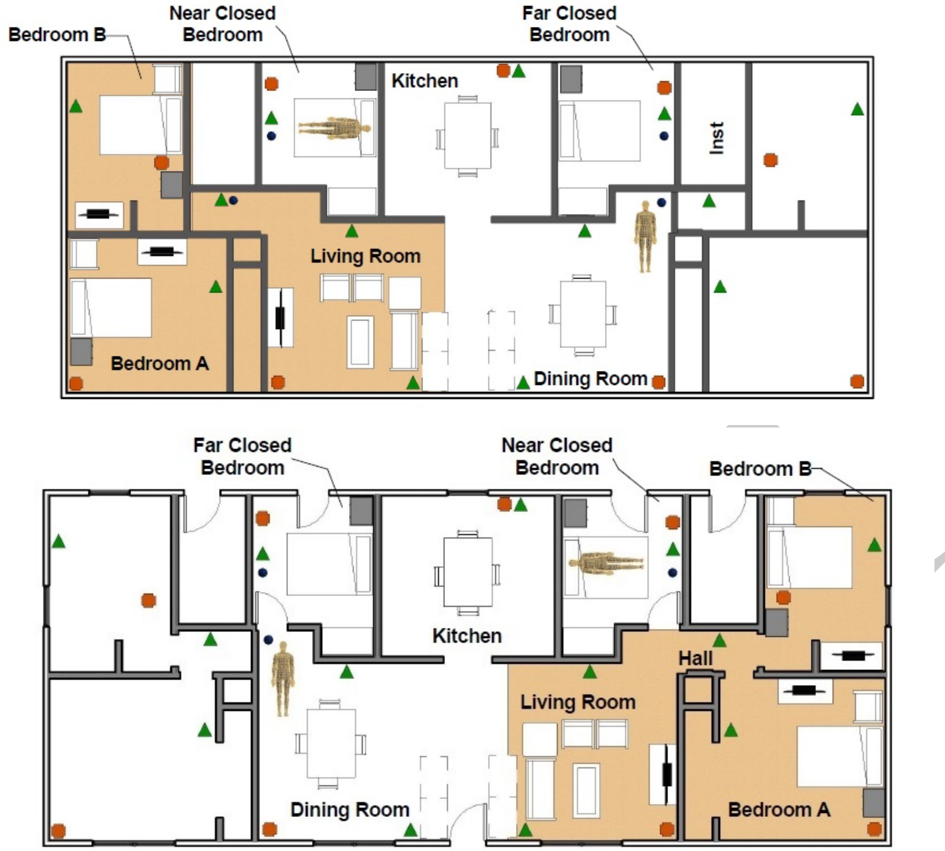

Figure 1: Layout of burn structure, location of victims, and Instrument Locations for Left (top) and Right (bottom) layouts

polyurethane foam padding and polyester carpet. All other rooms of the structure were also furnished to provide obstacles for the firefighter, but those furnishings were not involved in the fire. Figure 1 provides a rendering of the structure with the roof cut away to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the gray floor shows the cement floor or simulated tile locations.

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

3.4 Measures

3.4.1 Building Temperature Measurements

To assess fire dynamics throughout the scenarios, measurements included gas temperature, gas concentrations, pressure, heat flux, thermal imaging, and video recording. Detailed measurement locations can be found in Figure 1 and [7]. This manuscript will focus largely on gas temperatures, which were measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.5 mm nominal diameter. Thermocouple arrays were located in every room. The thermocouple locations in the living room, dining room, hallway, both closed bedrooms, and kitchen had an array of thermocouples with measurement locations of 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m and 2.1 m above the floor. The thermocouple locations in Bedroom A and Bedroom B had an array of thermocouples with measurement locations of 0.3 m, 0.9 m, 1.5 m, and 2.1 m above the floor.

3.4.2 Building Gas Concentration Measurements

Ambient concentrations of O_2, (CO), and carbon dioxide (CO_2) in the local environment were measured (OxyMat 6 and Ultramat 23 NDIR; Siemens) at 0.9 m from the floor inside and outside of the closed bedrooms. This measurement height corresponds with the height of the head of the adjacent to the simulated occupant sitting outside of the far bedroom and the simulated occupant lying on the bed in the near bedroom. This measurement height is also consistent with the height of the head of a potential occupant crawling to escape the fire. The uncertainty of the measured concentration is 1% of the maximum concentration measurement. The maximum concentrations measured were 5% for CO and 20% for CO2. The gases were extracted from the corners of rooms to minimize risk of damage from removing burned fuels. All data were collected at a frequency of 1 Hz.

3.4.3 Firefighter Intervention Measurements

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

3.5 Occupant Tenability

In order to estimate trapped occupant tenability, equations 2 and 4 were numerically integrated using an Euler scheme and a discrete time step of 1 Hz (1/60 min) using the building gas concentration measurements and building temperature measurements described above. The time to exceed the thresholds for all of the experiments in each house for both heat (only convection considered) and CO/CO_2 are calculated inside and outside of the near and far closed bedrooms. It should be noted that the values assume the simulated occupant was in that location for the duration of the experiment. These estimates may be considered lower bound scenarios as additional thermal risks may be present from exposure to large radiant heat exposures or from the additive effects of exposure to a variety of different fireground gases such as HCN.

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

3.6 Statistical Analysis

The combined uncertainty of Type K thermocouples is listed as 15% [8, 9] and the combined uncertainty of the gas analyzers used in these experiments is 12%. In order to assess the repeatability between experiments, the average temperatures at each victim location in the 30 seconds prior to firefighter intervention were computed and compared to the uncertainty of these sensors.

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

4 Results

4.1 Building Temperature Measurements

The 0.9 m (3 ft.) temperature was used to assess the thermal exposure to which an occupant trapped at different locations within the structure may be subjected. The average temperature in the 30 seconds prior to firefighter intervention in the hallway, outside of the fire rooms was 320±64°C. In the dining room, remote from the seat of the fire, the average temperature was 135±34°C. The coefficients of variance were 20% and 25% for the hallway and dining room locations, respectively. These values are greater than the combined instrument uncertainty of 15%, a difference which can partially be attributed to the wind. Since the test structure was not located in a controlled lab space, the presence or absence of wind could have a significant effect on flow paths within the structure. The 0.9 m (3 ft.) temperatures measured in the closed bedrooms were significantly lower than those measured in the areas of the structure open to the fire. The average temperature in the 30 seconds prior to intervention was 23±2°C in the near bedroom and 21±1°C in the far bedroom. The coefficient of variation for these sensors are 7.0% and 5.8% for the near and far bedrooms, respectively, less than the 15% combined uncertainty of the thermocouples.

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

The least severe thermal conditions were observed in the two closed bedrooms where temperatures at the time of firefighter intervention were lower in both locations than in the areas immediately outside of the closed door. Once firefighter intervention was initiated, whether from the interior or the exterior, there was no immediate effect on the temperatures or FED_{temp}s within the room. In the experiments where the closed bedroom doors were opened for search and rescue, however, there was a corresponding temperature increase and FED_{temp} rate increase. Although opening the bedroom door to facilitate search often resulted in a measurable increase in the FED_{temp} rate, the total FED in both closed bedrooms remained below 0.10 for both bedrooms and the 0.9 m (3 ft.) temperature never exceeded 40°C. Thus, even the most severe thermal conditions within the bedrooms to which a trapped occupant would be subjected were less severe than those encountered in open areas of the structure.

4.2 Building Gas Concentration Measurements

At the time of firefighter intervention, the FED calculations varied considerably between experiments. At the near hall location, just outside of the bedroom fires, the average FED value at the time of firefighter intervention was 1.06±0.96. In the dining room location, next to the first simulated occupant, the average FED was 0.34±0.36. The coefficients of variation were higher than those calculated for the building temperatures, and were 90% and 105% for the hallway and dining room, respectively. The variation that was noted in these measurements can be attributed to variations in the CO, CO_2, and O_2 measurements. The

Table 1: Final FED_{temp} Values at Each Measurement Location

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

variation in these measurements was greater than the uncertainty of the sensors. Additionally, because the FED equations presented in Equations 2 and 3 are exponential in nature, small measurement variations will result in larger variations in the FED calculation. Further, ISO 13571 [4] lists the uncertainty for the FED calculations as high as 35%. In the closed bedrooms, the FED magnitude at the time of firefighter intervention was negligible.

Incapacitation was reached at 467±67 s and 453±31 s in the hallway gas sample location for the transitional and interior attacks, respectively. On average, the dining room victim location reached incapacitation at a later time than the hallway, at 533±78 s and 618±136 s from ignition, for the transitional and interior attack, respectively. These times occur after the average firefighter intervention times (390±16 s for transitional attack, 442±24 s for interior attack). Table 2 lists the maximum FEDs observed for each measurement location in each experiment. The average total FED values for the locations open to the fire rooms were 3.08±1.17 and 2.31±1.03 for the near hall and dining room locations, respectively. These values were substantially higher than the FEDs recorded in the closed bedrooms, which were 0.63±0.58 and 1.09±0.54 for the near and far closed bedrooms, respectively. There was no significant difference between the two bedrooms (p=0.22). This indicates that the closed bedroom door is an effective barrier to products of combustion, which are noted in high concentrations low to the floor in the open areas of the house. Even in the bedroom closest to the seat of the fire in the bedroom, the conditions behind the closed door are significantly lower (p=0.005) than in the hallway immediately outside the bedroom. The near bedroom sample point was also significantly lower (p=0.003) than the sample point located in the dining room, next to the open victim.

Table 2: Final FED_{gas} Values at Each Measurement Location

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

n.a indicates a sensor malfunction at that location

4.3 Firefighter Intervention Measurements

Each group of firefighters participated in one transitional attack scenario and one interior attack scenario. The only direction given to the groups performing these tasks was which method of attack to perform and which direction the search crew should begin their search. A considerable amount of variation was noted in the time that the various groups took to complete fireground tasks such as hoseline deployment, hoseline advancement, and victim location and removal. Table 3 lists the average times (with standard deviations) that the groups took to perform these actions. The least amount of variation (defined by the coefficient of variation), approximately 20%, was noted in the hoseline deployment, which was defined as the time that the firefighter removed the hose from the fire engine to the time that the nozzle was "bled," ensuring that the attack team had a serviceable line. The variability in the line advancement, which was defined as the time from when the attack team entered the door to when they reached the hallway, was higher, at 55%. The highest variability was noted in the forcible entry task, which was 95%.

Table 3: Times for Firefighting Tactics

Task	average Time for Task Completion ± Standard Deviation (s)	Coefficient of Variation (%)
Hoseline deployment	79±16	20
Hoseline advancement	29±16	55
Forcible entry	22±21	95
Time to locate dining room victim	48±22	35
Time to remove dining room victim	37±13	45
Time to locate bedroom victim	140±54	39
Time to remove bedroom victim	60±38	63

The timeline of firefighter interventions varied with both the method of attack (transitional vs. interior) and the actions taken by the subjects during their execution of the fire attack (Table 4). From the time that the line was pulled from the engine, the transitional attack resulted in significantly faster water application to the fire ($p<0.001$) than the interior attack method. For the transitional attack, water was applied to the front bedroom in 82±9 s, whereas in the interior attack scenarios, entry to the structure was made in an average of 127±11 s after pulling the line. Most of the interior attack teams utilized a "shut down and move" technique, where water would be applied from a stationary position, before advancing and repeating the maneuver. The crews applied water sometime between entering the structure and reaching the hallway. The first interior water application occurred 10±6 s following entry, and most crews applied water for 3±2 s on this initial application.

Table 4: Times for Hose Deployment and Water Application

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

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

Table 5: Times to Find and Remove Occupants

Event	Interior Attack Time (s)	Transitional Attack Time (s)
Time to find dining room occupant	35.7±15.1	38.3±9.8
Time to remove dining room occupant	42.0±21.2	54.3±21.4
Time to find bedroom occupant	218.3±61.9	263.7±74.1
Time to remove bedroom occupant	49.8±63.5	55.5±21.1

As the search company opened the doors to the near and far bedrooms in order to gain access and complete their search, the bedroom was no longer isolated from the rest of the structure. Out of the twelve experiments, 8 search crews made entry into the far closed bedroom and searched it, and 4 passed over the bedroom, leaving the door closed and not searching. In the cases where the remote bedroom was opened and searched, an increase in FED rate was observed as products of combustion filled the room. For the four tests in which the door was not opened during the initial part of the search, this increase in FED rate was not observed. The peak FED rate calculated in the experiments where the search crew opened the door (0.0030±0.0010) was significantly higher (p=0.003) compared to the peak FED rate for experiments where the door to the far closed bedroom was not opened and searched (0.0010±0.0002). For the far closed bedroom, which was opened and searched earlier in the timeline of the experiment, opening the door resulted in an increase in the FED rate for any potential victims located in the room.

The significant increase in FED rate following the opening of the door to the far bedroom was not observed in the near bedroom. The near bedroom door was opened in all twelve of the experiments. There was no significant difference between the maximum FED rate prior to and following the search crew's entrance of the near closed bedroom.

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

For the other experiments, after water was applied, whether from the interior or the exterior, the FED rate in open areas of the structure began to decrease. For the gas sample location in the hallway outside of the fire rooms, this inflection point occurred 43 ± 28 s from the time that water was first applied for the transitional attack experiments and 35 ± 30 s from the time that the attack crew made entry for the interior attack experiments ($p=0.73$). For the gas sample location in the dining room, this inflection point occurred 100 ± 43 s from the time that water was first applied for the transitional attack experiments and 27 ± 24 s from the time that the attack crew made entry for the interior attack experiments. Apart from the two outliers experiments discussed previously, the FED rate did not increase at any time following water application. Thus, this FED rate inflection point can be taken as the time at which conditions would start to improve for occupants in an areas of the structure not isolated by a closed door or other barrier. For the near hall position, there was no significant difference between attack methods, but for the dining room location, the interior attack method did improve conditions significantly more rapidly than the transitional attack method ($p=0.02$). A possible reason for the more rapid improvement in the interior attack case is the ventilation that accompanies the opening of the front door and line advancement. As a flow path through the front door is established and fresh air enters the structure, products of combustion are displaced. The entrainment of fresh air, accompanied by the ongoing suppression, likely work in tandem to result in the improvement of conditions remote from the fire room. Table 4 shows that in the transitional attack scenarios, water was applied to the fire approximately 45 s sooner after dispatch for the transitional attack scenarios such as the time from dispatch until the FED_{GAS} rate inflection is 205 ± 36 s for interior attack and

169±24 s for transitional attack, which is not a significant difference between the scenarios (p=0.14). Similarly, in the dining room sample location, the time from dispatch to the inflection point was 225±46 s for transitional attack and 192±12 s for interior attack, a difference which is also not significant (p=0.27). Thus, while the interior attack resulted in a more rapid improvement in conditions in the dining room location from the time of water application, it also took longer from the time of dispatch to apply water to the fire, resulting in no significant difference when considering the two attack methods from a common time frame.

Similarly, following the application of water, temperatures decreased throughout the structure at the 0.9 m (3 ft.) heights, and continued to decrease for the remainder of the experiment. Temperatures gradually approached ambient as spot fires were extinguished and ventilation was provided. In order to evaluate the effectiveness of the suppression mode, a 60 second window after the time of initial firefighter intervention was examined. This window encompasses the time required to position the handline to apply water to both bedroom fires, and captures the highest rate of temperature decrease following suppression. In the hallway between the fire rooms, this temperature decrease was 261±101°C for the transitional attack scenarios and 313±69°C for the interior attack scenarios, which was not significantly different between the two attack scenarios (p=0.42). The maximum rate of decrease, however, occurred more quickly (p=0.004) after suppression for the transitional attack (8±4 s) than for the interior attack (33±8 s) . This is likely because the limited visibility and geometry hinders the interior attack, an obstacle which is not present in the transitional attack.

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

5 Discussion

5.1 Repeatability of Fireground Skills

The variation in the times to task presented in Table 3 can be attributed to several factors. The age of the subjects, their level of experience conducting fireground operations, and the frequency and quality of their training can all affect the proficiency of firefighters in fireground skills. The variations in these times are often quite large when put into context on the fireground. For example, the slowest hoseline advancement group took 4.75 times longer to advance from the front door to the hallway than the fastest group. The minimum time that the search crew breached the forcible entry prop was 5 s, while the maximum time was 71 s. The longest removal times for the dining room and bedroom occupants, respectively, were 93 and 96 s, whereas the shortest times were 13 s and 20 s, respectively.

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

Thus, although firefighters of similar experience and training levels were sought for this study, there was a significant amount of variability in the amount of time required to complete fireground tasks. This variability between groups is compounded when operating in a dynamic fireground under poor visibility conditions. Therefore, when considering fireground operations such as search and rescue or fire attack, it must be understood that the same fire department, and indeed the same firefighters, are not arriving at every fire scene, and there is a significant amount of variability in how even common fireground tasks are performed.

5.2 Open vs. Isolated Areas

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

When comparing the final FED$_{temp}$ magnitudes, note that if the radiative contribution had been considered, the FED value at the time of the end of the experiment would have been higher. This effect is likely to be much more significant in the hallway near the fire rooms, where radiant energy from the flames are likely to impact potential trapped occupants, compared to the opposite side of the structure.

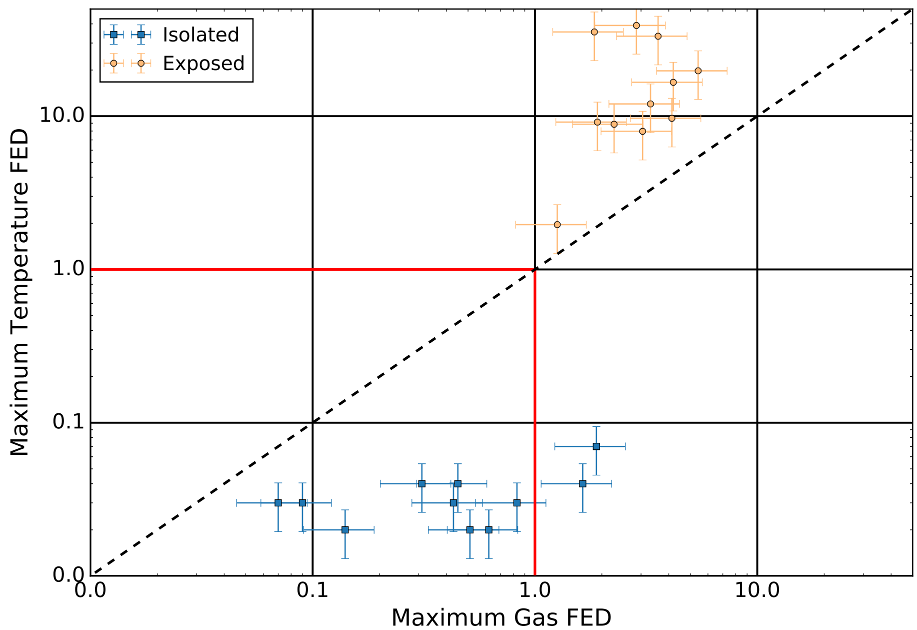

Figure 2: Maximum Hallway and Near Bedroom FED values. FED$_{gas}$ is shown on x-axis and FED$_{temp}$ is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0)

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

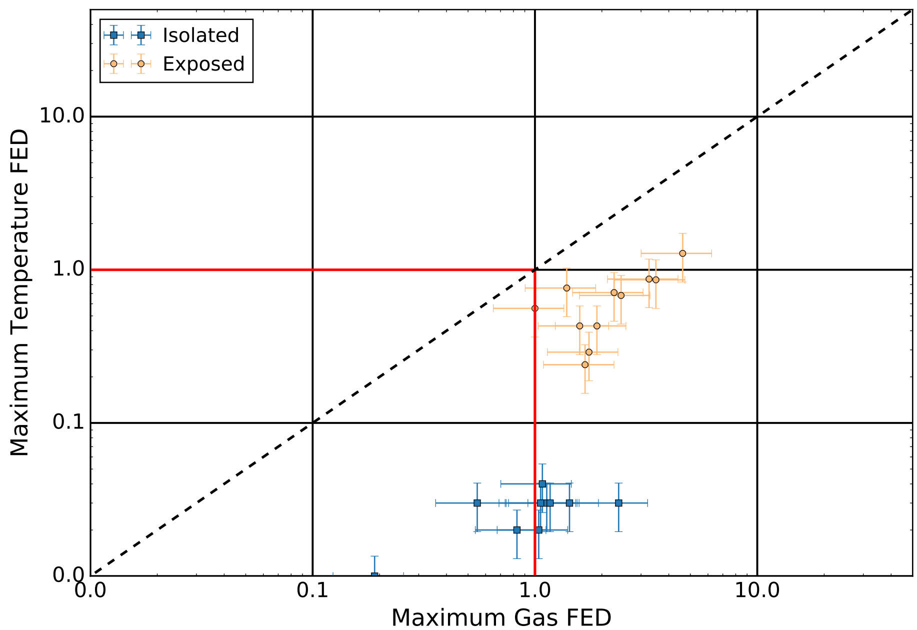

Figure 3: Maximum Dining Room and Far Bedroom FED values. FED_{gas} is shown on x-axis and FED_{temp} is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0)

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

5.3 Search Methods and Simulated Occupant Removal

The time to find and remove the simulated occupants (occupants) in the dining room and the near closed bedroom varied more between the six groups of firefighters that participated in the scenario than between the attack methods, side of the structure, or whether the group had been through the scenario previously. There was no statistically significant difference in the times to locate or remove the occupants between the transitional attack method versus the interior attack method. This would indicate that there was not a sufficient improvement in visibility as a result of the early water application in the transitional attack scenarios that aided the search crew in finding the occupant more rapidly. While temperatures and FED rates dropped following initial exterior water application, as described in Section 4.3, the structure was still filled with optically dense smoke at the time of firefighter entry. While suppression halts further production of products of combustion, the expulsion of products of combustion from the structure is a time-dependent process, and the rate at which smoke is exhausted and visibility is improved is related to the time of suppression and the number and area of ventilation openings. While ventilation prior to suppression can increase the burning rate of the fire, and thus increase the production rate of toxic gases, ventilation closely coordinated with suppression is important for timely expulsion of products of combustion

Conventional firefighting tactics [10, 11] dictate that areas close to the suspected seat of the fire should be searched first, as occupants trapped in these areas are exposed to the greatest risk. In these experiments, occupants trapped in the near hallway, are indeed at the greatest risk of thermal exposure, but this area is also the least likely location to find a tenable occupant. The other locations, while likely to reach untenable conditions for many occupants by the end of simulated activities, experienced significantly lower FEDs at the time of intervention. Consider Figure 4, which shows the FED values in the dining room and hallway at the time that the first occupant was found. These locations are approximately equidistant from the front door, and can compare if the search team first went towards the fire and found an occupant compared to a location on the opposite side of the structure. By searching away from the fire, the crew is more likely to find a viable occupant than where the search team first moved towards the fire. It is difficult to say conclusively whether the conditions at a certain point within a structure would be lethal, but the occupant found next to a post-flashover compartment fire has a higher likelihood of sustaining lethal burn injuries or incurring a lethal dose of products of combustion than one located remotely in the structure, a notion reinforced by Figure 4. Thus, occupants trapped close to the fire room should not be abandoned or neglected, but high priority should also be placed on the potential for viable occupants trapped remote from the seat of the fire that may also be in need of rapid removal. the search method employed by a firefighters on the fireground is ultimately dependent on local policies and procedures and the circumstances of the specific incident.

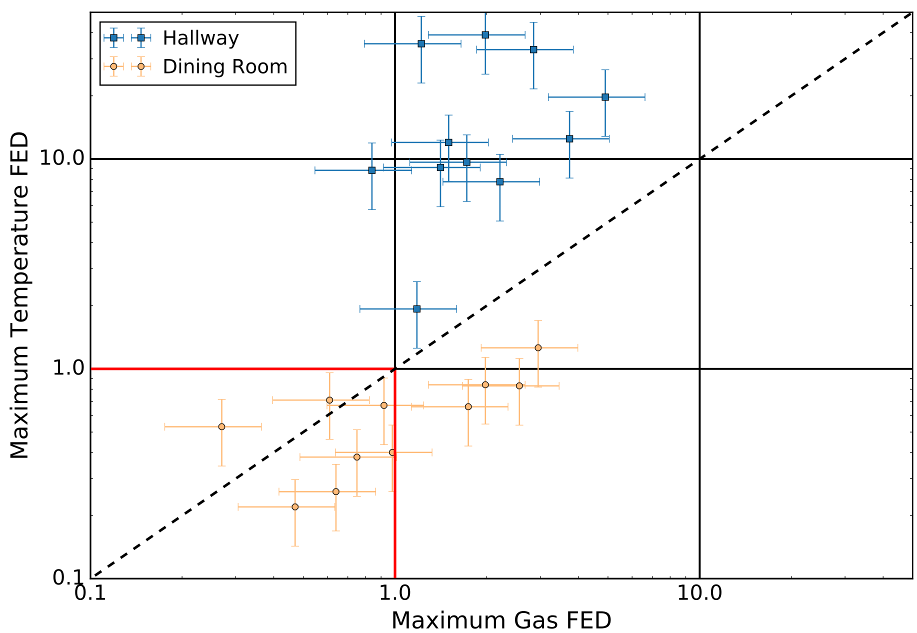

Figure 4: Near Hallway vs. Dining Room FED values at time of intervention. FED_{gas} is shown on x-axis and FED_{temp} is shown on y-axis. Red lines denote the FED at which incapacitation is expected for 50% of the population is expected (1.0)

It is important to note that the searches in these experiments were conducted in a single-story structure with a relatively simple geometry. Occupants were only required to be moved about 6 m (20 ft.) to be extracted from the structure. If the floor plan were larger or more complicated, the times required to find and remove occupants likely would have been longer. Following suppression, the rate of gas concentration decrease was not as high as the rate of temperature decline described in Section 4.3. Thus, although the FED rate was decreasing in the time that the search crew took to find and remove the occupants, they were still exposed to high concentrations of toxic gases. Because of the nature of the governing equations, the FED of any trapped occupants would continue to increase until they are removed from the structure. This is demonstrated in Figure 5, which plots the increase in FED toxicity from the time that the search crew made entry to the time that the dining room occupant is removed. The removal times for all 12 search crew repetitions were considered for all 12 experiments. Note that because there were no local gas concentration measurements for the simulated occupants, the stationary sample point in the dining room was assumed to represent the toxic exposure to the occupant for the duration of the removal process. While it is likely that the gas concentrations and resultant FED exposures would be different within the occupant removal path, the dining room concentrations offers an approximation to the toxic insult in order to explore this phenomenon. The chart shows that as the removal time for the simulated occupant increases, the tenability of the occupant is affected dramatically. This emphasizes the importance of rapid removal of occupants located during the search in an effort to minimize the toxic exposure of these occupants.

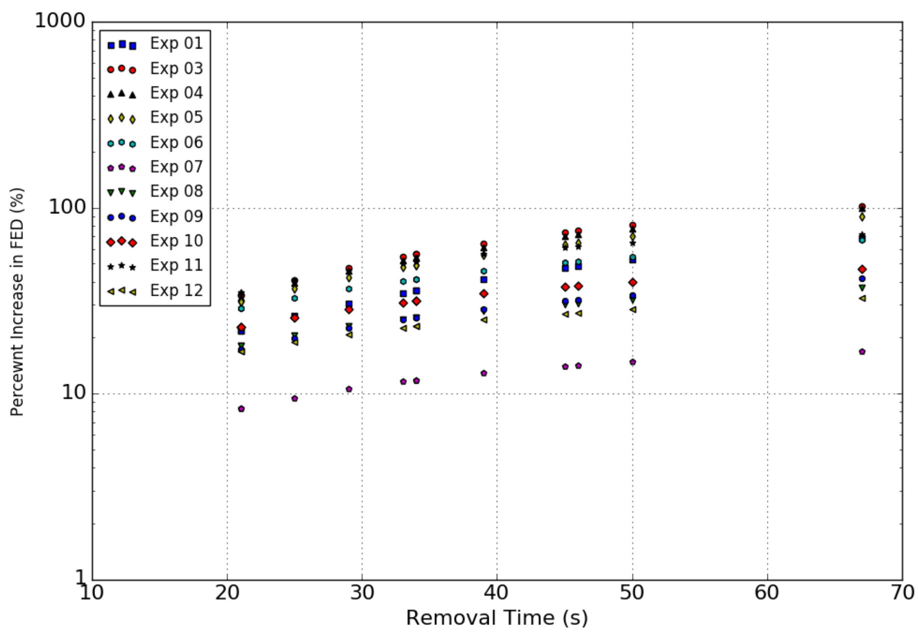

Figure 5: Relationship between occupant removal time and increase in FED between entry of search team and removal of dining room occupant

In this series of experiments, most of the simulated occupants were removed from the structure out the front door from the location that they were found. The shortest occupant removal time, however, was observed in Experiment 4, where the search crew removed the occupant out of the rear door of the near closed bedroom. This removal method exposed the occupant to toxic gases for the shortest duration, but also avoided dragging the occupant through the hallway and living room, where the concentrations of products of combustion were higher than in the closed bedroom. Thus, depending on the conditions within the structure, the location of the occupant within the structure, and the knowledge of the search company of alternative means of egress, the ideal path for occupant removal may be out of an opening separate from the one which the search team entered through, such as a rear or side door, or even through a window or down a ladder. this emphasizes the importance of situational awareness among the members of the search company and coordination of occupant removal.

5.4 Attack Methods and Outliers

With the exception of Experiment 3, the attack teams in the transitional attack scenarios applied at least 9 second of water through the window of each fire room. In the majority of these experiments, the water application resulted in a temperature reduction throughout the structure, but most drastically in the fire rooms and hallway immediately connected to these rooms. The decrease continued until the attack team could advance their hoseline to the hallway for final suppression. The attack crew in Experiment 3 directed their hose steam through the window for a shorter duration than the rest of the experiments, 4 s into Bedroom A and 3 s into Bedroom B. This short water application, combined with a delay in entry while the search crew forced entry into the structure, allowed for a significant period of regrowth before the attack team reached the hallway to complete final extinguishment. The initial temperature decreases at the 0.9 m (3 ft.) level in each of the fire rooms and the subsequent increases due to regrowth prior to final suppression are listed in Table 6. Following suppression, the 0.9 m (3 ft.) temperatures decreased by 463°C in Bedroom A and by 235°C in Bedroom B. Because of the delay between the short initial attack and the final suppression when the attack team reached the hallway, the 0.9 m (3 ft.) temperatures increased 269°C and 567°C in Bedrooms A and B, respectively. The temperatures in Bedroom B at the time that the attack team reached the end of the hallway were consistent with a post-flashover compartment fire. If the delay between initial and final suppression were longer, it is likely that conditions remote from the fire room would have started to deteriorate. This regrowth was not observed in the remainder of the transitional attack experiments, where the initial water application was longer. In many of these experiments, temperatures in the two fire rooms were still decreasing when the attack team reached the hallway. In the experiments where temperatures did begin to rebound, the increase was not of the same magnitude noted in Experiment 3. The average temperature prior to suppression, the average minimum temperature following suppression, and the average maximum temperature before the attack team reached the hallway for the other transitional attack experiments are listed in Table 6. The regrowth following the exterior attack in Experiment 3 resulted in a longer gap between suppression and the time at which the FED rate began to decrease. Thus, by failing to apply a sufficient amount of water during transitional attack, the effectiveness of the attack in improving conditions within the structure is limited.

Table 6: Temperature Reduction and Subsequent Regrowth in Experiment 3

Event	Experiment 3		Transitional Attack Average	
	Bedroom A 0.9 m (3 ft.)	Bedroom B 0.9 m (3 ft.)	Bedroom A 0.9 m (3 ft.)	Bedroom B 0.9 m (3 ft.)
Temp. (°C) prior to exterior suppression	617	820	542	759
Minimum temp. (°C) following exterior suppression	154	585	91	162
Maximum temp. (°C) prior to final, interior suppression	282	1152	104	175

Just as the duration of water application is important to the effectiveness of the attack, the location to which the water is applied is important. In the transitional attack scenarios, the exterior water application occurred directly into the two fires rooms, resulting in a drastic reduction in temperatures when a sufficient amount of water was used. In the interior attacks, several groups applied water between the time they entered the front door and the time they reached the hallway. The poor visibility within the structure during this time makes it difficult to assess the effectiveness of these initial bursts of water, but the most effective cooling in the interior attack experiments occurred once the attack crews had reached the hallway, allowing them to apply water directly to the contents of the burning rooms. In one scenario, Experiment 5, the attack crew did not apply any water until reaching the hallway. Upon reaching the hallway, an issue was encountered with the hose advancement, and the nozzle firefighter opened the nozzle, but was only able to apply water to the ceiling of the hallway for an initial period of time. The hose advancement issue was thereafter resolved, and the nozzle firefighter was once again able to advance and complete extinguishment. Prior to this final extinguishment, the temperature decreases in the area of the fire room were negligible, indicating that the water application was ineffective. The results of this scenario indicated that it is important that in order for effective and definitive suppression, water must be applied directly to burning fuels.

The suppression methods employed in this series of experiments indicated that, in order for suppression to be effective in improving conditions within the structure, a sufficient quantity of water must be applied to the burning contents of the room. In the transitional attack, water was applied earlier in the experimental timeline, resulting in a reduction in temperatures sooner than when compared to the interior attack experiments. After deploying their attack line, the crews conducting transitional scenarios were able to immediately apply water to the fire, resulting in water application significantly faster than the interior attack groups and a reduction in temperatures sooner than when compared to the interior attack experiments. Once the interior attack groups deployed their hose line, they were often delayed while waiting for the search crew to simulate forcing entry into the building. Despite the delay, the interior attack groups entered the structure significantly faster (174 ± 10 s) when compared to the transitional attack groups (213 ± 29 s) ($p=0.02$). Despite the early water application in the transitional attack experiments, there was no significant difference in the time at which the FED rate began to decrease between the two attack methods.

5.5 Limitations

The equations used to compute the FEDs at each of the sample points for these experiment have a great deal of uncertainty associated with them, as high as 35% in some cases. This high uncertainty, combined with the uncertainty of the measurements themselves, resulted in a large amount of scatter in the gas concentration data. Additionally, significant gas concentrations were not measured until the gas layer had descended to the point of the sample location, which in some experiments occurred later than others. A similarly large variation was not noted in the temperature measurements, indicating that although the thermal conditions within the structures were within a reasonable margin of uncertainty, the gas concentrations may be more susceptible to scatter. The gas sample locations in this series of experiments were fixed, which made accounting for the toxic exposure to simulated occupants during their removal from the structure difficult. Future work should attempt to assess how the occupants' toxic exposure changes during the removal process by using remote gas measurement equipment.

6 Conclusions

Utilizing a full sized single family residential structure with two fully involved compartments typical of room and contents fires in 21st century fires in the US, this study provides new data and insights into exposure conditions for trapped occupants and how variability in firefighting activities may affect tenability for those occupants. Consistent with fatality data from structure fires, occupants close to the origin of the fire sustained the most severe thermal exposures, likely reaching incapacitation from heat exposure prior to the exposure to products of combustion. These occupants also sustained the highest gas exposures of any simulated occupant location. Distant from this location but in areas open to the fire rooms, gas exposure levels reach FED values that were on average 169% higher than the thermal FED at this location but also 25% lower than those near the fire. The FEDs within the two closed bedrooms were found to be significantly lower than locations just outside of the closed door such that occupants trapped in the closed bedrooms would likely have been tenable well into the experiment.

Water application by the fire attack teams was associated with a rapid drop in temperatures throughout the structure, followed shortly afterward by a decrease in the FED rate. There was no significant difference between the magnitude of the temperature decrease or the time until the inflection point in the FED curve between transitional attack and interior attack. For the transitional attack scenarios, water was applied to the fire significantly earlier in the experimental timeline than in the interior attack scenarios, while in the interior attack scenarios, the attack team made entry to the structure significantly sooner than in the interior attack scenarios. For both attack methods, significant improvements in interior conditions were observed following effective water application, while ineffective water application reduced or delayed the positive effects.

The coefficient of variations of the groups' times to execute various fireground actions ranged from 20% to 95%. This emphasized the importance of training to develop proficiency in tasks such as hose advancement, forcible entry, and search techniques, as well as coordination between companies on the fireground to minimize miscommunication and improve efficiency. Importantly, as the removal time for the victim increased, the toxic exposure to the victim increased, despite the decreasing FED rate due to suppression. These results emphasized the need for rapid removal of occupants to limit toxic exposures.

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