ABSTRACT

Title of Thesis: Determining Available Safe Egress Time Using a Variable Fractional Effective Dosage Analysis of Heat and Asphyxiant Gases In Single-Story Occupancies

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The objective of this project is to determine available safe egress time in a single-story occupancy using a fractional effective dosage analysis with variable exposure for fast and slow growth fire scenarios. Required safe egress time was calculated using smoke alarm activation times from single-story residence fires in conjunction with human behavior and movement data for walking and crawling. Available safe egress time was calculated using a fractional effective dosage analysis with temperature and heat flux measurements as well as CO, CO_2, and O_2 concentrations throughout the structure. The two time quantities were compared to determine if safe egress was possible. Egress was possible in all scenarios where a smoke alarm alerted quickly. When egress was dependent on a smoke alarm located behind a closed bedroom door, egress was not possible for all fast growth fires and unlikely in most slow growth fires. However, the benefit of sheltering behind a closed door was significant when compared to an occupant's exposure without a bedroom door. This project shows the need for the installation of multiple smoke alarms within a structure.

Determining Available Safe Egress Time Using a Variable Fractional Effective Dosage Analysis of Heat and Asphyxiant Gases In Single-Story Occupancies

by

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Chapter 1: Introduction

When home smoke alarms were popularized in the 1970's, they cost $125, equivalent to $789 in 2019 [1]. In 2020, the average smoke alarm costs less than $40. This is particularly remarkable considering the advancements made to such smoke alarms over those fifty years. In the early years of smoke alarms, they were predicted to decrease residential fire deaths by 41% [2]. Almost 60% of all home fire deaths occured in residences where a smoke alarm was not present or failed to alert [3]. In fact, from 2012-2016, the installation of modern day smoke alarms decreased the death rate per 1,000 reported home fires from 12.3 with no functioning alarm to 5.7 with a functioning alarm [3]. This is significant because over half of the fire deaths were avoided due to simply having a working smoke alarm present in the home. There was also a marked decrease in non-fatal casualties as well [3]. This is largely attributed to the popularization of the smoke alarm, usage of which in American residential occupancies rose from less than 10% in 1975 to approximately 95% in 2000 [4].

In the past fifty years, home furnishings in the United States have largely moved from natural material composition to synthetic material composition. That is to say, fewer pieces of furniture are made solely of wood and cotton, and a greater proportion of the content is made of polymers and foams. Synthetic materials used in home furnishings have a greater heat of combustion than organic materials. This means that when burned, the synthetic materials release more energy in the form of heat than organic materials common to home furnishings. As the heat release rate of a house fire increases, the hazard increases, putting any occupants at an increased risk.

In the case of a house fire an occupant's available safe egress time must be greater than the required egress time to allow for survival. The available safe egress time (ASET) is determined by the tenability of the environment. The required safe egress time (RSET) takes into account detection time, alarm activation time, and the steps a person takes when responding to a threat, namely pre-movement and movement times. Using average walking speeds, among other tendencies of emergent human behavior, an occupant's required egress time can be estimated and modeled [2]. Alarm activation is an important part of the required egress time since often an occupant will not begin to exit the structure until the device has signaled. It is critical that the alarm signals soon enough to allow an occupant time to exit the building.

The objective of this project is to determine available safe egress time in a single-story occupancy using a fractional effective dosage (FED) analysis with variable exposure. Data from house fire experiments, specifically CO, CO_2, and O_2 concentrations throughout the structure, as well as temperatures, and smoke alarm activation times will be used to assess occupant tenability in both slow and fast fire growth scenarios.

Chapter 2: Literature Review

It is necessary to understand the differences between ASET and RSET, as well as how both of those times are calculated, in order to determine if a person could escape a single-story occupancy in the event of a fire. In addition, when planning a series of experiments it is critical to examine previous research in order to learn from those experiments and build on their conclusions to make a useful contribution to science that has not been done before.

2.1 Available Safe Egress Time

The ultimate purpose of a smoke alarm is to alert occupants to a dangerous situation so they can exit the building quickly and safely. Shown in Figure 2.1, the life and growth of a fire follows a typical timeline of events: ignition, growth, full development, and decay [6]. Although the heat release rate in a house fire can be on the level of millions of Watts, leading to the generation of high temperatures in the space, the most common cause of death by an occupant of a burning building is asphyxiation [7]. In fact, according to a study led by Richard Gann for the National Institute of Standards and Technology (NIST) in 2001, about 80 percent of U.S. fire victims succumb to smoke inhalation [8]. As the fire grows and burns more fuel, it

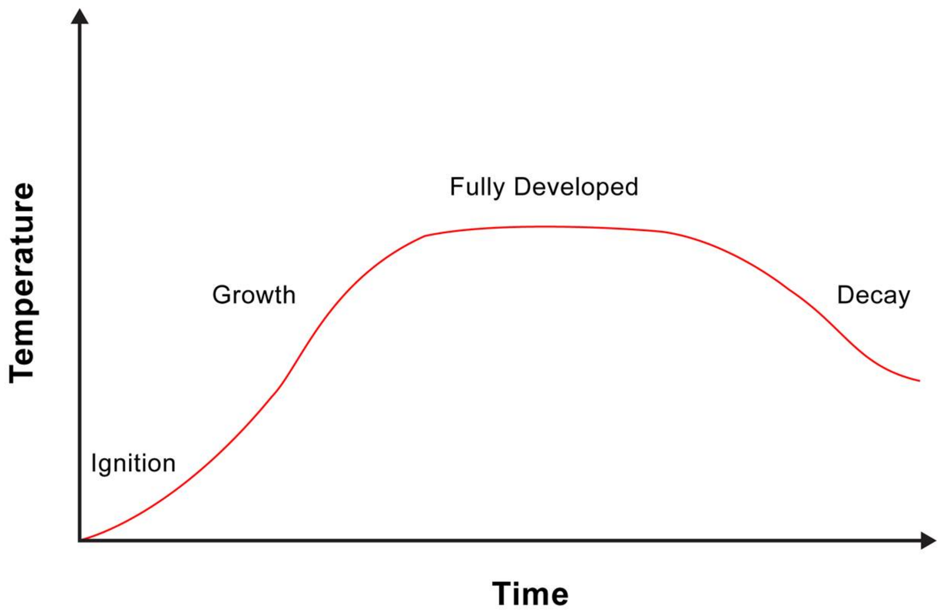

Figure 2.1: Typical Fire Growth Timeline

produces gases such as CO_2 which, when inhaled in large amounts or for long periods of time, can impair a victim and lead to oxygen hypoxia [9]. In addition, while other hazardous gases, such as CO are produced, the level of O_2 decreases. Therefore, it is important that an occupant escape a fire situation as quickly as possible to avoid inhaling these toxic, asphyxiant gases. If the activation of a smoke alarm acts as the starting point for an occupant's egress, it would follow that the alarm needs to be sensitive enough to allow that occupant adequate time to escape.

2.1.1 Fire Growth

Although a fire scenario depends heavily on factors such as fuel source, air supply, and fire type (flaming v. smoldering), most fires follow a similar timeline from ignition to extinction.

Figure 2.1 shows a sample of a fire growth timeline where the times for the growth, full development, and decay periods are situation dependant. Smoke alarms are designed to alert as quickly as possible after ignition so that egress and supression measures can be taken prior to the full development stage of the fire.

2.1.2 Tenability

Tenability analysis is a compounded method of estimating how long a person could be in a fire situation until they would become incapacitated or perish. A complete tenability analysis depends on factors such as smoke alarm activation time, fractional effective dosage (FED) of asphyxiant gases, smoke visibility, and biomechanical capabilities, among others [8]. This analysis will give estimates for the available safe egress time (ASET), or how long it would take before the structure is no longer tenable, and for the required safe egress time (RSET), or how much time a person would typically need in order to exit the structure. In order for a tenability analysis to be successful the ASET must be greater than the RSET. ASET is a critical aspect of fire modeling since any structure must be built under the conditions and considerations that a person should have a viable egress option in an emergency.

Asphyxiant gas concentrations play a large role in determining tenability. As the fire grows and produces hot gases, the level of O_2 decreases and the levels of CO and CO_2 increase. Although CO_2 can be harmful in large amounts, the main effect increased concentration has on egress is an increased respiratory rate. Increased breathing coupled with large amounts of CO and decreased O_2 leads to asphyxiation. The hazard due to exposure can be quantified using an FED analysis. The hazard presented by just CO is described in Table 2.1. [11].

CO Concentration	Effects
0 ppm	Fresh air
50 ppm	Maximum allowed for long-term exposure (up to 8 hours)
150 ppm	Maximum allowed for short-term exposure (up to 30 minutes)
400 ppm	Headache within 1-2 hours. Life threatening after 3 hours
1000 ppm	Loss of consciousness after 1 hour
3200 ppm	Headache within 5-10 minutes. Death in 30 minutes
6400 ppm	Headache/Nausea within 1-2 minutes. Death in 10-15 minutes
12800 ppm	Rapid incapacitation. Death in 1-3 minutes

Table 2.1: Carbon Monoxide Effects by Concentration

The contribution of CO_2 to incapacitation is calculated slightly differently due to the way it influences breathing rate [11]. Fractions of incapacitating gases such as CO are directly additive but CO_2 must be considered as a multiplicative effect on the combined effective dosage [10]. CO_2 is toxic at high concentrations, a phenomenon called hypercapnia. However, CO is the main threat when considering asphyxiation in atmospheres created by fire. The more CO_2 a person is exposed to the faster they inhale. As a result, a person would continue to inhale increased amounts of CO leading to asphyxiation.

As an environment fills up with gases such as CO and CO_2 there is a subsequent decrease in the percentage of oxygen in that space. A person in these conditions of decreased oxygen levels would suffer from what is known as low oxygen hypoxia. This leads to decreased brain and motor function once the O_2 levels have decreased from the typical 21% to 12% and below [10].

FED is a dimensionless quantity that depends on asphyxiant gas concentrations as well as exposure time. At an FED of 0.3, 11.3% of the population is likely to be suceptible to the effects of asphyxiant gas exposure. At an FED of 1.3, approximately 90% of the population is likely to be susceptible [11]. Higher susceptibility is expected for the elderly, the very young, and those with preexisting conditions such as asthma [11]. Death is predicted at an FED between 2 and 3 [11].

2.1.2.1 Fractional Effective Dosage

In a fire scenario, asphyxiant gases pose a potentially lethal hazard as a function of both toxic potency and exposure [8]. Certain gases might pose more of an immediate threat than others. The different impacts that various gases might have on a person's body can be modeled using the fractional effective dosage analysis method. The fractional effective dose (FED) is defined as "the ratio of the concentration and time product for a gaseous toxicant produced in a given test to that product of that toxicant that has been statistically determined from independent experimental data to produce lethality in 50 percent of test animals within a specified exposure and post-exposure period" [9]. This means that when the FED is equal to 1, the gaseous toxicants would be lethal to half of the exposed animals. The previous experimentation regarding FED of various toxicants common to combustion can be used in order to see how inhaling such gases would theoretically impact a person.

Toxicity depends on exposure over time [10]. An FED analysis for a stationary person in constant exposure could be calculated for individual time steps which could be added together to determine the compounded effect.

$$FED = \frac{\Delta t}{\text{Time to Incapacitate at } \mathrm{C}_{\text{Asphyxiant Gas}}} \tag{2.1}$$

The full FED analysis takes into account the effects of CO, CO_2, and O_2 for a time step Δt and includes a summation of all the incremental time steps in order to build a complete profile of the asphyxiant hazard. To calculate the specific asphyxiant gas concentration one can use different equations for different substances. The three substances considered in this experiment are CO, CO_2, and O_2. It is worth noting that while concentrations of CO and CO_2 grow in a fire scenario the O_2 analysis is a reduction of oxygen in the environment.

The concentration and fractional effective dosage of CO can be estimated using the following equations:

$$C_{CO} = (\frac{\%COHb}{3.32 \times 10^{-5}(RMV)t})^{0.97} \tag{2.2}$$

where % COHb denotes the carboxyhemoglobin formed in the body due to CO exposure, RMV is the respiratory minute volume, and t is the time to incapacitation by CO [11].

Carboxyhemoglobin (% COHb) is the amount of carbon monoxide that resides in a person's red blood cells during inhalation of CO gas. Respiratory mean volume (RMV) is the average volume, in liters, a person would inhale over the duration of a minute. The RMV depends on the level of activity expected of the person since heavier activity leads to an increased breathing rate than lighter activity. The FED due to an increase in CO concentration can be calculated using:

$$F_{CO} = \frac{8.29 \times 10^{-4} C_{CO}^{1.036} \Delta t}{30} \tag{2.3}$$

where F_{CO} is the fractional effective dosage due to CO, C_{CO} is the concentration of CO measured in ppm, and Δt is measured in minutes [11]. These two equations can be combined so that the fractional effective dosage due to CO can be determined by the concentration of CO in the environment. However, that combined equation is dependant on breathing capacity and exposure duration. For the sake of this analysis the equation will be simplified by assuming the person is of average size and is engaging in moderate activity, such as walking. That RMV is estimated to be 25 liters per minute [11]. Thus, the new equation is as follows:

$$F_{CO} = 2.76 \times 10^{-5} \Delta t C_{CO}^{1.036} \tag{2.4}$$

where F_{CO} is the fractional effective dosage due to CO, Δt is in minutes, and C_{CO} is the concentration of CO in ppm.

The amount of CO_2 in an environment changes a person's breathing rate, thus affecting the RMV. The CO_2 dependent RMV can be calculated as follows:

$$RMV = e^{0.25 C_{CO_2} + 1.909} \tag{2.5}$$

where C_{CO_2} is the concentration of carbon dioxide as a percent of the environmental atmosphere. [11]. This means that as the amount of CO_2 in the local environment, the higher a person's breathing rate will be and the more asphyxiant gases they will inhale. The volume of CO_2 can be determined using:

$$V_{CO_2} = \frac{e^{(0.25C_{CO_2}+1.909)}}{7.1} \tag{2.6}$$

C_{CO_2} is denoted as a percent concentration of CO_2. It is important to note that concentrations measured in parts per million (ppm) can be written as percentages by dividing them by a factor of 10,000. In other words, one percent is 10,000 ppm.

The following formula is used to determine the combined effect of CO and CO_2:

$$FED_{COandCO_2} = [2.76 \times 10^{-5} \Delta t C_{CO}^{1.036}] \times \frac{e^{(0.25C_{CO_2}+1.909)}}{7.1} \tag{2.7}$$

$$\text{or: } FED = [F_{CO}] \times V_{CO_2} \tag{2.8}$$

The fractional effective dosage of oxygen decrease can be determined using:

$$F_{O_2} = \frac{\Delta t}{e^{8.13-0.54(20.9-C_{O_2})}} \tag{2.9}$$

where Δt is in minutes and C_{O_2} is denoted as a percent.

Again, the full FED analysis takes into account the effects of CO, CO_2, and O_2 for a time step Δt and includes a summation of all the incremental time steps in order to build a complete profile of the asphyxiant hazard. The equation that takes into account the effects of CO and CO_2 increase as well as O_2 decrease is:

$$FED_{gas} = F_{O_2} + (V_{CO_2} \times F_{CO}) \tag{2.10}$$

For a typical FED analysis, the gas concentrations are measured at the same location for each time step. For this experiment, in order to take into account the variable gas concentrations at different points along the egress route, the gas concentration measurements will be taken at the location at which an occupant would be located during egress.

2.1.3 Temperature Effects

Although asphyxiant gas exposure does significantly impact FED, it is important to note that the energy level of those gases affects occupants as well. Increases in heat can compromise life safety in two ways: by burning the skin or upper respiratory tract and by reaching the threshold at which hyperthermia threatens survival [12]. The FED increase due to temperature can be determined as a sum of two parts, one dependant on radiant heat flux and one dependent on temperature.

2.1.3.1 FED of Radiant Heat

The tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2 [12]. Beyond that limit, time to burning of the skin can be determined using [11]:

$$t_{rad} = 10q^{-1.33} \tag{2.11}$$

Where t_{rad} is the time in minutes to burning of the skin due to radiant heat and q is the radiant heat flux in kW/m^2. The FED of radiant heat accumulated per minute of exposure is ${t_{rad}}^{-1}$.

2.1.3.2 FED of Convected Heat

The tenability limit for exposure to convected heat over time can be determined using the following equations:

$$t_{conv} = (3 \times 10^9)T^{-3.4} \tag{2.12}$$

Where t_{conv} is the time in minutes to hyperthermia due to convected heat and T is the temperature in °C [11]. The FED of convected heat accumulated per second of exposure is ${t_{conv}}^{-1}$

2.1.3.3 Combined FED

The FED due to a combination of radiant and convected heat exposure can be determined using the following equation:

$$FED = \sum\left(\frac{1}{t_{rad}} + \frac{1}{t_{conv}}\right) * \Delta t \tag{2.13}$$

It is important to note that when the measured radiant heat flux is less than 2.5 kW/m^2, the FED due to radiant heat should be set equal to zero [12]

When considering a variable FED analysis, the quantites for FED due to both radiant and convected heat can be determined for every second and then added together in order to account for the change in an occupant's location over time during egress.

When considering the combination of the effects due to asphyxiant gas and thermal exposure, each quantity, FED_{gas} and $FED_{thermal}$ should be considered as separate values not to be added together. Possiblity of egress is dependent on both quantites; the overall FED should be considered to be the greater of the two values.

2.2 Required Safe Egress Time

The RSET of an occupant is made up of three pieces that span from ignition of the fire to successful egress of the structure [13]. First, the time from ignition to detection and notification which can be determined experimentally or via a simulation. Second, the pre-movement time which involves actions such as waking up, recognizing a threat, collecting items, helping others, and so on. Although the pre-movement time varies situationally, it can be estimated to be between one and two minutes for a single family occupancy [14]. The third piece of RSET is the time it takes a person to physically move through and exit the structure. This can be estimated using known averages of human motion [14].

2.2.1 Smoke Alarm Activation

In order to evaluate an occupant's required safe egress time, it is necessary to understand how smoke alarms are activated. There are two types of smoke alarm that are highlighted in UL 217: an ionization alarm and a photoelectric alarm [15]. Previously, these devices had their own standards, UL 167 for ionization alarms and UL 168 for photoelectric alarms [2]. As a fire burns it releases hot gases, vapors, and particulates together in the form of a smoke plume, the buoyancy of which drives the plume to the ceiling. Some of the smoke is made up of CO and CO_2, the concentrations of which can be measured to determine exposure.

An ionization smoke alarm is activated when smoke particulates disrupt the flow of ions inside the device. A photoelectric smoke alarm is activated when smoke particulates scatter a light source inside the device. This means that when particulates enter the device they absorb some light waves, triggering the alarm. The size of particulates is important because they must be small enough to enter the devices but large enough to disrupt the flow of ions or scatter a light source.

The purpose of alarm activation is to alert an occupant of a dangerous scenario and to trigger their egress pattern. Once the alarm signals the occupant can begin to assess the situation and remove themselves from the threat.

For something that has played an integral part in human life and development since the stone age, fire is a deceptively complicated process to model. A good model takes a complicated process and, using appropriate assumptions and approximations, displays it as a more simple process. Inputs such as fuel composition, enclosure volume, ambient temperature, smoke movement, air entrainment, and others, add a multitude of variables to the original complicated process [16].

Although complete modeling of smoke alarms is incredibly complex, much has been done to simply imitate the capabilities of both photoelectric and ionization smoke alarms. Because photoelectric smoke alarms depend on the concept of light scattering, Archibald Tewarson's optical density calculations and Frederick Mowrer's smoke movement equations provide an estimate of when the sensor will become obfuscated [17], [18]. These calculations depend heavily on fuel types, oxygen concentration, mode of combustion (i.e. smoldering vs. flaming), and relative temperatures [17].

Ionization smoke alarms provide a different problem because the particulate content of smoke is not yet available to be modeled. When fuel undergoes the process of combustion, intermolecular bonds are broken resulting in less-complicated particles. For example, when methane (CH_4) is burned in air (O_2 + $3.76N_2$), its molecules are broken down stoichiometrically into water vapor (H_2O), carbon dioxide (CO_2), and nitrogen gas (N_2) [19]. Unfortunately for modelers, a real fire is not an ideal stoichiometric process. Partially broken down fuel molecules escape the flame into the atmosphere in the form of particulates. This partially combusted fuel could be broken down to the stoichiometric building blocks, but does not always complete the combustion process, especially in a fuel rich environment.

In addition, that same methane fire has over three hundred possible reactions in its complex combustion mechanism [19]. Methane chemical kinetics are relatively well understood but it is a simple hydrocarbon. The more complex the atomic structure of the fuel the more ways it could break apart during combustion. If the fuel does not burn completely then it could make the situation more hazardous as a fire increases. Specifically, in the event of flashover, the previously unburned fuel would undergo a second wave of combustion once it reaches an area with adequate oxygen, releasing more energy in the form of heat.

This partial combustion poses a problem considering that modern home furnishings are no longer being made primarily of natural materials, but instead are being made of synthetic things like polystyrene and polyurethane foam. In theory, a fuel composed of complex molecules could be burned cyclically several times over before breaking into its base components. Indeed, this concept is clear upon comparing the heats of combustion of these materials. Wood has an average heat of combustion of 12.6 kJ/g while flexible polyurethane foam has an average heat of combustion of 17.6 kJ/g [20]. This means that a polyurethane foam fire will produce almost 140% as much energy in the form of heat than a wood fire, assuming both fuel loads have the same mass. In addition, the smoke yield from the flexible polyurethane fire is nearly five times that of a wood fire given fuel loads of equal mass [20].

Global combustion reaction kinetics can give modelers some probabilistic definitions of what is most likely to happen during the combustion process of a given fuel [19]. That being said, the more complicated the molecular structure of the fuel the more potential combustion paths present themselves and therefore, the more difficult it is to accurately predict the way a fuel will combust. Ionization smoke alarms depend on recognizing smoke particulates in the immediate atmosphere in order to activate.

2.2.2 Pre-Movement Activity

After the smoke alarm has alerted a person naturally, it takes some time before beginning the egress process. When determining the RSET for an occupant in any building it is important not to forget pre-movement activity to ensure the most accurate estimate possible. Common pre-movement activities include waking up, getting dressed, investigating the source of the alarm, calling the fire department, and checking on family members [14]. According to Mileti and Sorensen's model on the influence of cognition on warning response, in order for a situation to be considered a threat a person must hear, understand, believe, and personalize the warning [14]. This thought process in response to the smoke alarm's warning is an essential part of the pre-movement activity calculation. Although thinking is inherently individual and in this case depends on factors such as prior experience to smoke alarm warnings or if the individual is asleep when the first signal occurs, the time from alarm activation to personalization of a threat can be estimated to take about 15 seconds [14]. Since this set of experiments is considering a single-story residential occupancy, it can be assumed that a building of this type would reasonably house a family. Taking into account the time for a person to understand the threat and collect their family members, the entire pre-movement time can be estimated to take between one and two minutes [14]. In a series of similar tests conducted in 2007, the pre-movement time estimated for a young family at night was 55 seconds and 80 seconds for an elderly family at night [6]. For the experiments present in this report the pre-movement time will be assumed as 90 seconds for conservatism.

For this project the occupant will be treated as if they spend the entire 90 second pre-movement time in their bedroom of origin. In reality, this might not be true since an occupant might investigate the situation, locate family members, or do other tasks that would take them out of the bedroom.

2.2.3 Egress

The egress process begins once an occupant begins to move from their initial position to the exit. Walking speed averages in certain situations have been determined experimentally which is useful for making egress calculations [14]. Velocities are written in meters per second. If the distance that a person has to walk is known, it can be divided by the velocity at which the person moves to get the amount of time it would take to move that distance.

In an environment with a density of less than 0.54 persons/m^2 the average walking speed of an able-bodied adult is 1.26 m/s while the average walking speed of a child is 1.08 m/s and the average walking speed of an elderly person is 1.04 m/s [21]. For people with mobility restrictions such as the disabled, the average walking speed can be estimated as 0.41 times that of the average person, or 0.52 m/s [21]. However, this estimate depends entirely on the level of impairment. With the presence of smoke in the environment, average rates of motion will decrease due to sub-optimal visual and breathing capabilities [14]. Upright movement rates in a smoke-filled environment can be estimated to be, for able-bodied adults, 0.8 m/s [21]. Average crawling speeds for able-bodied adults can be estimated to be 0.75 m/s [21].

2.2.4 Visibility

The impact of visilibity on egress is not considered in this study due to the rapid transition between clear and completely obscured conditions in the hallway of the residence. In reality, decreased visibility can reduce walking speed and therefore can lengthen egress times [5]. This adds an additional threat to an occupant because their time to exposure is longer. It is also worth noting that while not considered in this project, there exists some visibility level at which an occupant attempting egress will decide not to proceed and will retreat to the room of origin [14].

2.3 Previous Research

In 1975, the Illinois Institute of Technology Research Institute and Underwriters Laboratories conducted a series of residential fire experiments known as the Indiana Dunes Tests in order to ”evaluate the requirements for fire alarms to protect residential occupancies” [6]. Subsequently, in 2007 another series of experiments were conducted by NIST in order to validate the results of the Indiana Dunes Tests with more modern fuels and smoke alarms [6]. The original Indiana Dunes Tests were critical in restructuring building codes to include smoke alarm requirements.

2.3.1 Indiana Dunes Tests, 1975

The purpose of these tests was to determine then-current smoke alarm sensitivity in residencies [6]. The fuel sources were common combustable items in an occupancy at the time of the study [6]. The time from ignition to alarm activation was measured in these experiments. This set of experiments used three minutes as an arbitrary reference number for RSET [6].

Major shortcomings of this series of experiments were the lack of consistancy between residences tested, as the tests were conducted in various homes scheduled for demolition [6]. In addition, the study neglected to measure the gas concentration data that an occupant would be exposed to determine ASET. The study was able to conclude that smoke alarms installed in homes increased occupant survivability, however, in 2007 NIST decided to conduct a similar series of experiments while accommodating for modern changes as well as the deficiencies of the 1975 tests [6].

2.3.2 Indiana Dunes Tests, 2007

This set of experiments was called "Performance of Home Smoke Alarms: Analysis of the Response of Several Available Technologies in Residential Fire Settings", done by NIST as a follow-up to the 1975 tests. The purpose of these tests was to evaluate the performance of then-current smoke alarms [6]. In addition to collecting simple alarm times the team at NIST also measured environment temperature, smoke and gas species concentrations, and convective flow velocities at the level of the smoke alarms [6]. Although smoke alarms were the focus of this set of experiments, alert times from CO alarms, heat alarms, and tell-tale sprinklers were also collected [6].

This experiment concluded that escape times were systematically shorter than those found in the first Indiana Dunes Test studies over 30 years prior [6]. The team at NIST determined that the shorter escape times could be contrinbuted to "some combination of faster fire development times for today's products that provide the main fuel source for fires, ...different criteria for time to untenable conditions, and improved understanding of the speed and range of threats to tenability" [6]. They were also able to conclude that smoke alarms in bedrooms helped increase the time available for egress by as much as 900 seconds due to an occupants inability to hear alarms farther away [6].

Chapter 3: Experimental Approach

The purpose of these experiments is to use gas concentration and thermal conditions from single-story residence fires to determine available safe egress time and compare that to the required safe egress time in order to assess tenability. Both fast and slow growth fire scenarios will be considered as well as egress via walking and crawling.

This series of experiments was conducted as a portion of the Residential Size-Up and Search & Rescue experiment series done by UL Firefighter Safety Research Institute (FSRI) in order to study ventilation and search techniques in single story occupancies. Ten of these experiments are considered in this thesis, five with a fast-growing bedroom fire and five with a slow-growing kitchen fire. Full details describing this set of experiments can be found in the references of this report [22]. The tests are labeled accordingly B1-B5 for bedroom fires and K1-K5 for kitchen fires.

The five tests for each experiment type (bedroom and kitchen origin) are intended to be replicates so the data can be compared. Each of the tests has some variation but it occurrs after egress would have been acheived or been deemed impossible. The variations between the tests are described in Table 3.1.

Test No.	Front Door	Bed 1 Door	Bed 2 Door	Ventilation	Windows
B1	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 removed
B2	Open	Closed	Open	Hydraulic	Bed 3 removed then Bed 1 removed
B3	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 removed
B4	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 opened
B5	Open	Closed	Open	Hydraulic	Bed 1 opened
K1	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 removed
K2	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 opened
K3	Open	Closed	Open	Hydraulic	Bed 2 and Bed 3 removed then Bed 1 removed
K4	Open	Closed	Open	Hydraulic	Bed 3 opened then Bed 1 and Bed 2 opened
K5	Open	Closed	Open	Hydraulic	Bed 3 opened then Bed 1 opened

Table 3.1: Experiment Types with Variations

3.1 Experimental Setup

3.1.1 Structure

The experimental structure is a single-family detached residence partitioned into four bedrooms, a kitchen/dining area, one living room, and one hallway. The floor plan of the one-story building is shown in Figure 3.1.

The ignition point(s) are located on the bed in Bedroom 4 and the range in the

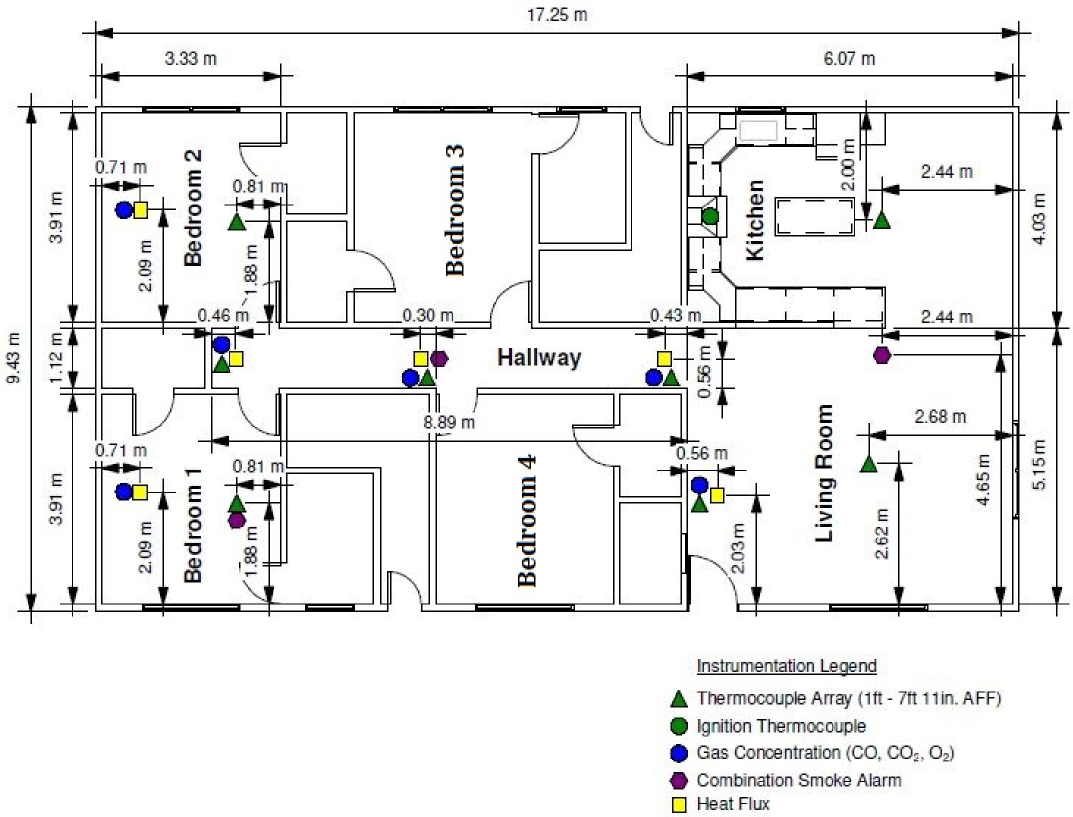

Figure 3.1: Structure Floor Plan with Instruments

kitchen. Various instruments for data collection are placed throughout the structure in order to measure temperature, heat flux, and gas concentrations at different points in the building.

In order to account for the variable exposure of asphyxiant gases, data from different gas sampling points is used depending on where the occupant would be located during the egress process. Figure 4.1 shows the floor plan split into six zones, one for each of the gas concentration measurement systems. If a person is located in a zone, they are assumed to be inhaling the gases being measured by the device specific to that zone. A person starting from Bedroom 1 or Bedroom 2 would pass through five of these zones; one for the respective bedroom and four more along the path of egress. It is important to note that the ignition location is Bedroom 4 and the smoke alarm locations are outside the door, down the hall in the kitchen, and down the hall and behind a closed door in Bedroom 1. Bedroom 2 has an open door. Gas samples from Bedrooms 1 and 2 can be compared to show any effects of a closed door on tenability.

3.1.2 Instrumentation

A thermocouple is a sensor used to measure temperature at a specific location. Temperature measurements are taken and recorded once per second. A thermocouple is placed at each smoke alarm for the duration of the experiment. In addition, thermocouple arrays are placed throughout the structure at gas sampling points. These arrays measure temperature in 0.3 m increments from floor to ceiling. The temperature at 0.9 m above the floor will be considered in this analysis since that it the estimated height of a person attempting crawling egress.

The smoke alarm model used in this series of experiments is a commercially available, UL listed residential single station combination smoke alarm, meaning it uses both ionization and photoelectric sensors. Three alarms are used for each burn test. Each smoke alarm was installed following the guidelines specified in the International Code Council (ICC) Residential Code [23].

The alarms used are powered solely by the 9-Volt battery and each exists as a stand-alone unit rather than a part of an interconnected system. Each alarm is wired separately so as to access individual alarm activation times. For each fire experiment, the time of ignition is specified so the time between ignition and alarm activation can be measured. In addition, distance between the ignition site and an alarm is measured and noted.

A heat flux gauge is used to measure energy flux on or through a surface. Heat flux gauges are placed near the gas sampling points. This helps to characterize how heat is moving through the space from the flaming fuel load to the location of interest. The heat flux measurements are used to determine how temperature changes FED throughout the egress process.

Gas sampling is collected in locations noted in Figure 3.1. A vapor trap system is used to remove moisture from the gas samples. A vapor trap measurement system is comprised of a condensing coil and two moisture reservoirs. Stainless steel tubing are used as gas sampling points within the structure. The stainless steel sampling line is connected to the condensing coil and particulate filters located just outside of the structure. Once the gas sample is cooled, dried, and filtered, it passes through the O_2, CO_2, and CO gas analyzers. In order to minimize transport time during the experiments the gas samples are continuously pulled from the structure using a vacuum/pressure diaphragm pump.

Gas concentration data is collected at elevations of 0.9 m and 0.3 m above the floor. The data from the 0.9 m elevation is used in the FED analysis for both walking and crawling. The gas concentration data for 0.3 m would be appropriate for an incapacitated victim on the floor and therefore is not used for the FED analysis as an incapacitated victim is incapable of egress under their own power.

3.1.3 Fuel Packages

The ignition sources used in the experiments were a simulated cooking fire near the stovetop range for fires with kitchen origin and an upholstered chair next to a full size bed for fires with bedroom origin. The kitchen fire would spread from the ignition point to the wooden wall-mounted cabinets, and into the living room where other furniture such as a sofa ignited during the fire growth stage of the process. The bedroom fire spread from the chair to the full-size bed located in the same room. Due to the compartmentalized nature of the floor plan, the bedroom fires were reasonably self contained in terms of fire spread. However, areas in the rest of the house experienced smoke and heat exposure.

3.2 Experimental Procedure

Experiments were conducted with either a kitchen or bedroom fire origin. After background data was collected the respective fuels were ignited. The time for each smoke alarm to activate was measured as well as temperature, heat flux, and the concentrations of CO, CO_2, and O_2 at various points throughout the structure. Although several other quantities were measured for the Residential Size-Up and

Search & Rescue experiments, the smoke alarm activation times, temperatures, heat flux, and asphyxiant gas concentrations in Bedrooms 1 and 2 and along the path of egress are the only ones pertinent to this thesis. All measurements were taken through background, ignition, fire growth, and suppression.

3.2.1 Bedroom Fires

Each bedroom fire experiment follows the same timeline of events. First, all of the necessary instruments are placed in the structure. Then, background data is collected for several minutes. This provides control conditions with which to compare the data collected during the fire. Temperature, heat flux, and gas concentration data are collected every second at all of the sampling points identified in Figure 3.1 from the beginning of background through the end of the test.

Ignition is achieved using a remote fire starter. The ignition source is an upholstered arm chair located next to a full-size bed in Bedroom 4. As the fire grows using these fuel sources, smoke and hot gases are produced. In time, these products activate the smoke alarms located on the ceiling in the structure at the points identified in Figure 3.1. The smoke alarm activation would, in theory, start the egress process for an occupant.

The fire continues to grow, igniting and burning the material provided from the upholstered chair and the full-size bed. This is the only furniture located in the burn room. After some time, the ventilation variations specified in Table 3.1 are performed. After this, a team of firefighters conducts supression. All ventilation and suppression measures occur after an occupant would have performed egress.

The data from the smoke alarms, thermocouples, heat flux gauges, and gas analyzers are collected in a spreadsheet. This information is used for an FED analysis.

3.2.2 Kitchen Fires

Each kitchen fire experiment follows a similar timeline of events to the bedroom fires. First, all of the necessary instruments are placed in the structure and background data is collected.

Ignition is achieved using a remote fire starter. The ignition source is a simulated cooking fire near the stovetop range. As this fire grows, it ignites the wooden wall-mounted cabinets in the kitchen. As more smoke and hot gases are released, the smoke alarms are activated. In theory, this would begin the egress process for an occupant in the residence.

The fire continues to grow and spreads into the living room where a sofa is ignited. In all tests this occurs after egress would have happened. After some time, the ventilation variations specified in Table 3.1 are performed by a team of firefighters. Suppression follows these events. After all of the test events, the experiment is concluded.

The data from the smoke alarms, thermocouples, heat flux gauges, and gas analyzers are collected in a spreadsheet. This information is used for an FED analysis.

Chapter 4: Experimental Results

4.1 Egress Timeline

In order to consider the changes in gas exposure as an occupant exits the structure, it is necessary to consider the timeline of events and the occupant's hypothetical location during the entirety of the fire scenario. Table 4.1 outlines the timeline of events and the location of the occupant relative to the nearest gas concentration data collection point.

Timeline Step	Occupant Location
Ignition	Bedroom 1 or 2
Fire Growth	Bedroom 1 or 2
Smoke Alarm Activation	Bedroom 1 or 2
Pre-Movement Time	Bedroom 1 or 2
Begin Egress	Bedroom 1 or 2
Move 1.95m to Hallway	Bedroom 1 or 2
Enter Hallway	Hallway End
Move 4.65m to Hallway Middle	Hallway End
Enter Hallway Middle	Hallway Middle
Move 4.44m to Hallway Start	Hallway Middle
Enter Hallway Start	Hallway Start
Move 2.67m to Living Room	Hallway Start
Enter Living Room	Living Room
Move 4.6m to Front Door	Living Room
Exit Structure	

Table 4.1: Occupant Location During Egress Process

This egress process can be superimposed upon the floorplan of the structure in order to visualize the different zones an occupant would occupy along their path. This is seen in Figure 4.1.

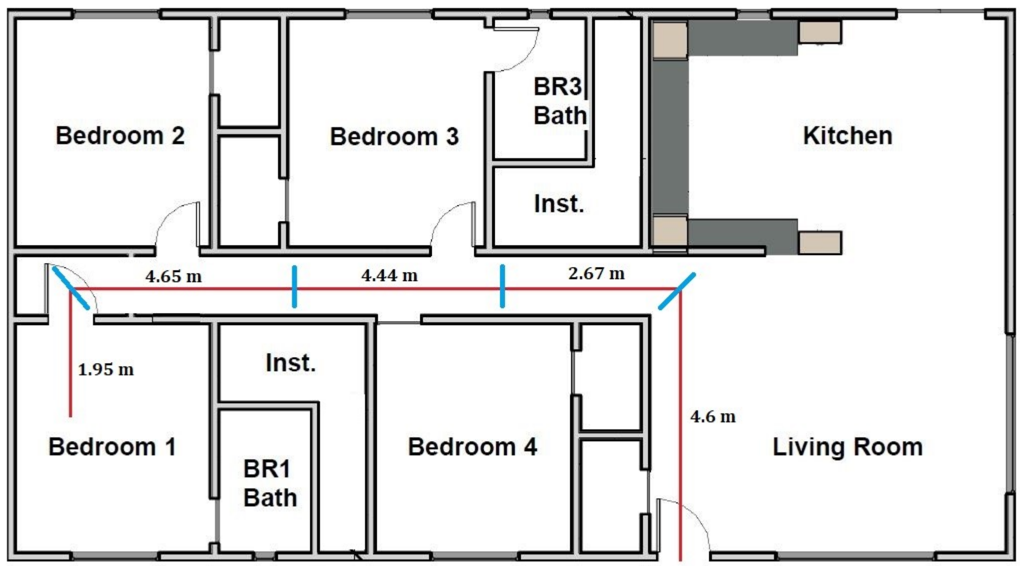

Figure 4.1: Structure Floor Plan with Zones

The movement steps described depend on the speed at which the occupant is walking or crawling. As previously noted, the average walking speed for an average, mobile adult is 1.26 m/s while the average crawling speed is 0.75 m/s. This information can be used to determine how much time the occupant will spend in a certain zone before continuing through the egress path. Because the gas concentration data is collected at one second increments the times spent in each zone will be rounded up to the next second in the FED analysis. Although the usual FED approach rounds to the nearest second, this analysis rounds up to the second for conservatism. Table 4.2 can be expanded to include the time spent in each step, as follows.

Timeline Step	Occupant Location	Time, Walk	Time, Crawl
Ignition	Bedroom 1 or 2		
Fire Growth	Bedroom 1 or 2	From Data	From Data
Smoke Alarm Activation	Bedroom 1 or 2		
Pre-Movement Time	Bedroom 1 or 2	90	90
Begin Egress	Bedroom 1 or 2		
Move 1.95m to Hallway	Bedroom 1 or 2	1.6	2.6
Enter Hallway	Hallway End		
Move 4.65m to Hallway Middle	Hallway End	3.7	6.2
Enter Hallway Middle	Hallway Middle		
Move 4.44m to Hallway Start	Hallway Middle	3.5	6.0
Enter Hallway Start	Hallway Start		
Move 2.67m to Living Room	Hallway Start	2.1	3.6
Enter Living Room	Living Room		
Move 4.6m to Front Door	Living Room	3.7	6.0
Exit Structure			
Total Time Needed for Pre-Movement and Egress		104.6 Sec	114.4 Sec

Table 4.2: Total Times for Zone Occupation (sec)

4.2 Smoke Alarm Activation Times

As part of the analysis of RSET for an occupant in the single-story residence used for these experiments, it is necessary to determine the amount of time between the instant of ignition and the instant of alarm activation. A measurement of alarm activation time was taken for devices located in the kichen, the hallway, and Bedroom 1 as seen in Table 4.3. The specific locations of these smoke alarms is shown in Figure 3.1. Table 4.3 shows the activation times by location for each burn experiment.

Visually, Figures 4.2 and 4.3 clearly show the trends between alarm activation order

Experiment Number	Kitchen Alarm	Hallway Alarm	Bedroom 1 Alarm
B1	134	93	184
B2	104	72	196
B3	107	75	263
B4	107	75	168
B5	108	91	198
K1	166	461	616
K2	197	435	839
K3	32	334	960
K4	279	462	927
K5	133	509	880

Table 4.3: Smoke Alarm Activation Times (sec)

and fire location. For example, in kitchen fires, the kitchen alarm is consistently the first to activate. This makes sense due to the proximity between the alarm and the ignition source in the kitchen.

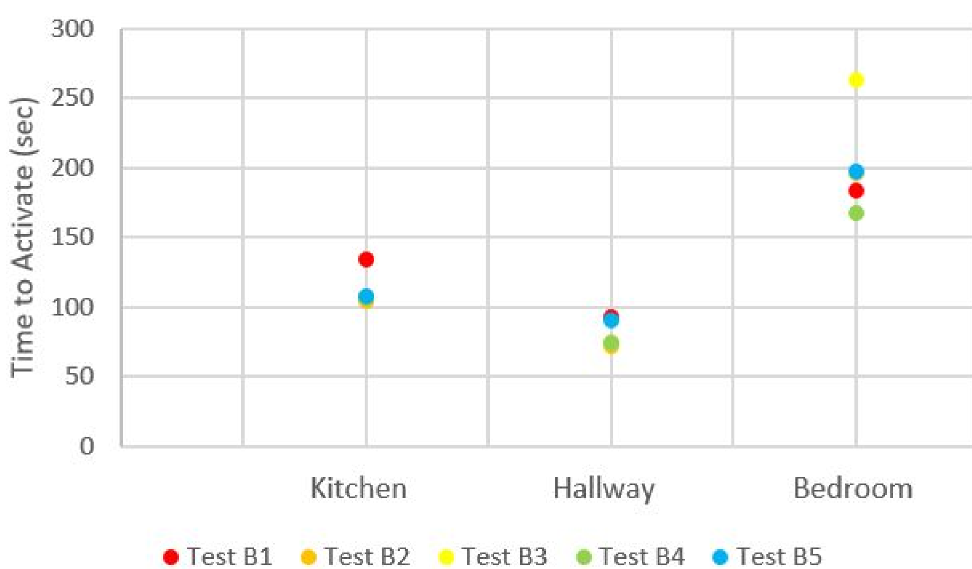

Figure 4.2: Smoke Alarm Activation Times by Location for Bedroom Fires

Even though the smoke alarm in Bedroom 1 is in close proximity to the fire source in Bedroom 4, Bedroom 1 has a closed door which restricts smoke movement.

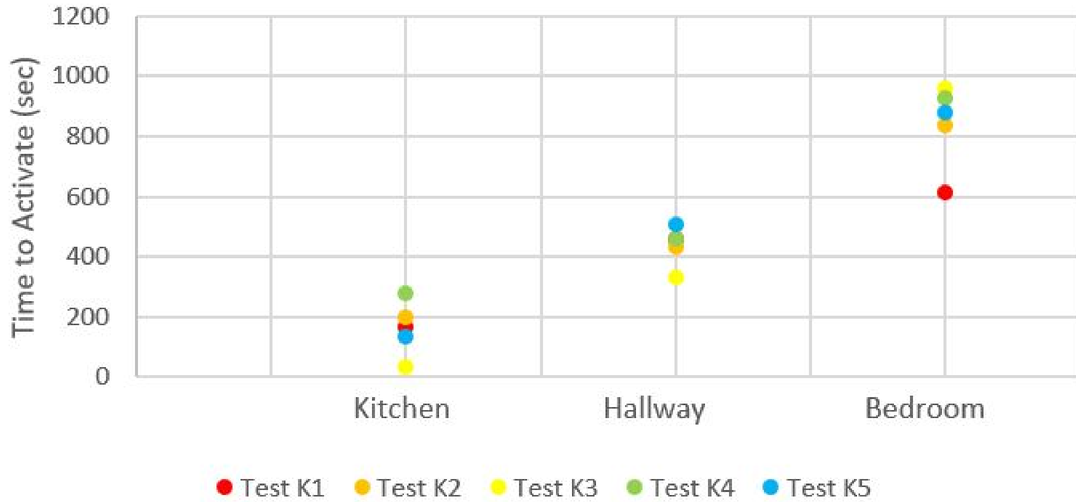

Figure 4.3: Smoke Alarm Activation Times by Location for Kitchen Fires

4.3 Total RSET

The single-story occupancy is compact enough that a smoke alarm in any of the three locations would be audible throughout the structure. That being said, RSET will be calculated with both a best case scenario (from the earliest alarm) and a worst case scenario (from the latest alarm). From Table 4.2 it is known that the time necessary for pre-movement and egress is approximately 105 seconds when walking and 115 seconds when crawling. Adding the smoke alarm activation times from Table 4.3, and the total RSET can be determined as indicated in Figures 4.2 and 4.3 and Table 4.4.

Experiment Number	RSET, Walking, Best Case	RSET, Walking, Worst Case	RSET, Crawling, Best Case	RSET, Crawling, Worst Case
B1	198	289	208	299
B2	177	301	187	311
B3	180	368	190	378
B4	180	273	190	283
B5	196	303	206	313
K1	271	721	281	731
K2	302	944	312	954
K3	137	1065	147	1075
K4	384	532	394	542
K5	238	985	248	995

Table 4.4: Total Required Safe Egress Times (sec)

4.4 Collected Data

For each bedroom and kitchen fire, percent concentrations of O_2, CO_2, and CO were measured at several sample points along the path of egress along with temperature and heat flux.

4.4.1 Gas Concentrations

For each experiment, CO, CO_2, and O_2 concentrations were measured over time. Figure 4.4 shows an example of how the concentrations of those gases change over time depending on location during a bedroom fire experiment, B1. The data shown in Figure 4.4 is over the duration of the test.

In Figure 4.4 the orange vertical lines show the times at which either the best or worst case smoke alarm has activated and the purple vertical lines show the corresponding times at which egress is accomplished.

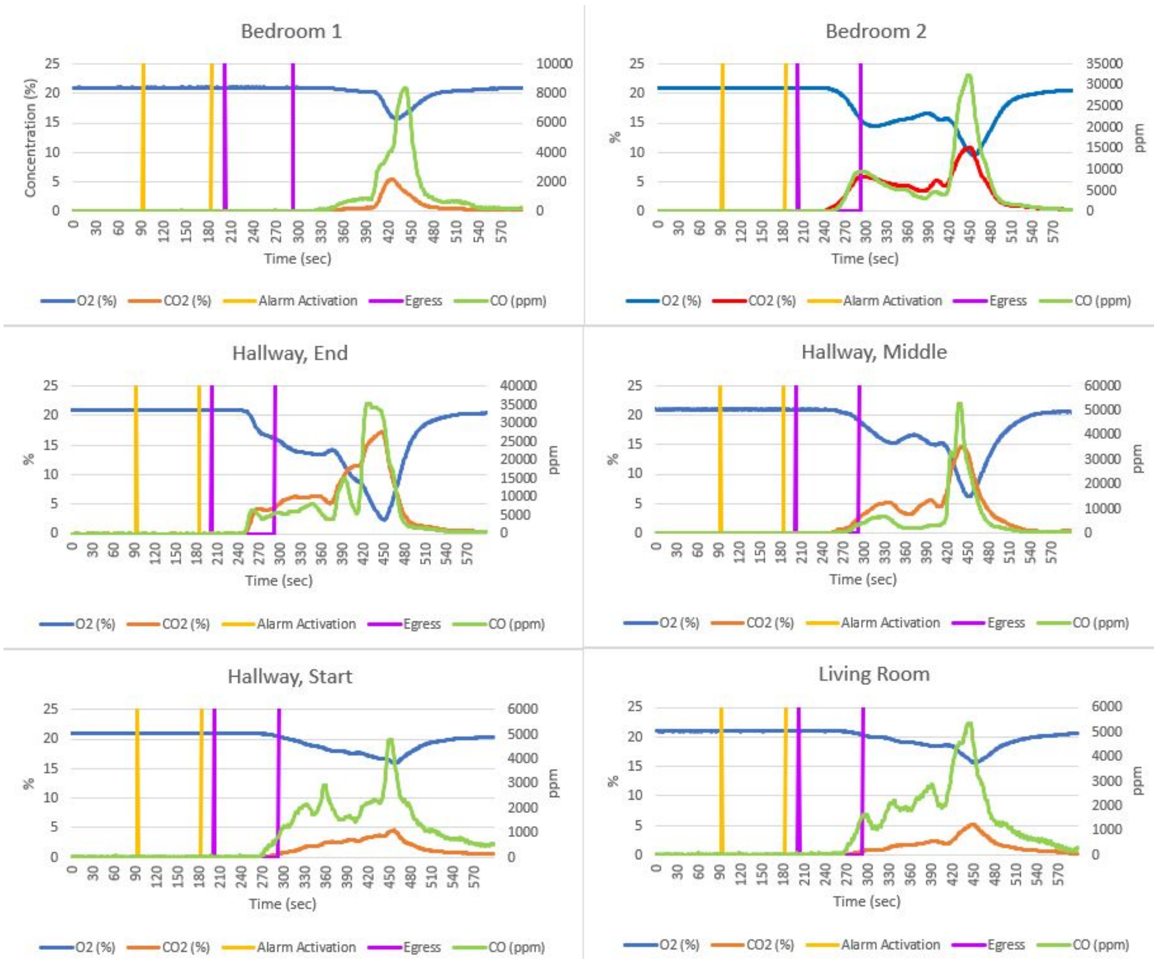

Figure 4.4: Gas Concentrations v. Time by Location for B1

As time passes, the concentrations of CO_2 increase, especially in the hallway. This is due to the large output of CO_2 by the fire in Bedroom 4. CO concentrations increase as well and are measured in ppm on the secondary y-axis rather than in percent. In many locations the CO level surpasses the dashed yellow line, denoting extremely hazardous conditions, however egress has already been accomplished in all test scenarios. In Bedroom 1 the O_2 level only decreases to 18.2% while at the end of the hallway it decreases to 8.8%, however this occurs after RSET. The closed bedroom door restricts most of the smoke from entering Bedroom 1 which allows for a smaller decrease in O_2 concentration.

Figure 4.5 shows how concentrations of CO, CO_2, and O_2 change over time depending on location during a kitchen fire experiment, K1. The data shown in Figure 4.5 is over the duration of the test. Similarly to Figure 4.4, the yellow dashed line indicates extreme hazard caused by CO and the orange and purple lines represent smoke alarm activation and RSET, respectively.

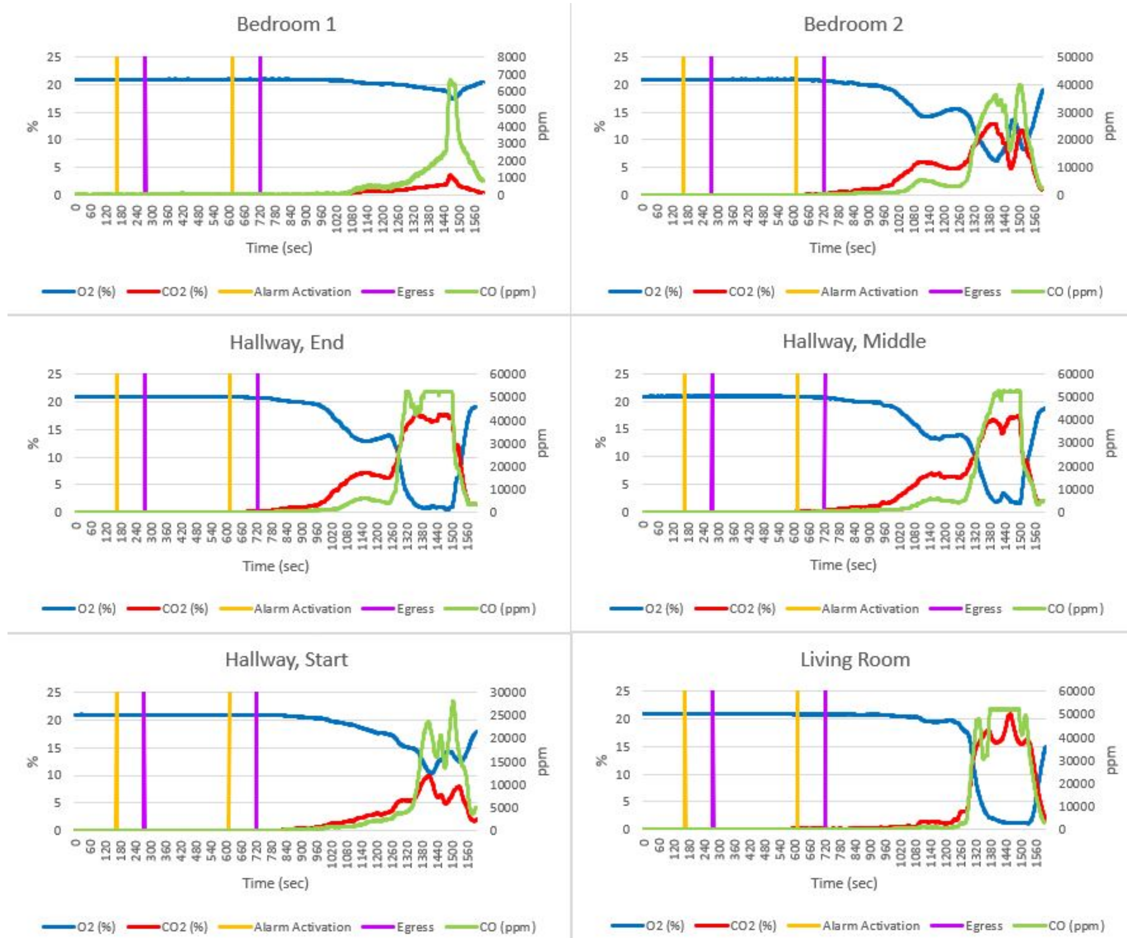

Figure 4.5: Gas Concentrations v. Time by Location for K1

The most significant differences can be seen in the gas concentrations measured in the living room and the hallway. This is expected due to the proximity between the fire origin in the kitchen and the living room as well as the open layout to the hallway. Complete gas concentration plots for each experiment can be found in Appendix B.

4.4.2 Temperature and Heat Flux

Heat flux and temperature were measured at points along the egress path located in close proximity to the gas sampling points. This data will provide the basis for establishing FED from radiant and convected heat. Figure 4.6 shows the temperature at an elevation of 0.9 m at the data sampling points along the egress path in the residence for experiment B1. The temperature data is shown over the duration of the test.

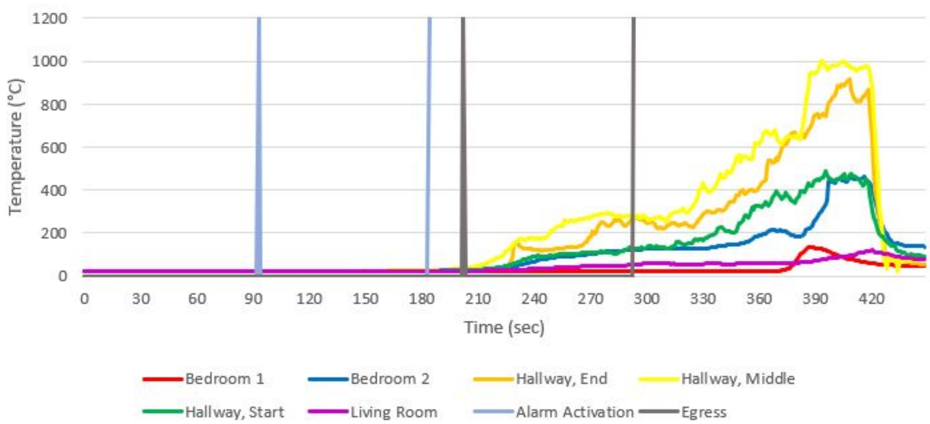

Figure 4.6: Temperature at 0.9 m v. Time for Bedroom Fires

Figure 4.6 shows the temperature data taken at various points at a height above the floor of 0.9 meters. The temperature data collection points are located along the egress path located in close proximity to the gas sampling points. The vertical blue lines show when either the worst or best case smoke alarm alerted and the gray vertical lines denote the corresponding RSET times.

Figure 4.6 shows a significant increase in temperature along the hallway. This is expected since the fire origin is in Bedroom 4. The lowest temperatures can be seen in Bedroom 1 and the living room which is also expected due to the thermal barrier provided by the closed door and distance from the fire, respectively.

Figure 4.7 shows the temperature at an elevation of 0.9 m at the data sampling points along the egress path for experiment K1. The temperature data is shown from ignition to suppression. Similarly to Figure 4.6, the vertical blue and gray lines show the times for smoke alarm activation and RSET, respectively.

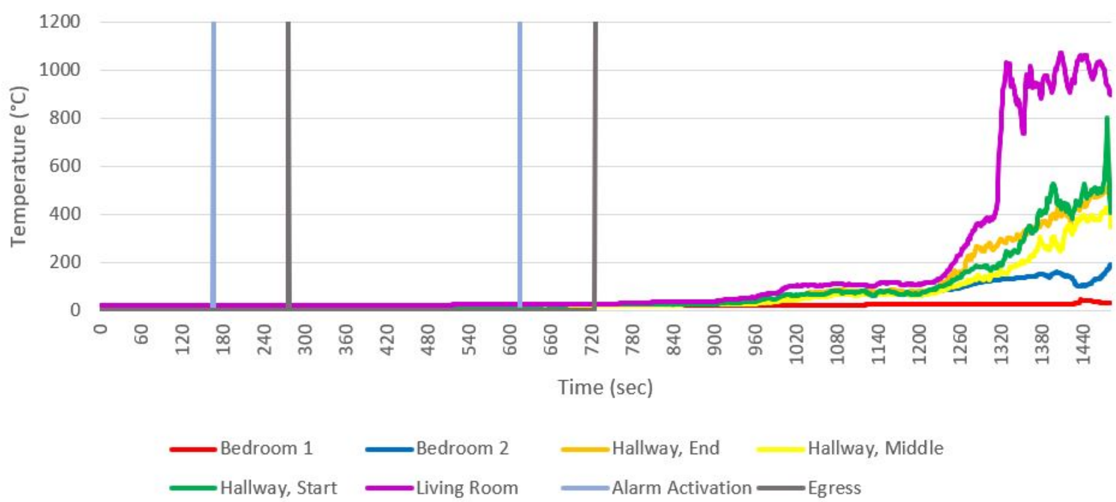

Figure 4.7: Temperature at 0.9 m v. Time for Kitchen Fires

Figure 4.7 shows a large increase in temperature in the living room as well as in the hallway. This is to be expected due to the open floorplan between the kitchen and the living room. It is interesting to note that the hallway, end zone is hotter than the hallway, middle zone even though it is farther away from the ignition source. This is likely due to the accumulation of hot gases at the end of the hallway caused in part by the closed door of Bedroom 1. Graphs showing the temperature at 0.9 m v. time for each of the experiments can be found in Appendix C.

Figure 4.8 shows heat flux data at the different data sampling points in the structure for experiment B1. The heat flux gagues are located at the floor. The heat flux data is shown for the duration of the test.

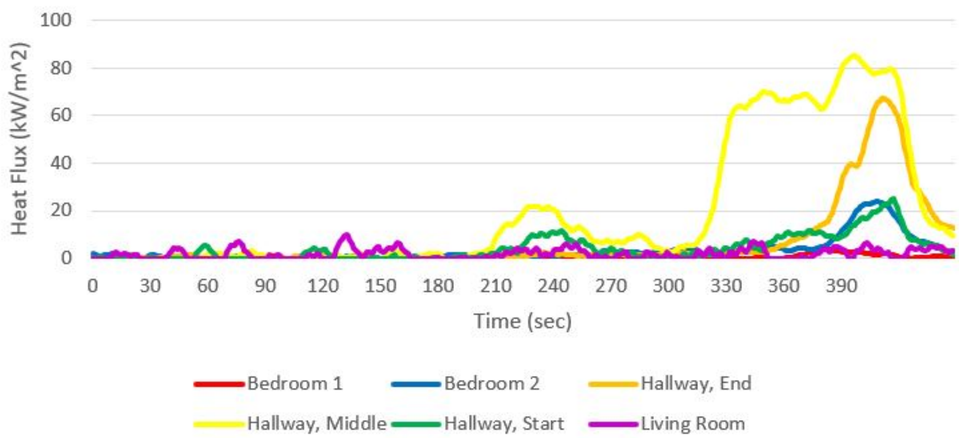

Figure 4.8: Heat Flux v. Time for Bedroom Fires

The largest increases in heat flux can be seen in the middle and end of the hallway. This trend is similar to that seen in 4.7 because of the close proximity of the fire origin in Bedroom 4 to the instruments in the hallway.

Figure 4.9 shows the changes in radiative heat flux at different sampling points in the structure for experiment K2. Although experiment K1 has been used as an example for kitchen fires up to this point, there was an error in heat flux data collection for this experiment so the data from K4 will be shown here instead. The heat flux data is shown for the duration of the tests.

In Figure 4.9 only the heat flux gauge in the living room registers significant thermal energy passing through the point of measurement. This is largely consistent with the other Kitchen Fire data sets, which makes sense because during the time of egress,

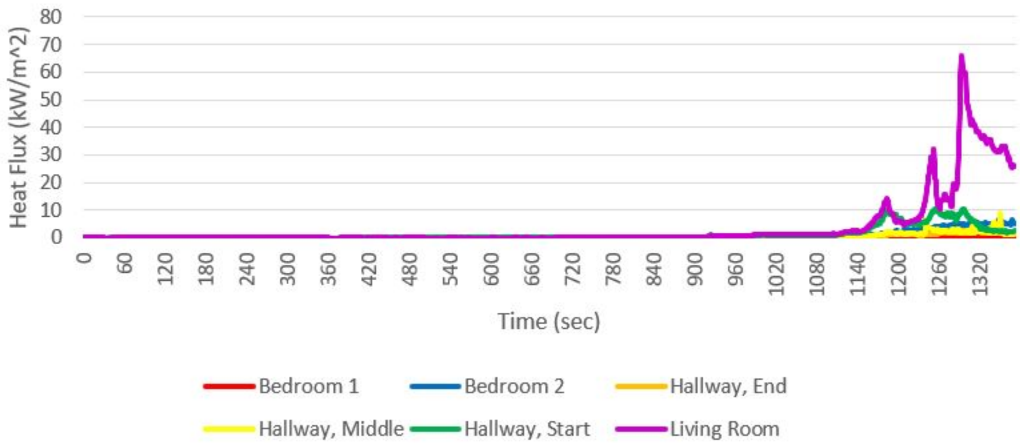

Figure 4.9: Heat Flux v. Time for Kitchen Fires

the fire is in the kitchen and the occupant is in the bedroom or the hallway.

4.5 Video Validation

Video footage was collected for all experiments done in this series. Video data from regular and infrared cameras can be used to see where the smoke layer (containing the heat and asphyxiant gases) is located at a certain time. In a house fire, the hot gas layer collects at the ceiling, then grows downward as the fire continues to produce smoke into the building. Therefore, video data will show the height of the hot gas layer which will act as a validation for the temperature data indicating the location of that hot gas layer over time.

Figure 4.10 shows two snapshots of the video data taken during experiment B1 at a t = 232 seconds and t = 255 seconds. Figures 4.4 and 4.6 show an increase in asphyxiant gas concentrations and temperature, respectively, over that same time period between t = 232 seconds and t = 255 seconds. This video footage acts as validation to the assumption that the hot gas layer produced by the fire coincides with the spike in the gas concentrations and temperature seen in the data. This rela-

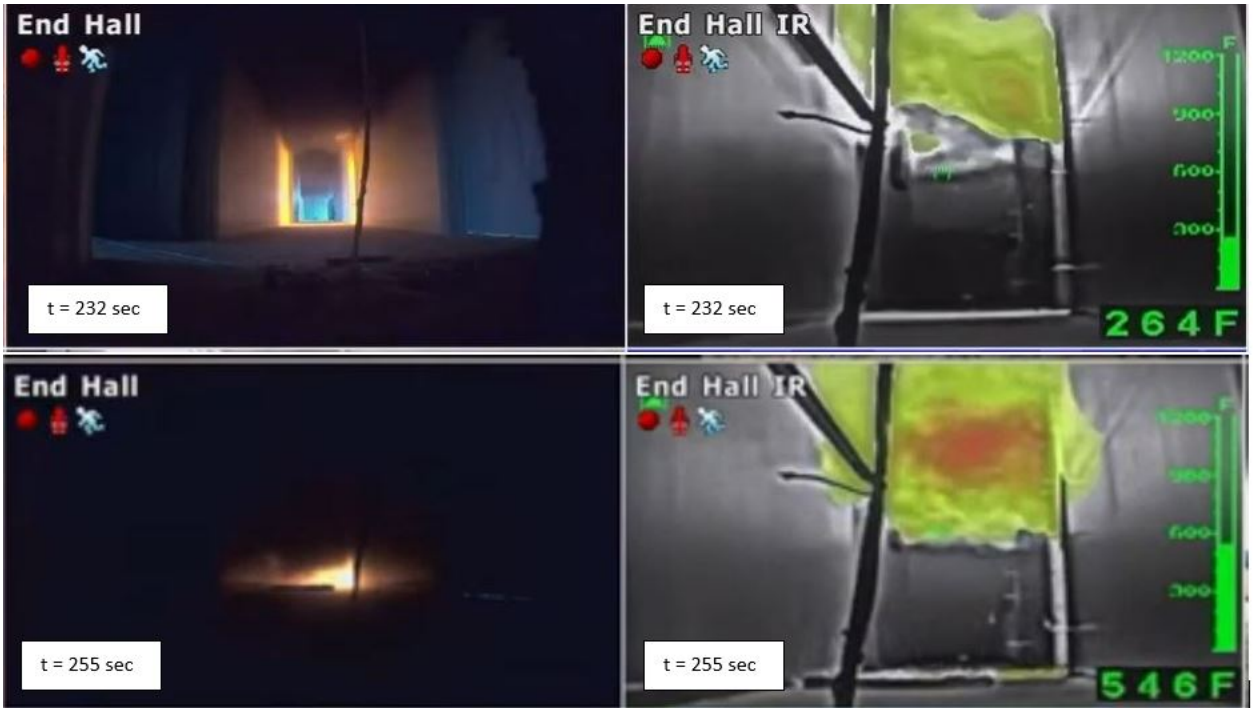

Figure 4.10: Video Footage of Hot Gas Layer Produced by Fire in Experiment B1

tionship is particularly useful because the equations for FED_{conv} and FED_{rad} assume that exposure to an environment of any temperature increases a person's FED over time. This is obviously inaccurate, since a person could survive in room temperature conditions indefinitely. In order to correctly analyze the thread posed by FED_{therm}, the only data points that should be considered are when egress overlaps with the increased thermal conditions.

Chapter 5: FED Modeling Analysis

Fractional Effective Dosage (FED) analysis is a compilation of equations used to predict the cumulative effect of asphyxiant gases on a person. The total FED at the endpoint of an occupant's egress relates the cumulative effects of increasing temperature, radiative heat flux, inhaling CO, CO_2, as well as the diminishing O_2 levels over the entire exposure period. The results from the FED analysis using empirical data will be discussed to see how a person would fare under the specified conditions. This data will provide insight on the ASET permitted by the bounds of this experiment.

Ten burn experiments were considered for this data series; five bedroom fires and five kitchen fires. For all ten scenarios, the door to Bedroom 1 was kept closed while the door to Bedroom 4, the site of ignition for the bedroom fire tests, was kept open.

5.1 Variable FED Calculations - Full Example

This section contains a complete example of the variable FED calculation in order to show an overview of the method and analysis.

The experiment considered in this example will be test B3 due to the regularity of the data in this specific test. To begin a variable FED analysis, first one must identify the location of an occupant at any given point throughout egress. This can be found using the smoke alarm activation times and egress movement calculations given in Table 4.3 and 4.2, respectively.

Next, the data collected by the thermocouples, heat flux gauges, and gas anayzers must be sorted to find the points that coincide with the specific times and locations that correlate to the egress process. These steps must be repeated to account for best and worst case scenarios as well as walking and crawling egress. In order to consider the effects of Bedroom 1's closed door, this analysis must be done for egress starting in both Bedroom 1 and Bedroom 2. In Figure 5.1, the cells are color coded to indicate

BW	WW			BC	WC			B1		
0	O2 (%)	CO2 (%)	CO (%)		O2 (%)	CO2 (%)	CO (%)	O2 (%)	CO2 (%)	CO (%)
	20.94	0.02	0.01	0.00	20.94	0.02	0.01	20.94	0.02	0.01
	20.93	0.04	0.00		20.93	0.04	0.00	20.93	0.04	0.00
	20.68	0.21	0.03		20.68	0.21	0.03	20.68	0.21	0.03
	20.69	0.18	0.03		20.69	0.18	0.03	20.69	0.18	0.03
	10.10	7.28	0.83		10.10	7.28	0.83	20.73	0.16	0.03
	10.34	7.06	0.76		10.34	7.06	0.76	20.73	0.18	0.04
	10.52	6.81	0.70		10.52	6.81	0.70	20.71	0.18	0.03
	10.73	6.58	0.65		10.73	6.58	0.65	20.69	0.19	0.03
	11.34	7.05	1.13		11.00	6.34	0.61	20.67	0.20	0.03
	11.48	6.77	1.05		11.19	6.10	0.57	20.68	0.21	0.03
	11.59	6.41	0.95		11.45	5.84	0.52	20.73	0.18	0.04
	11.76	6.02	0.85		11.76	6.02	0.85	20.70	0.18	0.04
	18.25	2.65	0.22		12.00	5.62	0.77	20.68	0.18	0.03
	18.21	2.68	0.21		12.20	5.19	0.69	20.67	0.20	0.03
	18.11	2.67	0.20		12.53	4.82	0.62	20.65	0.21	0.03
	18.06	2.25	0.18		12.83	4.40	0.56	20.70	0.20	0.03
	18.06	2.22	0.17		13.03	4.06	0.51	20.70	0.17	0.03
	18.13	2.15	0.17		18.10	2.57	0.22	20.70	0.15	0.03
	18.18	2.13	0.17		18.08	2.59	0.21	20.68	0.19	0.03
					18.05	2.55	0.21	20.66	0.21	0.03
					17.99	2.54	0.20	20.69	0.17	0.03
					18.22	2.07	0.16	20.68	0.20	0.03
					18.25	2.05	0.16	20.69	0.17	0.03
					18.28	2.01	0.16	20.67	0.18	0.03
					18.32	1.96	0.16	20.68	0.20	0.03
					18.35	1.92	0.15	20.67	0.20	0.03
					18.35	1.87	0.15	20.67	0.20	0.04

Figure 5.1: Assembled Data Points for FED Analysis Example

the location of an occupant during egress, it is worth noting that the data displayed is only a small section of the data analyzed for each test. Red denotes Bedroom 1, orange denotes Hallway, End, yellow denotes Hallway, Middle, green denotes Hallway, End, and purple denotes Living Room. Each section of color coded data has been taken from the appropriate sampling point in order to study the difference in exposure through the egress process.

Once all the data points are assembled, one should execute the three different FED analysis processes. The CO, CO_2, and O_2 concentrations are used to determine FED_{gas}. An example of a spreadsheet used for this analysis is provided in Figure 5.2.

Time	0	1	2	3	4	5	6	7	8	9	10	11
	WW											
	CO (ppm)	71.35018	12.3477	81.0076	145.391	177.582	209.774	145.391	151.829	206.554	261.28	309.567
	CO (%)	0.00713502	-0.0012	0.0081	0.01454	0.01776	0.02098	0.01454	0.01518	0.02066	0.02613	0.03096
	CO2 (%)	0.02315106	0.03764	0.00866	-0.0171	-0.0251	-0.009	0.03764	0.00384	0.02315	0.01993	0.00384
	O2 (%)	20.9385451	20.9257	20.9305	20.9691	20.9514	20.8983	20.8822	20.8774	20.8951	20.879	20.8838
	FED	1.7689E-06	1E-05	5.7E-05	0.00014	0.00025	0.00037	0.00046	0.00055	0.00067	0.00082	0.00101
	FEDico	0.00229629	0.00037	0.00262	0.0048	0.00591	0.00702	0.0048	0.00502	0.00691	0.00881	0.0105
	Vco2	0	1.04818	1.04243	1.0441	1.04569	1.0425	1.04818	1.04147	1.0453	1.04466	1.04147
	FEDio2	0.00010613	0.00011	0.00011	0.0001	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011
	FED, time	0.00010613	0.0005	0.00284	0.00512	0.00628	0.00743	0.00514	0.00534	0.00733	0.00931	0.01105
	FED, sum	0.00010613	0.0006	0.00344	0.00856	0.01484	0.02226	0.02741	0.03274	0.04007	0.04939	0.06044
	Gas	0	0.00039	0.00273	0.00501	0.00618	0.00732	0.00503	0.00523	0.00722	0.0092	0.01094
	WC											
	CO (ppm)	71.35018	12.3477	81.0076	145.391	177.582	209.774	145.391	151.829	206.554	261.28	309.567
	CO (%)	0.00713502	-0.0012	0.0081	0.01454	0.01776	0.02098	0.01454	0.01518	0.02066	0.02613	0.03096
	CO2 (%)	0.02315106	0.03764	0.00866	-0.0171	-0.0251	-0.009	0.03764	0.00384	0.02315	0.01993	0.00384
	O2 (%)	20.9385451	20.9257	20.9305	20.9691	20.9514	20.8983	20.8822	20.8774	20.8951	20.879	20.8838
	FED	1.7689E-06	1E-05	5.7E-05	0.00014	0.00025	0.00037	0.00046	0.00055	0.00067	0.00082	0.00101
	FEDico	0.00229629	0.00037	0.00262	0.0048	0.00591	0.00702	0.0048	0.00502	0.00691	0.00881	0.0105
	Vco2	0	1.04818	1.04243	1.0441	1.04569	1.0425	1.04818	1.04147	1.0453	1.04466	1.04147
	FEDio2	0.00010613	0.00011	0.00011	0.0001	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011
	FED, time	0.00010613	0.0005	0.00284	0.00512	0.00628	0.00743	0.00514	0.00534	0.00733	0.00931	0.01105
	FED, sum	0.00010613	0.0006	0.00344	0.00856	0.01484	0.02226	0.02741	0.03274	0.04007	0.04939	0.06044
	Gas	0	0.00039	0.00273	0.00501	0.00618	0.00732	0.00503	0.00523	0.00722	0.0092	0.01094

Figure 5.2: FED Analysis Spreadsheet Example

The temperature data points are used to determine FED_{conv} using Equation 2.11 and the heat flux data points are used to determine FED_{rad} using Equation 2.10. The sum of FED_{conv}^{-1} and FED_{rad}^{-1} is equal to $FED_{thermal}$, as stated in Equation 2.12. Similarly to Figure 5.2, an FED spreadsheet is used to determine FED due to convective and radiative heat.

Once the relationships between FED and time have been established one can generate the necessary plots to show how the tenability changes over time in a residence fire. This entire analysis should be repeated for all bedroom and kitchen experiments.

5.2 Variable FED Calculations - Gas Concentrations

A typical FED analysis considers the asphyxiant gases someone would be exposed to over time in one location. This thesis focuses on a variable FED analysis in order to build a profile of the asphyxiant gas exposure over several locations. Each plot in Appendix A shows the FED over time for best and worst case walking and crawling scenarios. In addition, each plot shows the FED profile behind the closed bedroom door, as well as comparison plots showing the FED profiles for an occupant starting in an open bedroom.

5.2.1 Bedroom Fires

Figure 5.1 shows the FED data for one of the bedroom fires. In this figure, FED is shown as a function of time for the best case scenario (both walking and crawling) and the worst case scenario (both walking and crawling) for an occupant starting in both Bedroom 1 and Bedroom 2. These plots also show the FED behind the closed door of Bedroom 1. In each scenario, the occupant would begin in either Bedroom 1 (door closed) or Bedroom 2 (door opened). If the first smoke alarm to activate begins the egress process, then it is considered a best case scenario. If the last smoke alarm to activate, the one located in Bedroom 1, begins the egress process, then it is considered a worst case scenario.

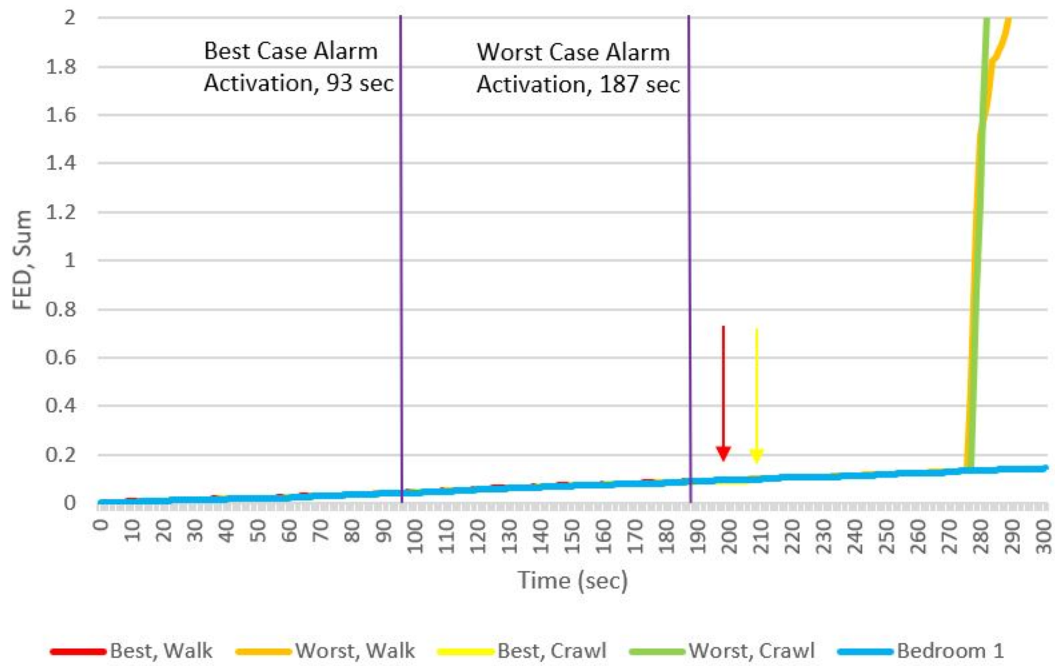

Figure 5.3: FED_{gas} v. Time for Experiment B1

If an occupant was to stay inside Bedroom 1 for the duration of this test, they would receive a low FED assuming the door does not fail. In this series of experiments the fire was suppressed prior to burnout. Although an occupant in Bedroom 1 would receive a low FED for the time span considered, the room would likely not remain tenable for an entire house fire event.

All of the data lines are the same before egress begins because the occupant would be inside Bedroom 1 for all cases. The marks on Figure 5.1 for both best case scenarios overlap with those for Bedroom 1 throughout the entire egress process. The gas concentrations in the hallway and living room are similar to those in Bedroom 1. This shows that at the time of best case scenario egress, the fire is not developed enough to have an asphyxiant effect on an occupant during egress. An FED of 0.3 would cause incapacitation for around 10% of the population, most likely the elderly, the very young, and those with pre-existing conditions.

The worst case scenario shows significantly different results. Once the occupant leaves Bedroom 1 the FED increases rapidly and reaches levels greater than 2 before egress can be completed. This shows that for this test, a worst case scenario attempt at egress would be fatal. In the short time between the best and worst case scenarios the path of egress became untenable.

5.2.2 Kitchen Fires

Figure 5.2 shows the gas concentration FED data for one of the kitchen fires. In this figure, FED is shown as a function of time for the best case scenario (both walking and crawling) and the worst case scenario (both walking and crawling) for an occupant starting from both Bedroom 1 or Bedroom 2. These plots also show the FED behind the closed door of Bedroom 1. As with Figure 5.2, the data lines overlap for most of the test since the occupant remains in one of the two bedrooms before egress. This is likely due to the geometry of the floorplan and the distance traveled by an occupant attempting egress.

If an occupant was to stay inside Bedroom 1 for the duration of this test, they would receive an FED of almost 0.9. That being said, the duration of the test is over twelve minutes. The marks in Figure 5.2 that correspond to the best case scenario are al-

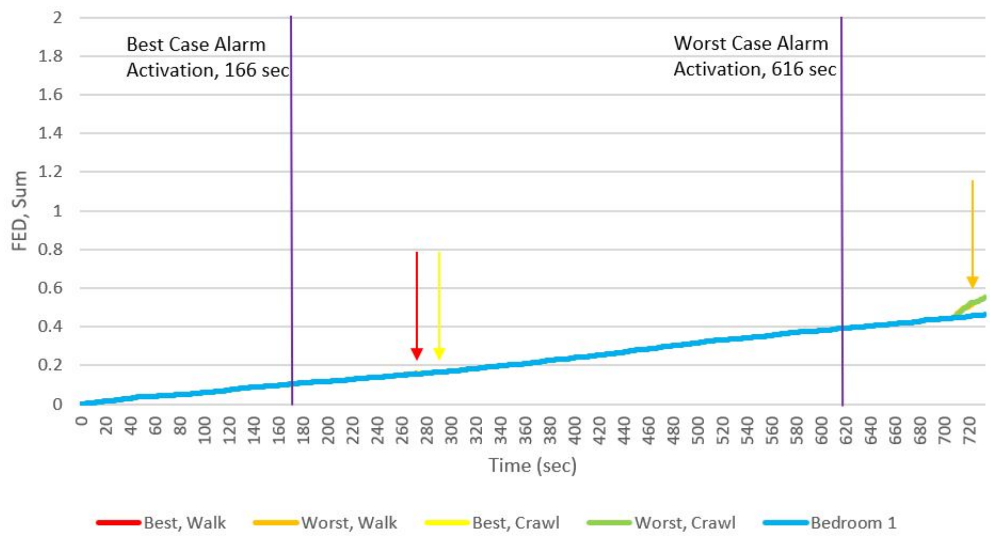

Figure 5.4: FED_{gas} v. Time for Experiment K1

most indistinguishable from the data line for Bedroom 1. This shows that at the time of best case scenario egress, the fire is not developed enough to have an asphyxiant effect on an occupant during egress.

The worst case scenario shows a distinct increase in FED during egress. This makes sense because the fire would be growing and an occupant attempting egress would be inhaling increased amounts of CO and CO_2. For this test, a worst scenario attempt at egress would result in an FED of nearly 1, the level at which approximately 50% of the population would be susceptible to the asphyxiant effects.

5.3 Variable FED Calculations - Heat Flux and Temperature

A typical thermal FED analysis considers the radiative and convected heat someone would be exposed to over time in one location. This thesis focuses on a variable FED analysis in order to build a profile of the heat exposure over several locations. Each plot in the appendix shows the FED over time for best and worst case walking and crawling scenarios. In addition, each plot shows the FED profile behind the closed bedroom door.

5.3.1 Bedroom Fires

Figure 5.3 shows the thermal FED for experiment B1. As seen from Figure 4.9, the heat flux at any point in the structure during egress never exceeds 2.5 kW/m^2 so the FED due to radiant heat flux can be assumed to be negligible. Therefore, only the temperature component, represented as convected heat, makes an impact on the FED. This is true for all of the bedroom fires and can be seen in the corresponding plots located in Appendix A.

Figure 5.5: FED$_{therm}$ v. Time for Experiment B1

Figure 5.3 shows that the FED caused by temperature increase is very low for the best case scenarios. An occupant attempting walking egress for the worst case alarm scenario would receive an FED of 1.07 which would incapacitate about 50% of the population. An occupant attempting crawling egress for the same worst case scenario would receive an FED of 1.7 which would incapacitate almost the entire population.

5.3.2 Kitchen Fires

Figure 5.4 shows the thermal FED for experiment K1. Since Figure 4.10 shows a heat flux less than 2.5 kW/m^2 for all zones in the structure except for the end of the hallway, FED due to radiative heat flux is negligible in those zones. Figure 4.10 also shows a heat flux of greater than 2.5 kW/m^2 at the end of the hallway for times after 617 seconds. For each of the egress scenarios, if an occupant is located in the zone at the end of the hallway after that time, the FED due to radiative heat flux will be calculated and added to the FED due to convected heat.

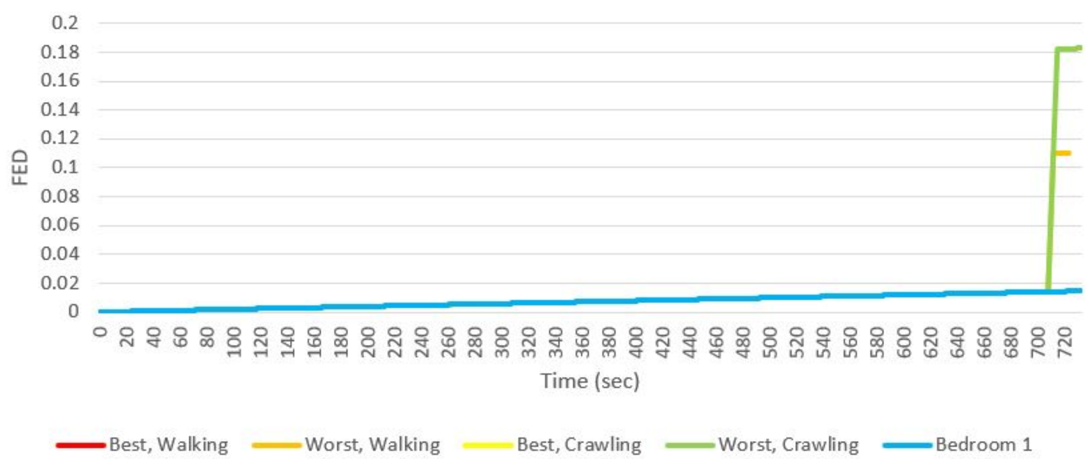

Figure 5.6: FED$_{therm}$ v. Time for Experiment K1

Figure 5.4 does show an increase in FED for the worst case test scenarios due to both radiative heat flux and temperature rise. The best case test scenarios and Bedroom 1 show very small FED levels, all less than 0.015. Figures from each experiment showing the relationship between thermal FED over time for each of the egress scenarios can be found in Appendix A.

5.4 Variable FED Calculations - Combined

Figure 5.5 shows the combined FED as a function of total time to egress for bedroom fires. The relationship between FED and RSET for bedroom fires is difficult

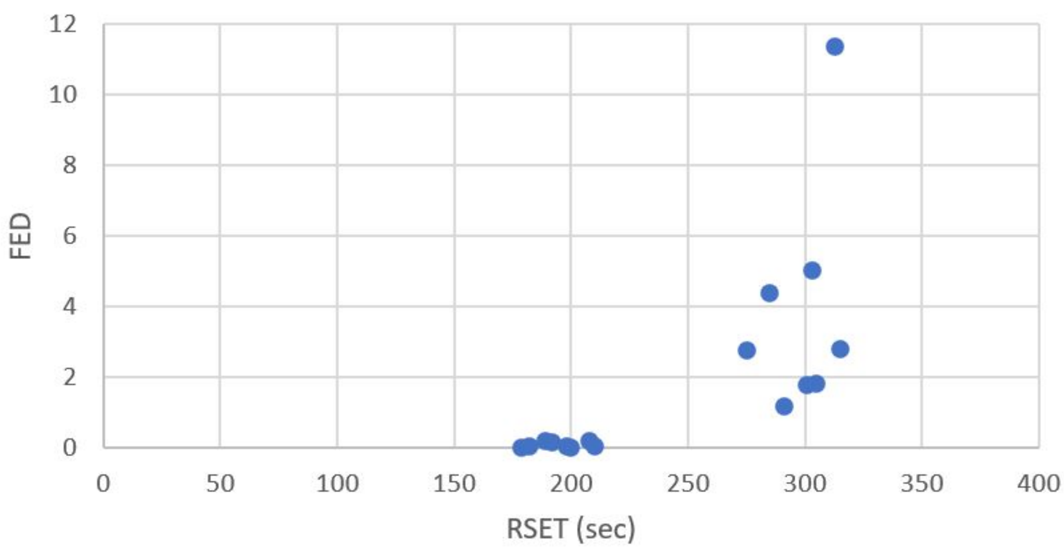

Figure 5.7: FED_{total} v. RSET for Bedroom Fires

to distinguish but certainly points to the idea that FED is less for faster egress times. Thet being said, Figure 5.5 appears to be a step function, likely due to the closed bedroom door behind which the occupants begin their egress.

A plot of the relationship between FED and time to total egress for kitchen fires, Figure 5.6, shows a more distinct pattern than in Figure 5.5. It is clear that there exists a power-law relationship between FED and time to total egress for the kitchen fire scenarios. This is likely due to the fact that as the fire progresses and releases more heat, smoke, and particulates, the hazard to an occupant increases as well in the form of heat and FED.

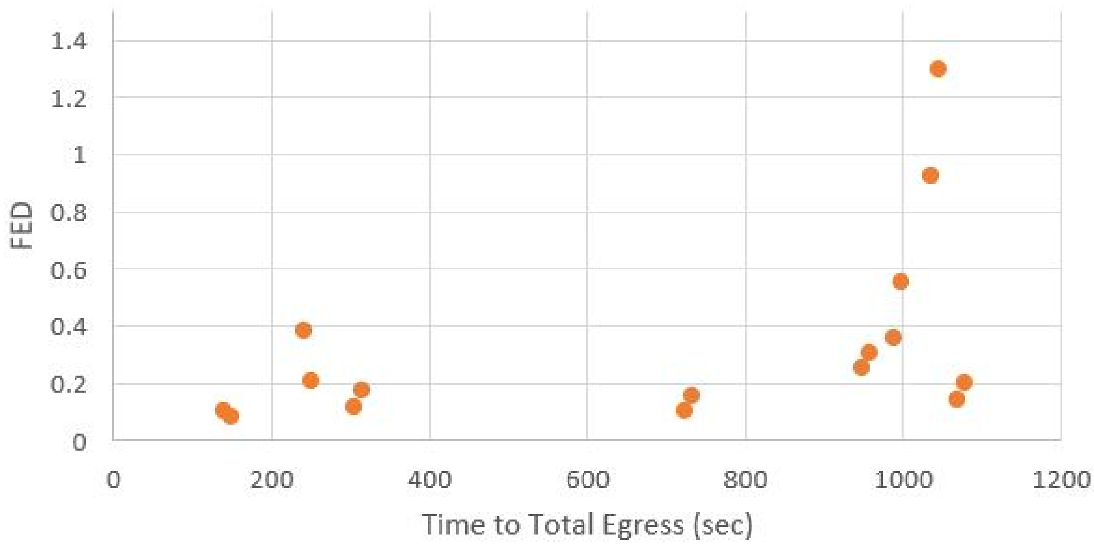

Figure 5.8: FED_{total} v. RSET for Kitchen Fires

A plot depicting the relationship between FED and time to egress for each experiment can be found in Appendix A. Each of these plots take into account best case and worst case scenarios for both walking and crawling egress. Each of these plots show that the longer it takes for a person to exit the building in a fire scenario, the more asphyxiant gases and heat effects they are being exposed to. This makes sense because as the person is attempting egress the fire continues to grow and produce smoke, particulates, heat, and asphyxiant gases. In addition, since bodily harm from heat and asphyxiant gas inhalation is compounded over the length of exposure, the longer it takes a person to exit the building the greater the effect of said exposure.

Table 5.1 shows the FED_{total} for all bedroom fire cases while considering an egress origin of Bedroom 1 versus Bedroom 2. Table 5.1 shows that although the best case

Occupant in Bedroom 1				Occupant in Bedroom 2			
Best, Walk	Worst, Walk	Best, Crawl	Worst, Crawl	Best, Walk	Worst, Walk	Best, Crawl	Worst, Crawl
0	0.5	0.05	0.8	0	0.5	0.05	0.8
0	1.9	0.2	4.5	0	2.2	0.2	4.8
0	0.18	0.2	0.4	0	2.8	0.24	2.9
0.02	1.7	0.2	2.0	0.02	1.5	0.2	2.3
0.04	0.8	0.2	1.3	0.04	2.5	0.2	2.6
Average							
0.012	0.93	0.16	1.8	0.012	1.9	0.16	2.7

Table 5.1: FED_{total} for Bedroom Fires with Bedroom 1 and Bedroom 2 Origin

FED levels are equal for occupant origin in both bedrooms, there is a large difference between FED levels for worst case scenarios. The best case FED levels are the same since egress occurs before the fire has grown significantly that the closed door could provide an advantage. Although the worst case scenario FED levels are greater for egress starting in Bedroom 2, all values are so high as to be lethal for any occupant. A similar table can be written to display the combined FED data for kitchen fires: As

Occupant in Bedroom 1				Occupant in Bedroom 2			
Best, Walk	Worst, Walk	Best, Crawl	Worst, Crawl	Best, Walk	Worst, Walk	Best, Crawl	Worst, Crawl
0	0	0	0	0	0	0	0
0.12	0.26	0.18	0.31	0.12	0.26	0.18	0.31
0.11	0.15	0.09	0.2	0.11	0.21	0.09	0.22
0	0	0	0.01	0	0.09	0	0.09
0.39	0.36	0.09	0.56	0.39	0.36	0.21	0.56
Average							
0.12	0.16	0.1	0.22	0.12	0.18	0.1	0.24

Table 5.2: FED_{total} for Kitchen Fires with Bedroom 1 and Bedroom 2 Origin

with Table 5.1, Table 5.2 shows similar FED levels from each bedroom for the best case scenarios and slightly higher ones for Bedroom 2 in the worst case scenarios. This is to be expected since the closed door of Bedroom 1 can act as a barrier between an occupant and harmful heat and gas concentrations.

Since FED_{gas} cannot be added to $FED_{thermal}$, the value listed in the Tables 5.1 and 5.2 is the maximum FED between the two.

Chapter 6: Discussion

As expected from the data provided, early egress provides occupants with a much lower FED than lengthy egress. Therefore, to begin egress as quickly as possible, it is important for residential occupancies to have working smoke alarms installed. In order to avoid the worst case scenario, in this experimental program, egress does not begin until the alarm in Bedroom 1 activates, the smoke alarms in a residence could be hardwired so that if any one is triggered, all units will alert.

6.1 FED and Occupant Susceptibility

The definition of FED analysis states that at a level of 1, approximately half of the population would be susceptible to the effects of asphyxiant gas exposure. Only 11.3% of the population is likely to be susceptible to the effects of toxic gas exposure at an FED of 0.3. This section of the population is likely to be comprised of the elderly, the very young, and those with preexisting conditions such as asthma. For all ten experiments, if egress is accomplished in under approximately four minutes, the FED level is below 0.3.

About 90% of the population is likely to be susceptible to the effects of toxic gas exposure at an FED of 1.3. While all of the best scenario experiments resulted in FED levels below this mark, the fires with prolonged egress showed much greater FED levels. This is due to the cumulative nature of asphyxiant gas exposure over time as well as the increase in temperature along the path of egress.

The goal of these experiments is to compare the calculated RSET with the data-based ASET to determine if safe egress is possible for each of the test scenarios. Therefore, if FED is greater than 1, it can be concluded that ASET is less than RSET and safe egress is not possible. Table 6.1 shows a breakdown of the qualitative results of each of the tests done as a part of this thesis. In this table each test is assigned one of three categories, Tier 1: $0 < \text{FED} < 0.3$, Tier 2: $0.3 < \text{FED} < 1$, Tier 3: $\text{FED} > 1$. All tests determined to be in Tier 1 or Tier 2 show that ASET is greater than RSET and the final FED is between 0 and 1, therefore providing a greater than 50% chance probability of tenability. Scenarios in Tier 3 show that ASET is less than RSET because the final FED is greater than 1, therefore denoting the likely probability of incapacitation. A similar table can be made to analyze the success status for the analyses conduced with egress from Bedroom 2, without the benefit of the closed door. Although ”success” in this project is determined when incapacitation rates are less than 50%, this would not be a practical benchmark. Even the Tier 1 incapacitation rates of 11.3% of the population would likely be too high for building

Bedroom Fires				Kitchen Fires			
Best, Walk	Best, Crawl	Worst, Walk	Worst, Crawl	Best, Walk	Best, Crawl	Worst, Walk	Worst, Crawl
Tier 1	Tier 2	Tier 1	Tier 2	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 3	Tier 1	Tier 3	Tier 1	Tier 1	Tier 1	Tier 2
Tier 1	Tier 1	Tier 1	Tier 2	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 3	Tier 1	Tier 3	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 2	Tier 1	Tier 3	Tier 2	Tier 2	Tier 1	Tier 2

Table 6.1: Success Status for All Test Scenarios: Egress from Bedroom 1

Bedroom Fires				Kitchen Fires			
Best, Walk	Best, Crawl	Worst, Walk	Worst, Crawl	Best, Walk	Best, Crawl	Worst, Walk	Worst, Crawl
Tier 1	Tier 2	Tier 1	Tier 2	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 3	Tier 1	Tier 3	Tier 1	Tier 1	Tier 1	Tier 2
Tier 1	Tier 3	Tier 1	Tier 3	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 3	Tier 1	Tier 3	Tier 1	Tier 1	Tier 1	Tier 1
Tier 1	Tier 3	Tier 1	Tier 3	Tier 2	Tier 2	Tier 1	Tier 2

Table 6.2: Success Status for All Test Scenarios: Egress from Bedroom 2

planners to consider a success. These results point to the necessity of adherence to residential building codes.

6.2 Residential Smoke Alarm Placement

Although the main causes for smoke alarm malfunction are due to poor maintenance, improper device placement can limit proper function [3]. The smoke alarms used in these experiments were installed following the guildelines from the ICC International Residence Code. The results of this study show that if all alarms are installed and maintained properly, safe egres is always possible, as can be seen from the best case scenarios. The ICC also recommends that multiple devices be placed in a residence and that these individual units be interconnected. This means that when one alarm alerts, all units respond as well providing more effective notification throughout a structure. The research done for this project provides strong support for the benefit of following the requirements noted in the Internaltional Residence Code for smoke alarm placement and interconnections [23].

6.3 The Closed Bedroom Door

Although FED levels are low for most of the best case scenario tests, that is due to the limited exposure window during egress. Clearly seen in each plot from the appendix, the running FED total stays consistently low and only spikes up during egress, a phenomenon that is especially noticeable for the worst case scenario tests. The sudden FED spike shows the effects of a closed bedroom door on asphyxiant gas exposure. Although the FED level does increase for an occupant remaining in Bedroom 1, it increases at a greater rate and to a higher end value for occupants attempting worst case scenario egress.

If a fire scenario arises in which an occupant finds themself trapped behind a closed door, they can shelter in place for some time while awaiting help. Since the residence considered for these experiments is only one story, the trapped occupant might find additional means of egress such as escaping out of a window. It is useful to compare FED levels for both kitchen and bedroom fires in order to better visualize the advantage provided by a closed bedroom door. Tables 5.1 and 5.2 illustrate the differences between FED for an occupant located in Bedroom 1 versus Bedroom 2. Figure 6.1

shows this data comparatively for bedroom fire experiments. The worst case FED

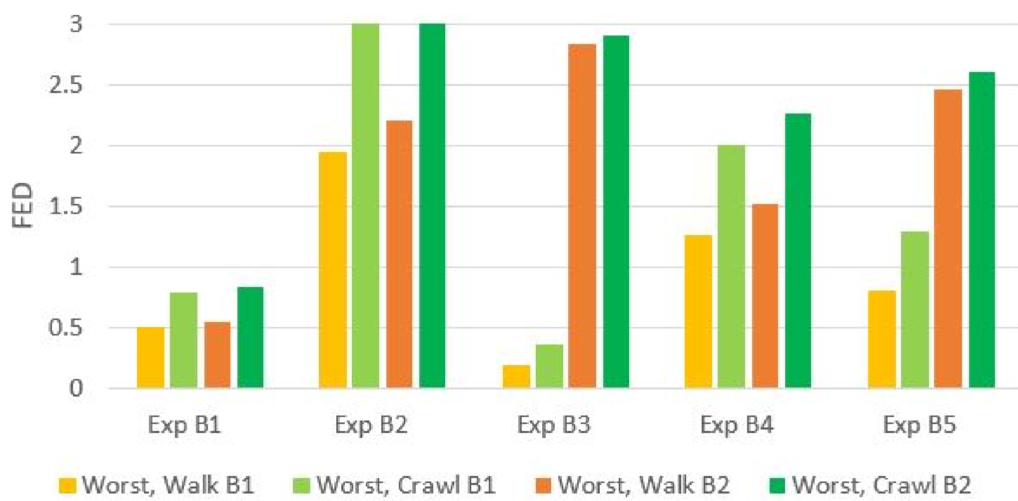

Figure 6.1: FED_{total} for Bedroom Fires Depending on Occupant Location - Bedroom 1 or Bedroom 2

quantities for an occupant located in Bedroom 1 are 0.9 for walking egress and 1.8 for crawling egress. In Bedroom 2, without the benefit of a closed door, an occupant would experience much larger doses of asphyxiant gases, worst case FED quantites of 1.9 for walking egress and 2.7 for crawling egress. Although most of these scenarios would result in incapacitation no matter which bedroom is the origin for egress, the difference between the FED amounts is significant.

Figure 6.2 shows FED analyses for kitchen fires depending on if an occupant began in Bedroom 1 or Bedroom 2. The FED quantities for occupants starting in either bedroom are very similar. Although both of these values are small, the difference between them shows just how effective the protection of a closed bedroom door can be. In the cases shown in Figure 6.1 and Figure 6.2, staying behind a closed bedroom

Figure 6.2: FED for Bedroom Fires Depending on Occupant Location - Bedroom 1 or Bedroom 2

door could certainly be the difference between life and death.

Chapter 7: Summary

The goal of this research was to perform a variable FED analysis of CO, CO_2, and O_2 in a single story residence. This series of tests was successful in that FED was determined for several fire experiments of both kitchen and bedroom origin. Although the path of egress in the structure was simple and allows for quick escape, there is a significant increase in FED for tests where smoke alarms alerted after several minutes rather than alerting more quickly. For this series of tests a smoke alarm only alerted after several minutes if it was located behind a closed door which significantly inhibited smoke movement. In the cases where a residence only had the smoke alarm in the closed bedroom, safe egress was never possible except for in the case of a few slow-growth fires, but even then, egress posed a significant risk to the occupant. In order to provide occupants with as much safe egress time as possible, several working smoke alarms should be installed in a residence to detect threats in multiple locations. In many of the test scenarios an occupant would be able to egress safely. In the cases where an occupant would not be able to egress safely, the conditions in a bedroom with a closed door were significantly more tenable than with an open door. Therefore, it is important to employ the use of a closed bedroom door when possible to offer as much protection as possible from asphyxiant gas exposure.

Although this series of experiments provided insight into available safe egress analysis, there is still plenty of work to be done. In order to better understand smoke alarm activation efficiency this experiment could be repeated with several different smoke alarms. This would help to offer a comparison between models such as, for example, ionization and photoelectric smoke alarms compared to the combination alarm used in these tests. In addition, data from experiments with different fire scenarios, such as living room origin, would be beneficial to analyze.

The information gathered for the FED analysis would be useful when modeling the fire event. Differences between a model and reality show the need for a more accurate model. It would be interesting to compare egress data with the results computed by egress modeling software to see if any inconsistencies between the two exist. The results of these experiments are reliable because the tests were conducted in a single-story residence rather than a typical laboratory.

The series of experiments done for the Residential Size-Up and Search & Rescue tests by UL FSRI focused on a single-story occupancy but collecting asphyxiant gas concentrations at various sample locations could be performed in any structure in order to determine how building geometry dictates smoke movement.

The gas concentration data used in both the walking and crawling FED analysis was taken from an elevation of 0.9 m above the floor. A gas sample at 1.5 m would be useful to provide more accurate walking data. The differences between the walking and crawling exposures could be compared more effectively with this addition measurement.

The fire sources in these experiments were not characterized, meaning that the heat release rates were not measured. This was due to the realistic residential setting of the experiments rather than a laboratory. It would be useful to compare the results of these experiments with those from computational fire models such as Fire Dynamics Simulator (FDS). However, without the information given by a characterized fuel source, it would be difficult to build an accurate mathematical comparison.

Chapter Ab.: Abbreviations and Symbols

ASET - Available Safe Egress Time
RSET - Required Safe Egress Time
B1-B5 - Bedroom Fire Experiments 1 through 5
K1-K5 - Kitchen Fire Experiments 1 through 5
BW - Best Case Scenario, Walking
    BC - Best Case Scenario, Crawling
    WW - Worst Case Scenario, Walking
    WC - Worst Case Scenario, Crawling
FED - Fractional Effective Dosage
    FED_{gas} - Fractional Effective Dosage due to asphyxiant gas exposure
    FED_{therm} - Fractional Effective Dosage due to thermal components (heat and radiative heat flux exposure)

CO - Carbon Monoxide
CO_2 - Carbon Dioxide
CH_4 - Methane
H_2O - Water Vapor
O_2 - Oxygen Gas
N_2 - Nitrogen Gas

C_{CO} - Concentration of Carbon Monoxide [ppm]
%COHb - Carboxyhemoglobin [%]
F_{CO} - Fractional Effective Dosage due to Carbon Monoxide
F_{O_2} - Fractional Effective Dosage due to Oxygen Decrease
RMV - Respiratory Minute Volume [L/min]
t - Time [sec]
    t_{rad} - Time of exposure to radiative heat flux [sec]
    t_{conv} - Time of exposure to convected heat [sec]
V_{CO_2} - Volume of Carbon Dioxide [L]

Chapter A: Appendix A - FED Plots (Asphyxiant Gas and Heat)

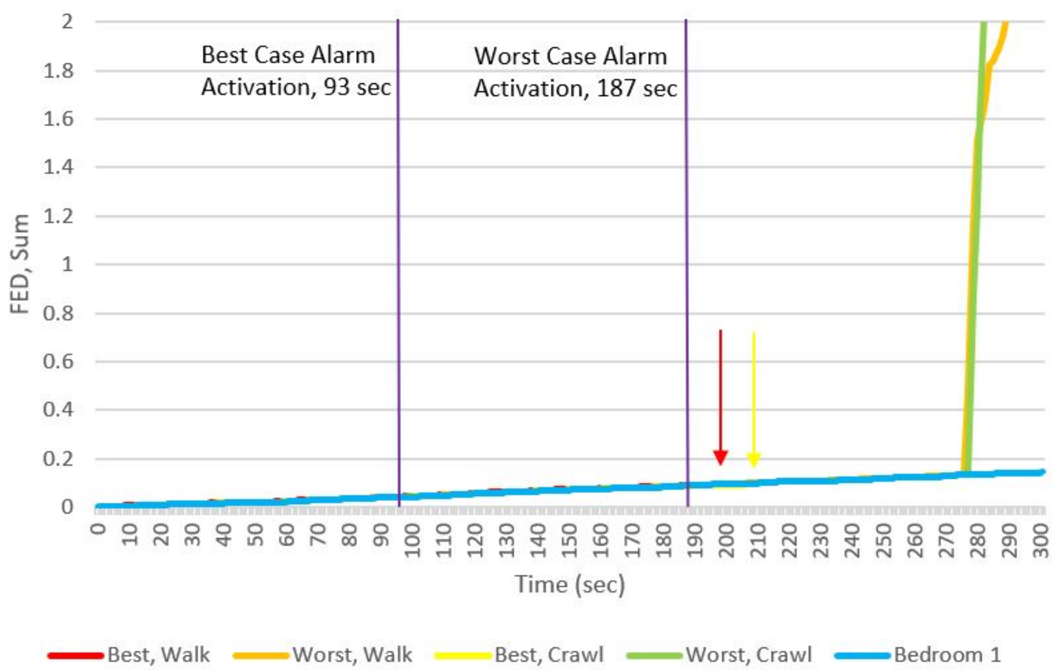

Figure A.1: FED v. Egress Time: Experiment B1

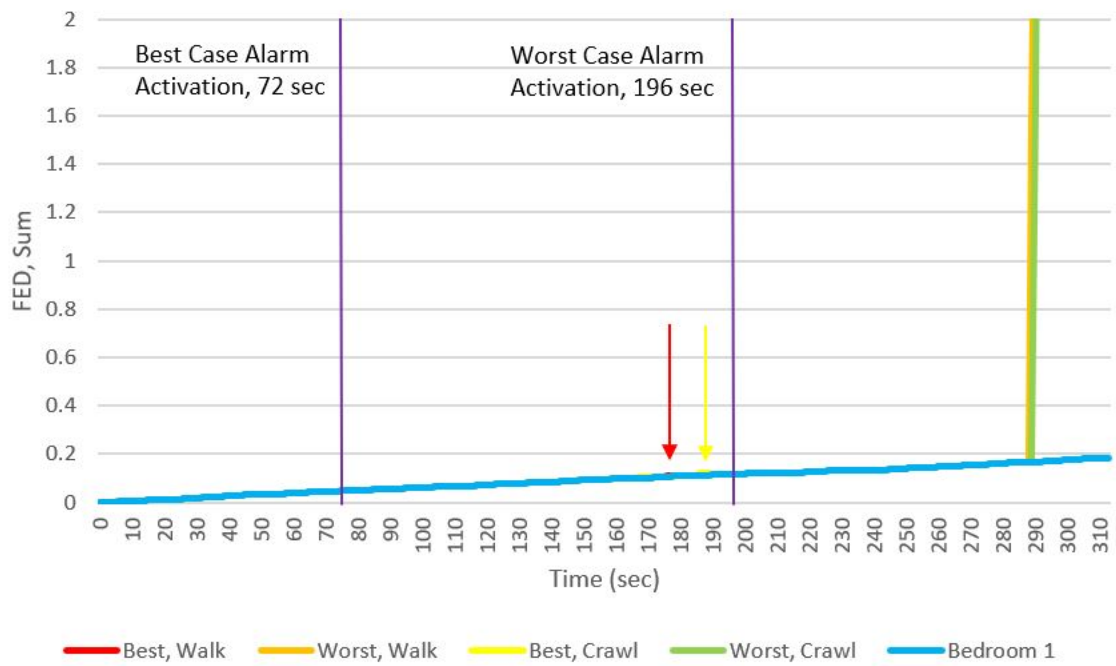

Figure A.2: FED v. Egress Time: Experiment B2

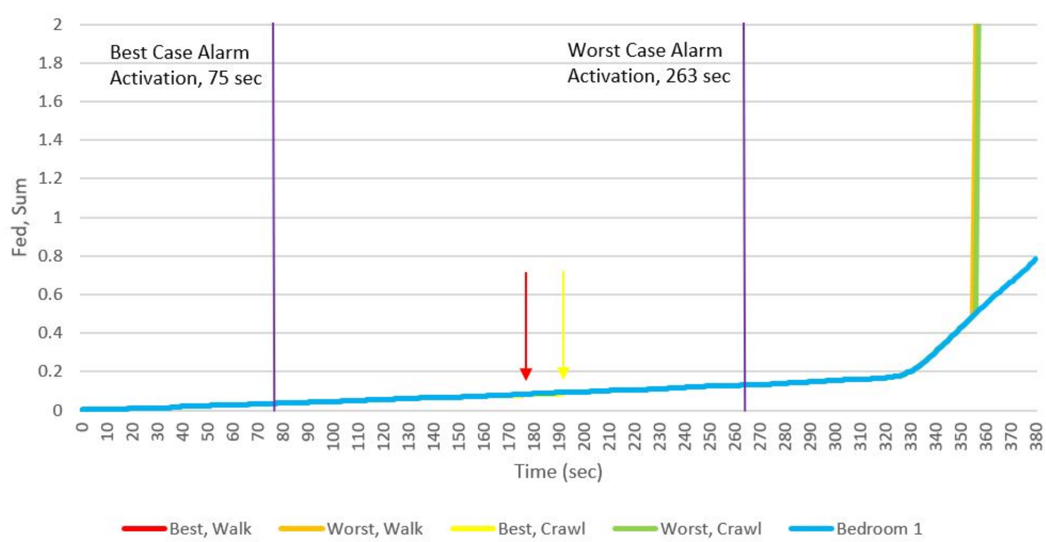

Figure A.3: FED v. Egress Time: Experiment B3

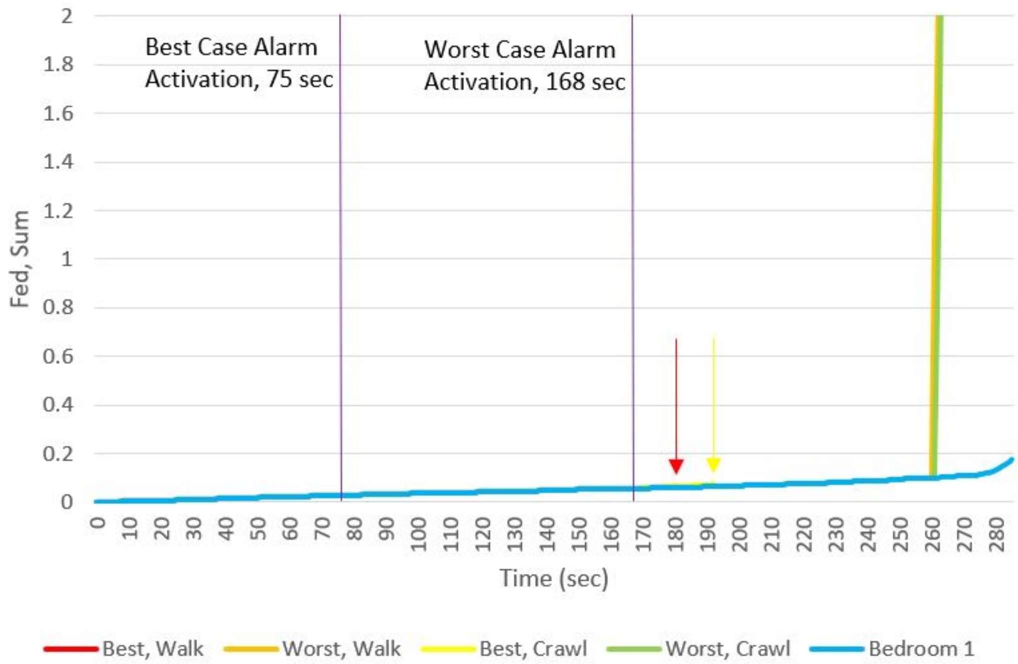

Figure A.4: FED v. Egress Time: Experiment B4

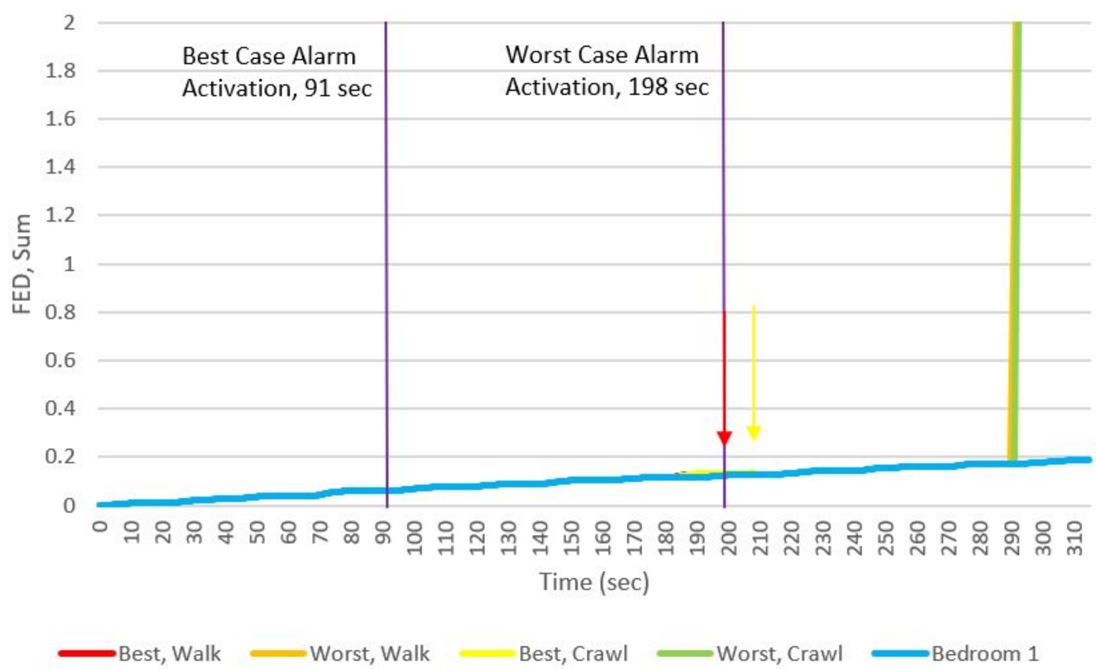

Figure A.5: FED v. Egress Time: Experiment B5

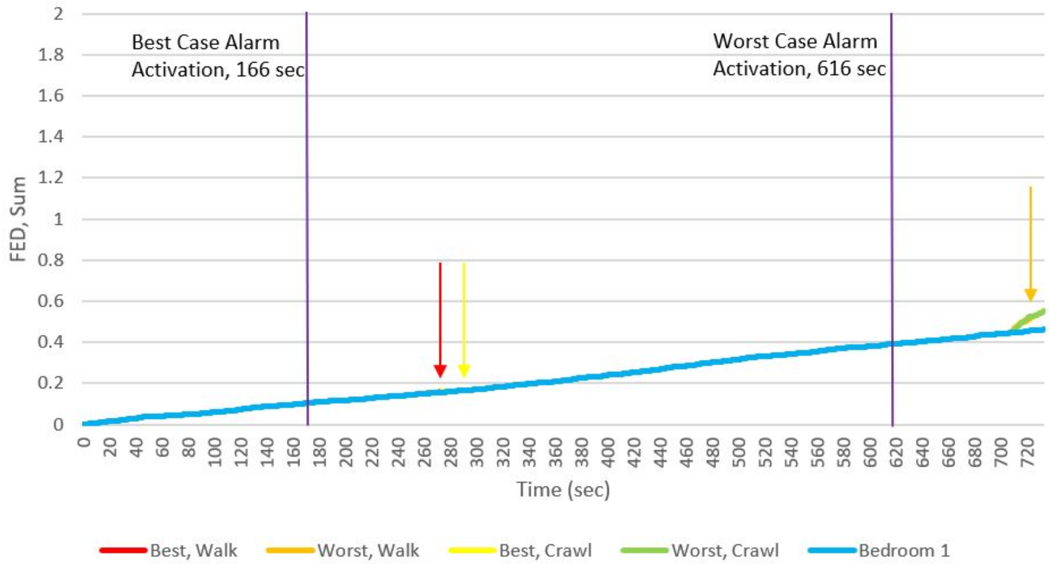

Figure A.6: FED v. Egress Time: Experiment K1

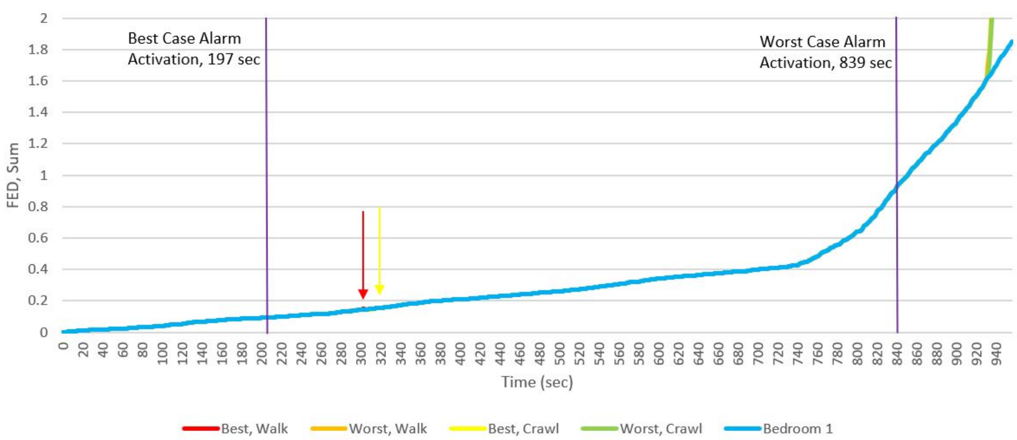

Figure A.7: FED v. Egress Time: Experiment K2

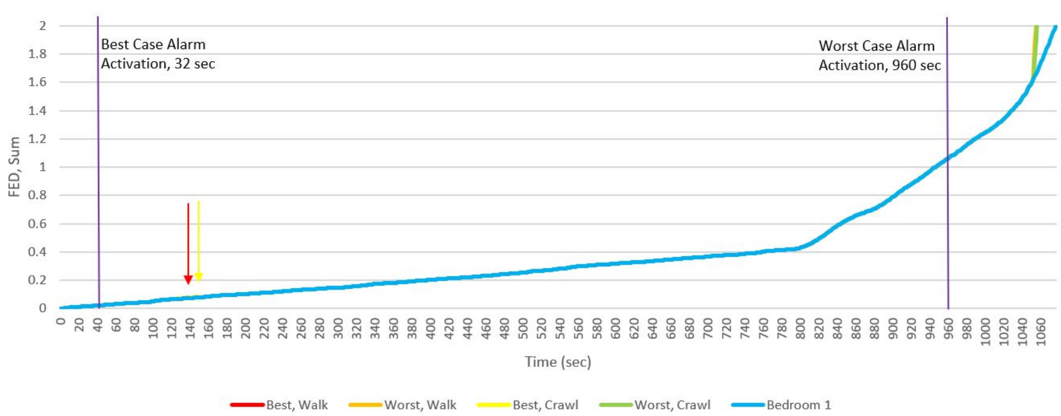

Figure A.8: FED v. Egress Time: Experiment K3

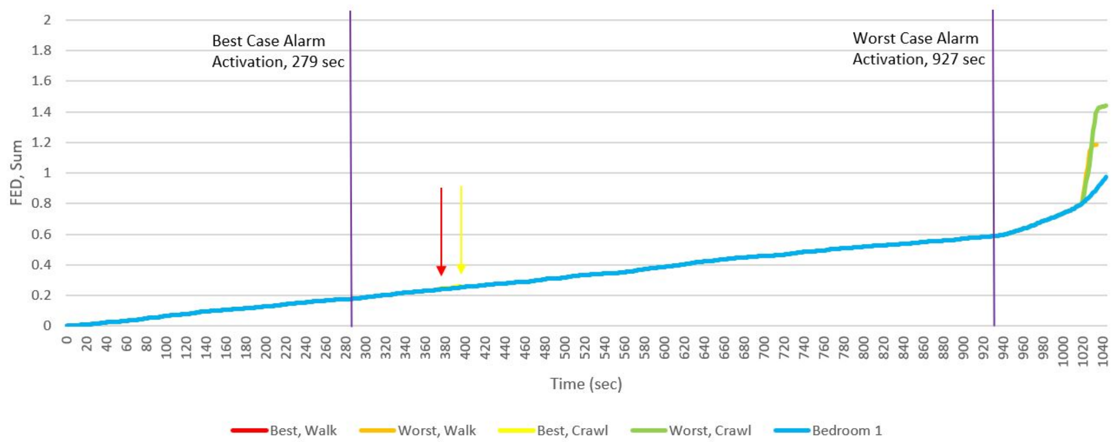

Figure A.9: FED v. Egress Time: Experiment K4

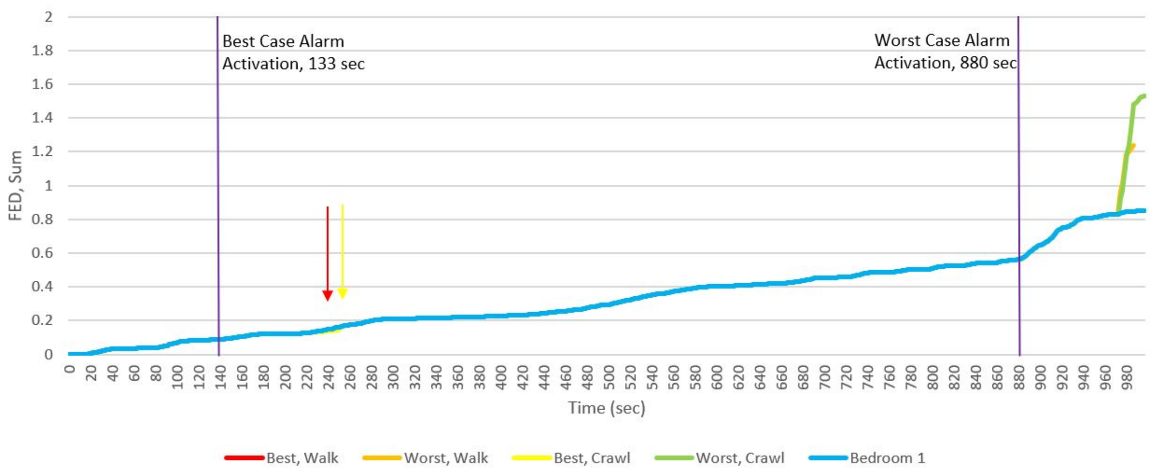

Figure A.10: FED v. Egress Time: Experiment K5

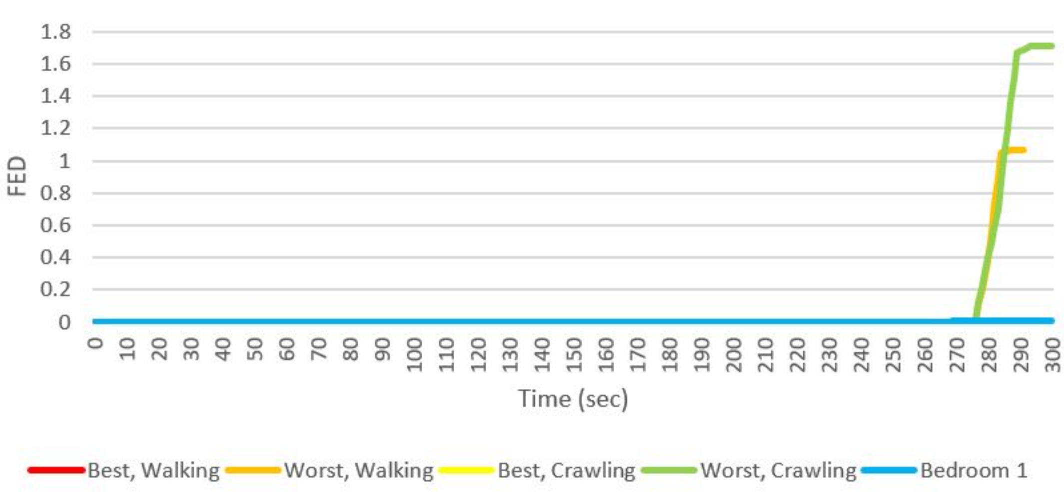

Figure A.11: Thermal FED v. Time: Experiment B1

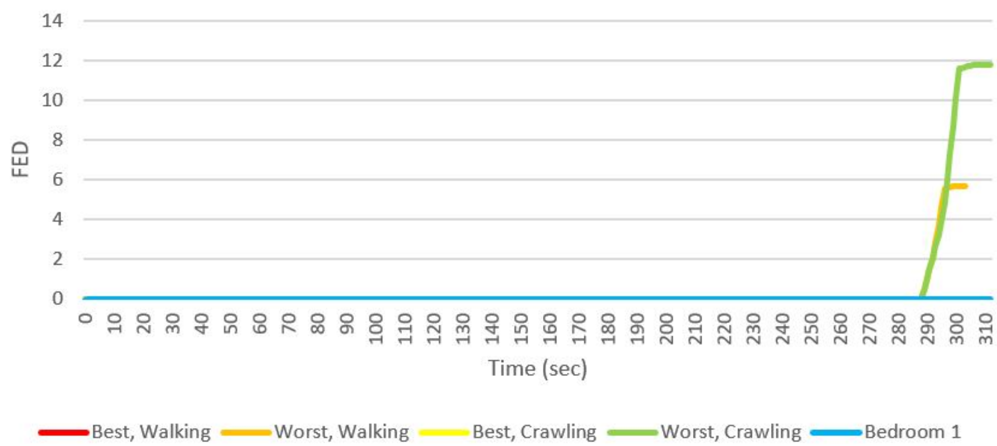

Figure A.12: Thermal FED v. Time: Experiment B2

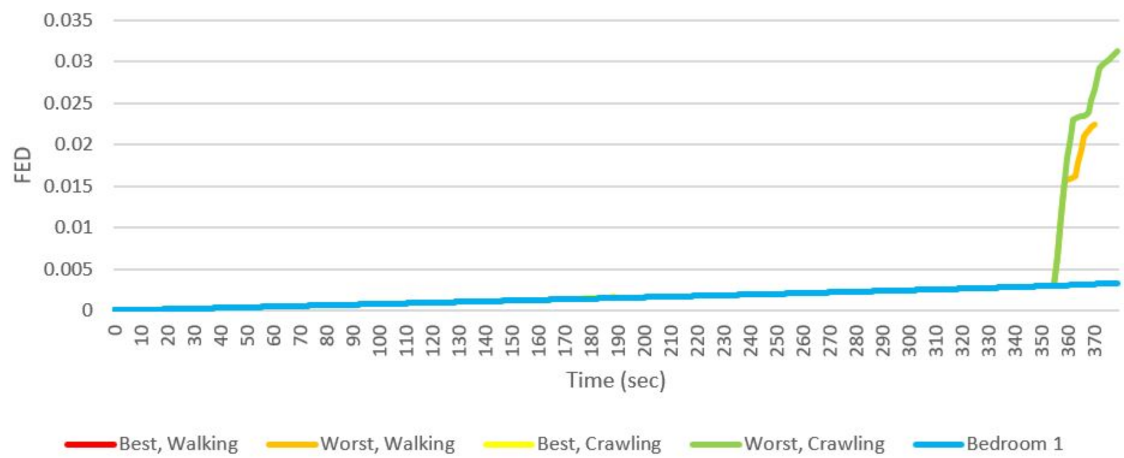

Figure A.13: Thermal FED v. Time: Experiment B3

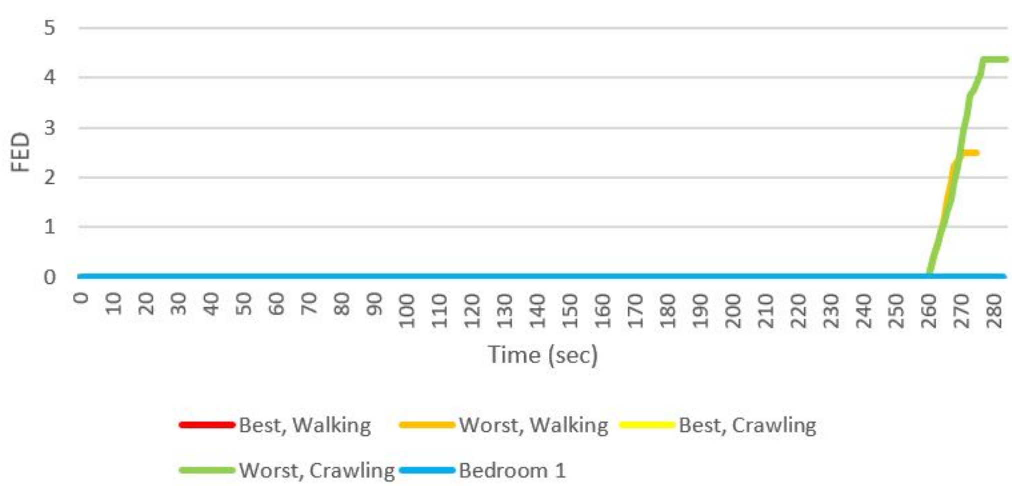

Figure A.14: Thermal FED v. Time: Experiment B4

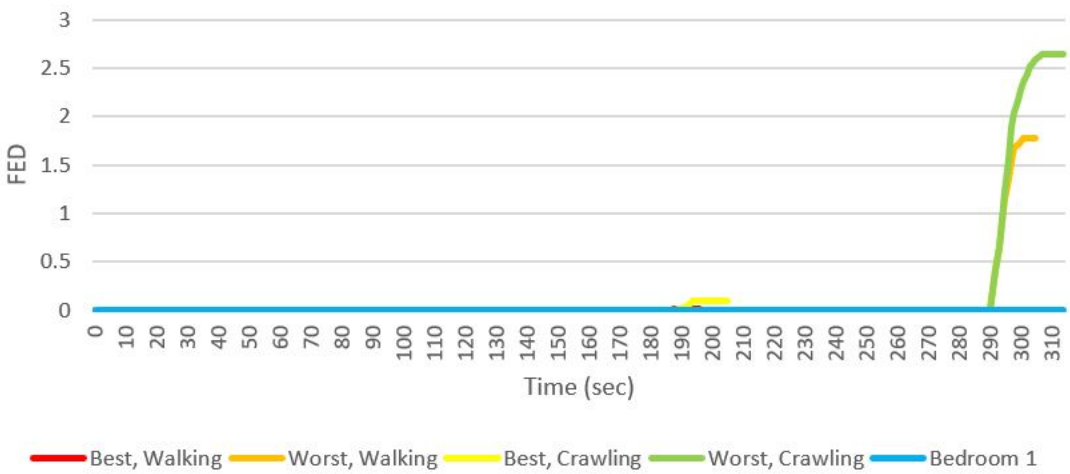

Figure A.15: Thermal FED v. Time: Experiment B5

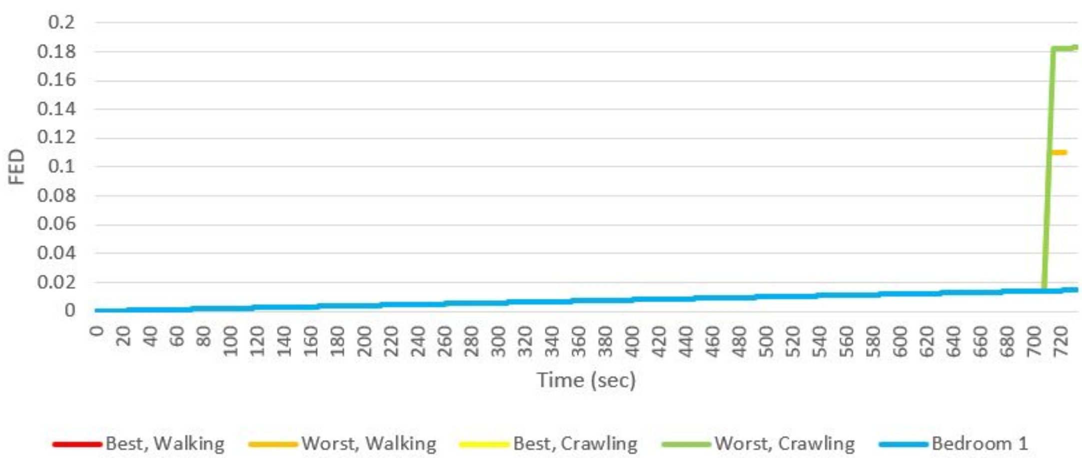

Figure A.16: Thermal FED v. Time: Experiment K1

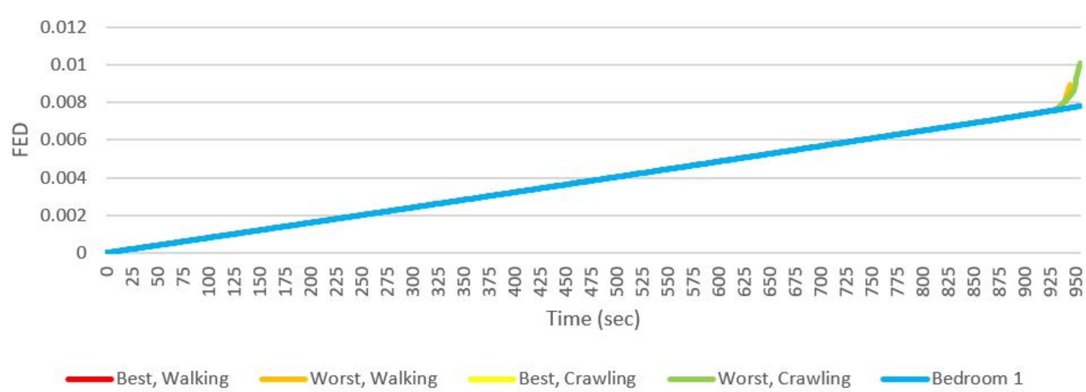

Figure A.17: Thermal FED v. Time: Experiment K2

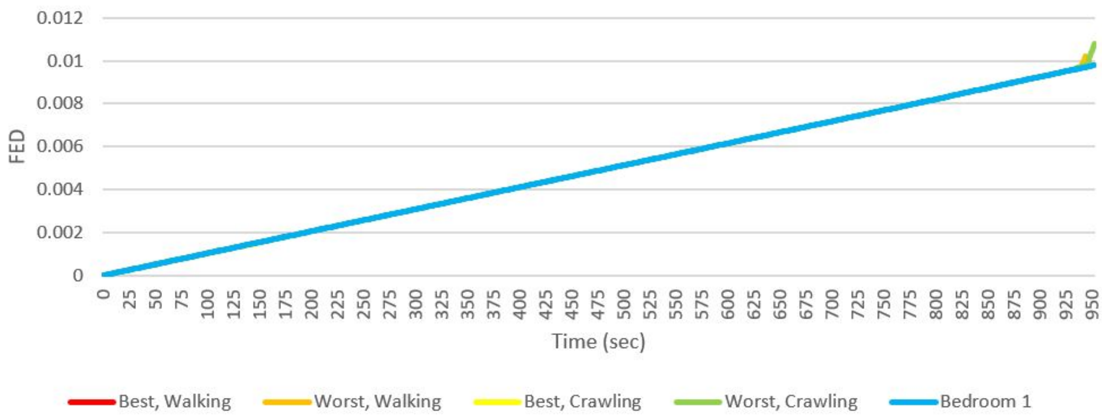

Figure A.18: Thermal FED v. Time: Experiment K3

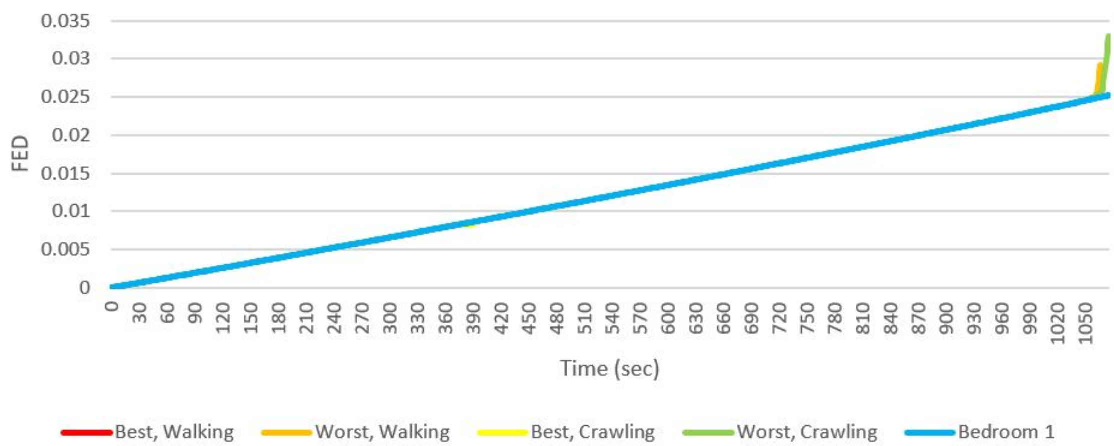

Figure A.19: Thermal FED v. Time: Experiment K4

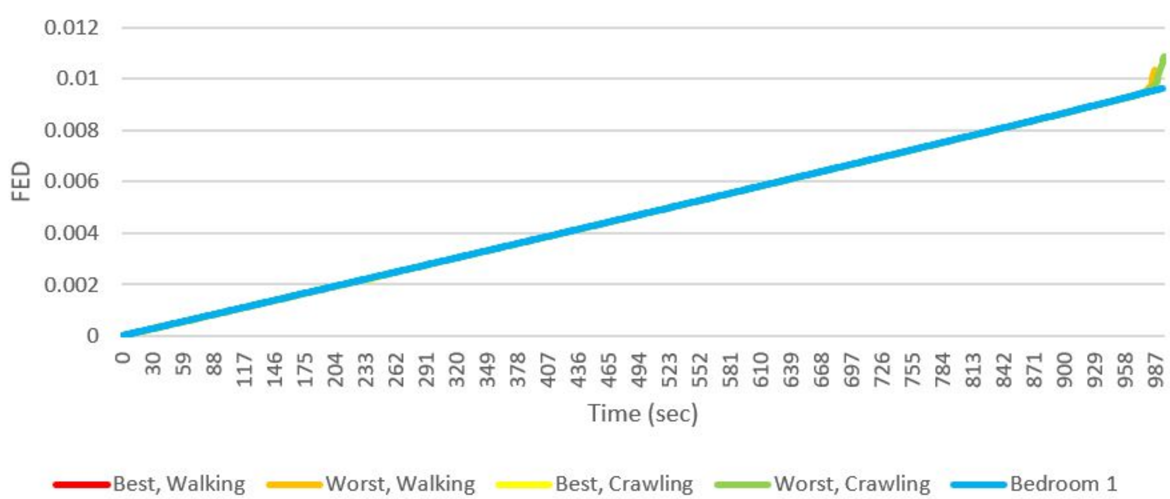

Figure A.20: Thermal FED v. Time: Experiment K5

Chapter B: Appendix B - Gas Concentration Data

Due to the large volume of data used in this experiment a Google Drive has been created to house the necessary spreadsheets. The drive can be accessed via the following link:

https://drive.google.com/drive/folders/1oGu5uLtcKJtvvEIqAIUxRnZbykiav58n?usp=sharing

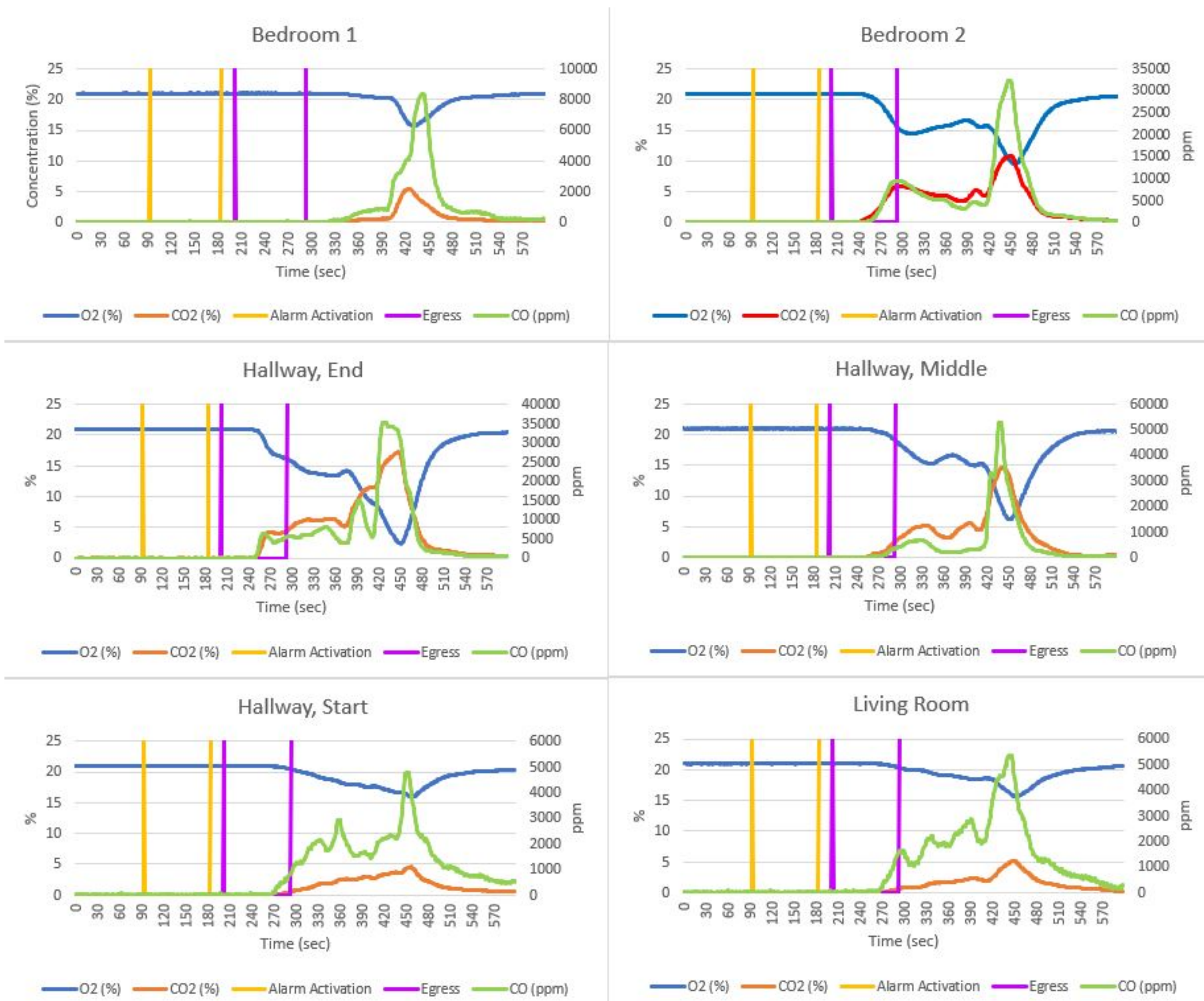

Figure B.1: Gas Concentrations v. Time for Experiment B1 in Sample Locations

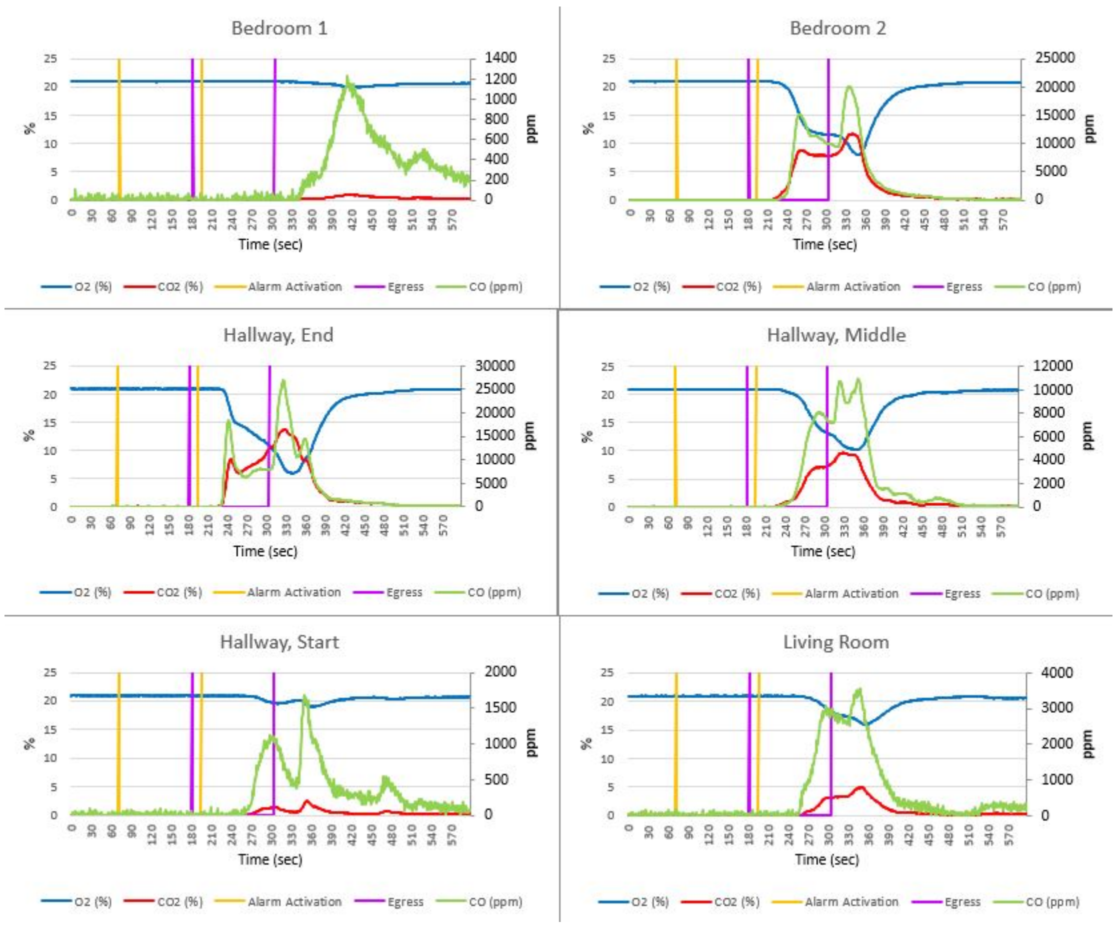

Figure B.2: Gas Concentrations v. Time for Experiment B2 in Sample Locations

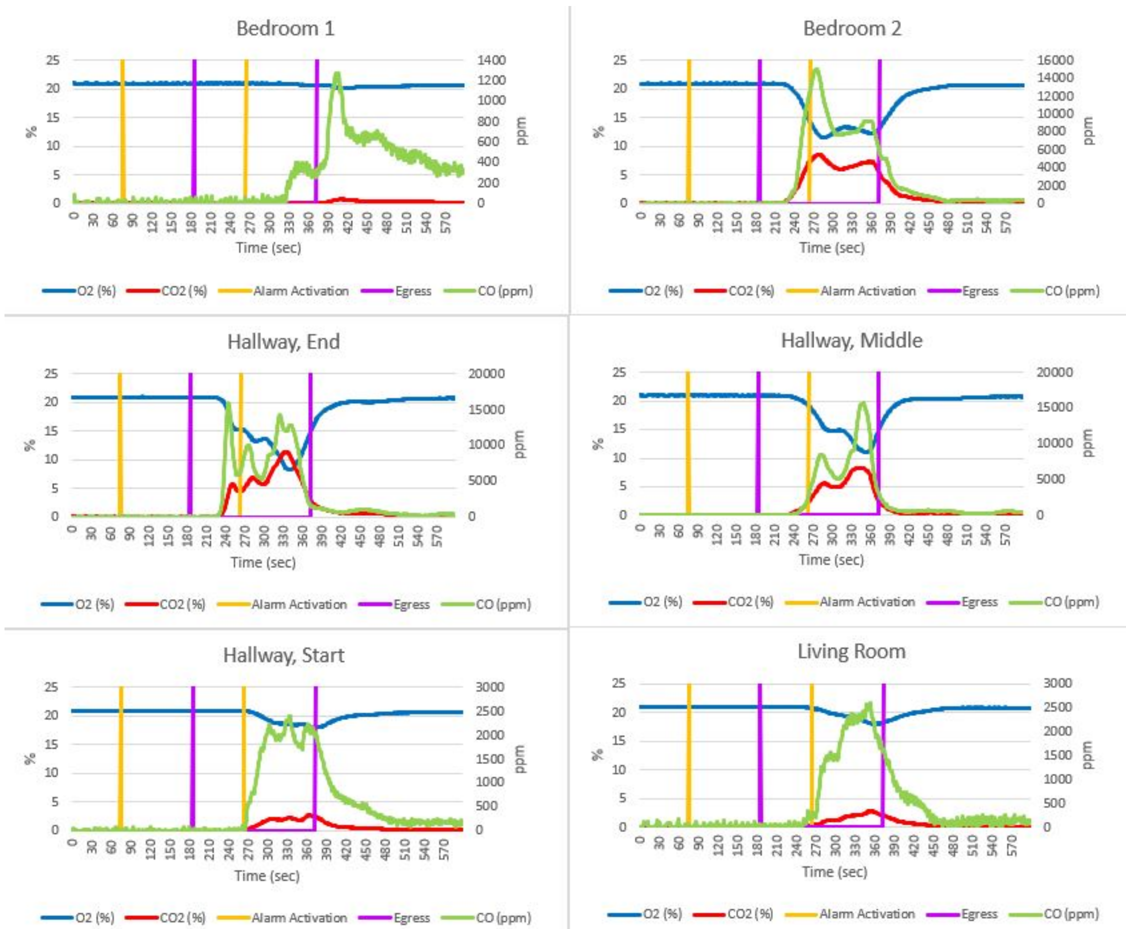

Figure B.3: Gas Concentrations v. Time for Experiment B3 in Sample Locations

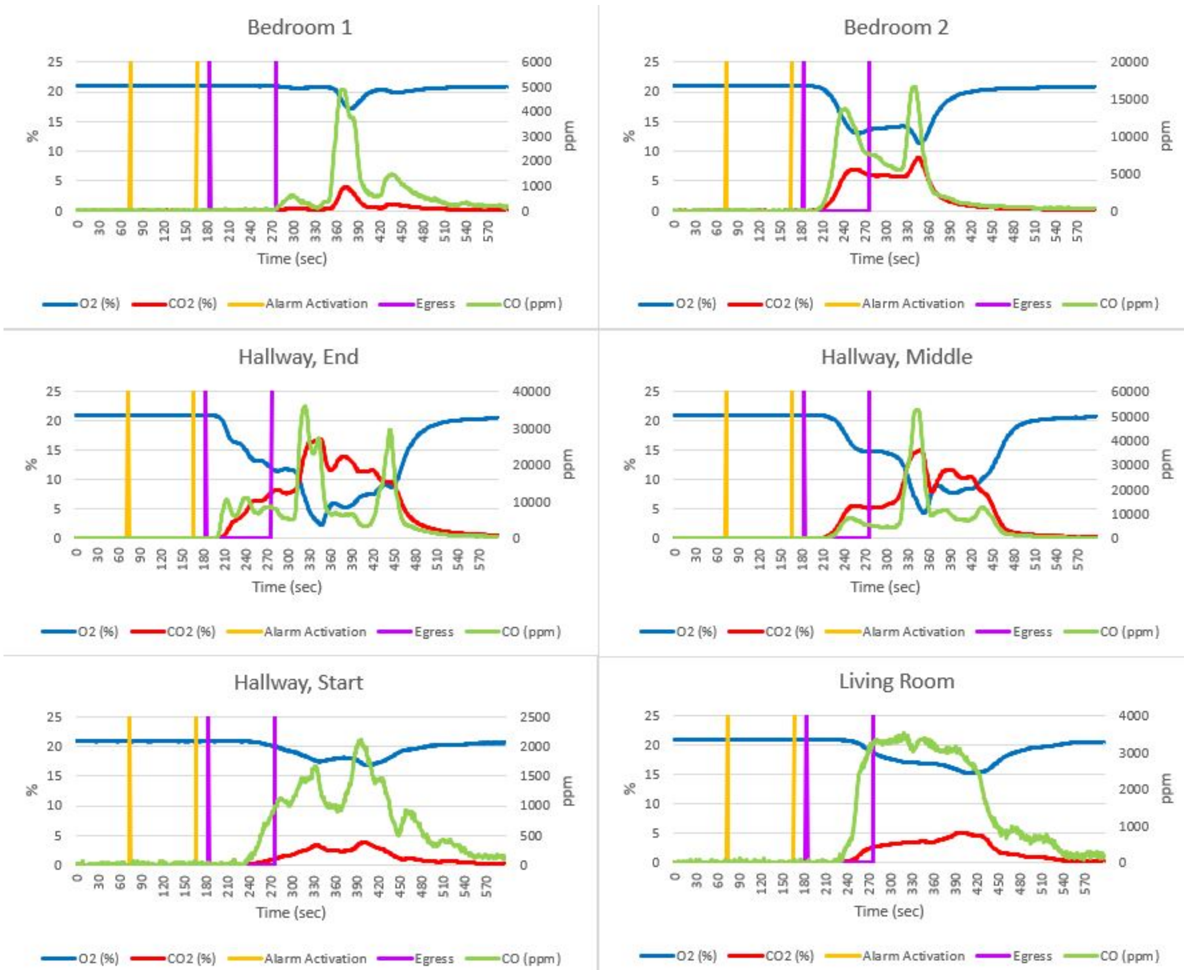

Figure B.4: Gas Concentrations v. Time for Experiment B4 in Sample Locations

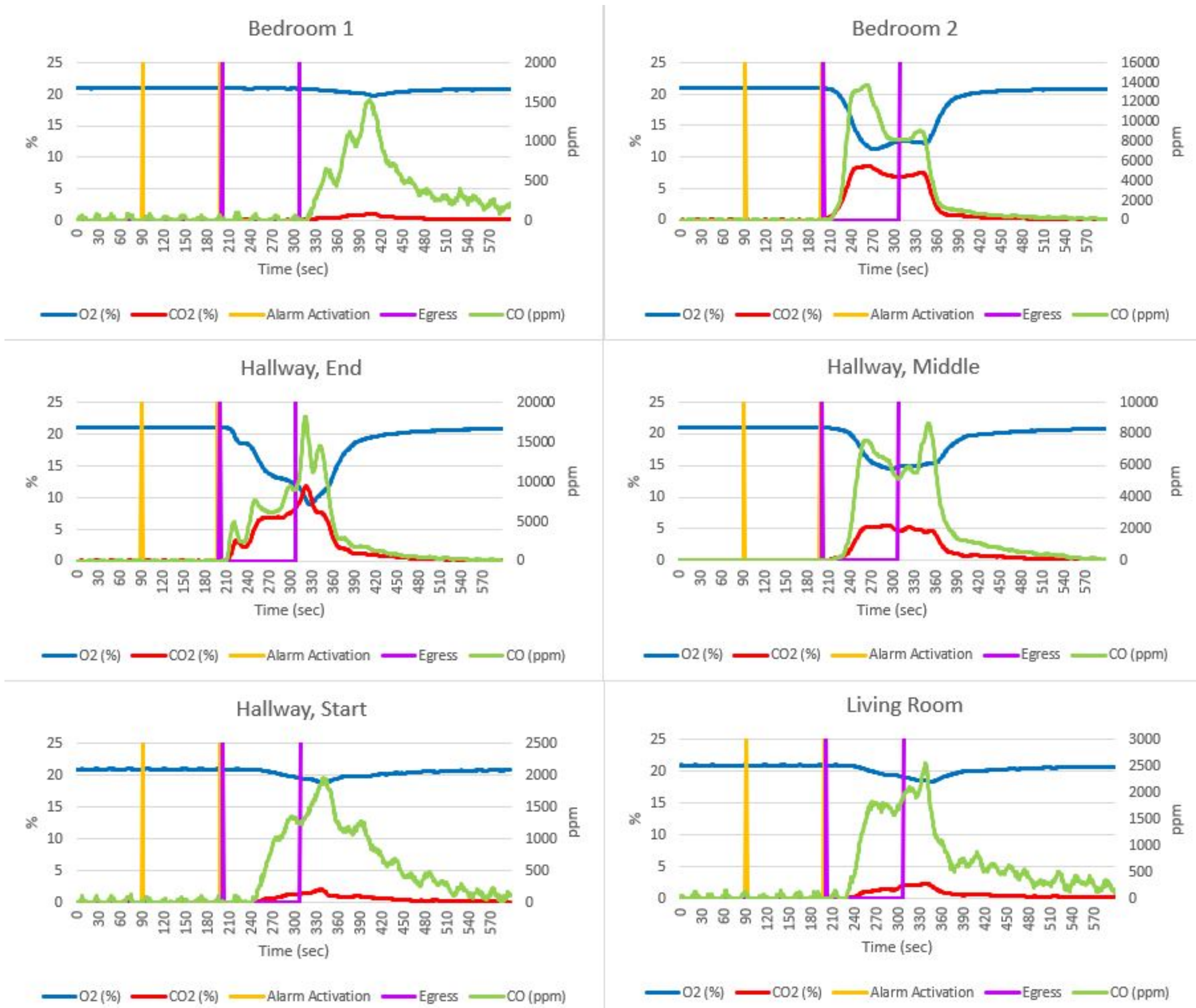

Figure B.5: Gas Concentrations v. Time for Experiment B5 in Sample Locations

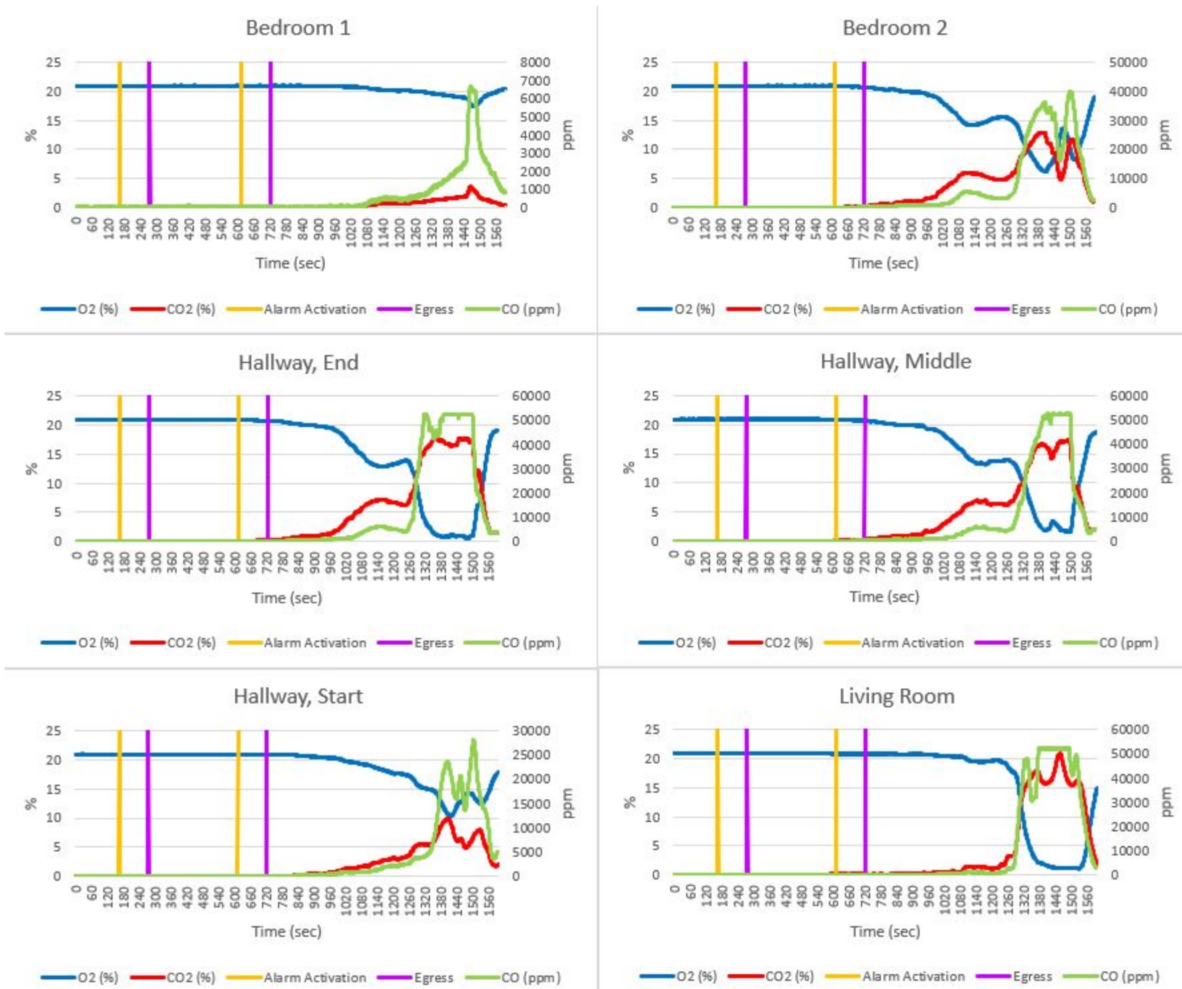

Figure B.6: Gas Concentrations v. Time for Experiment K1 in Sample Locations

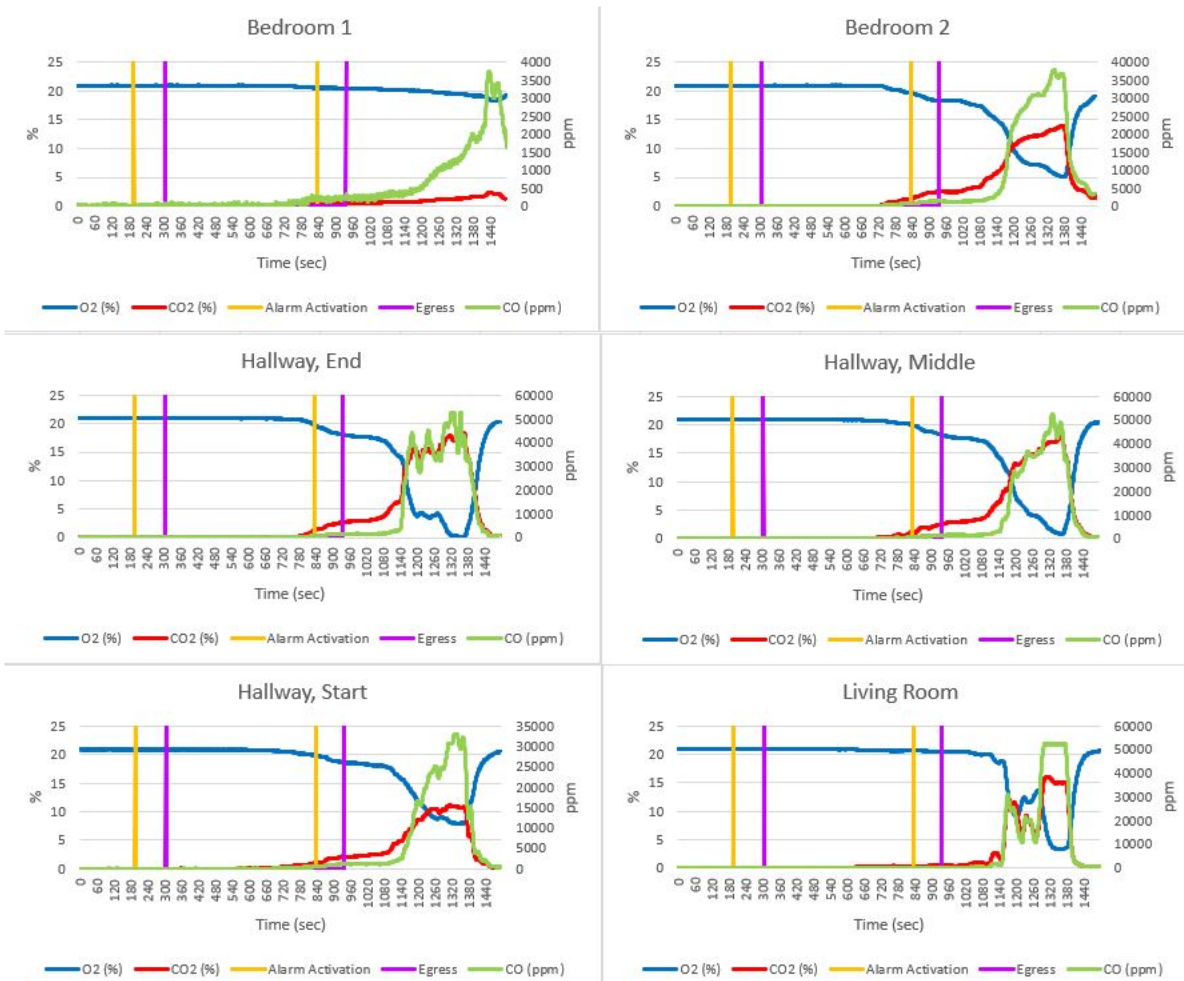

Figure B.7: Gas Concentrations v. Time for Experiment K2 in Sample Locations

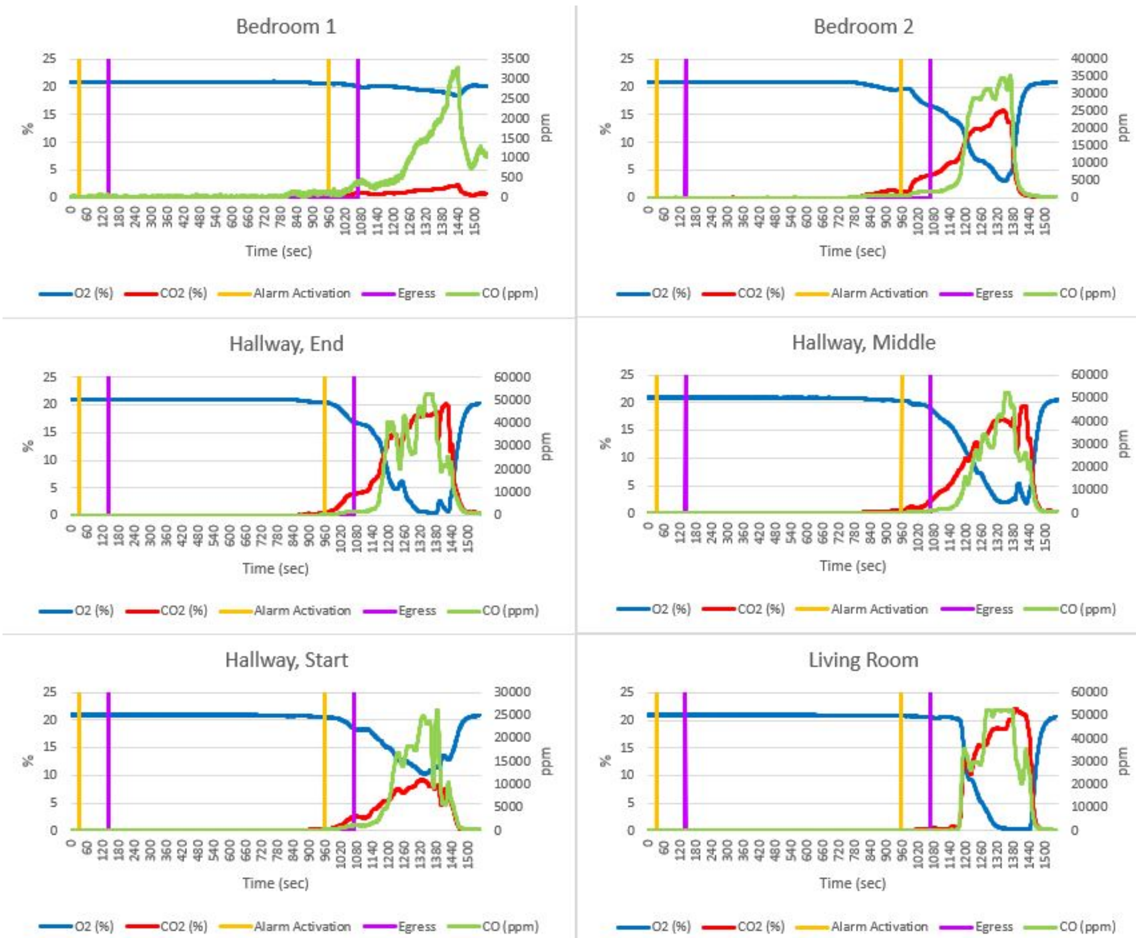

Figure B.8: Gas Concentrations v. Time for Experiment K3 in Sample Locations

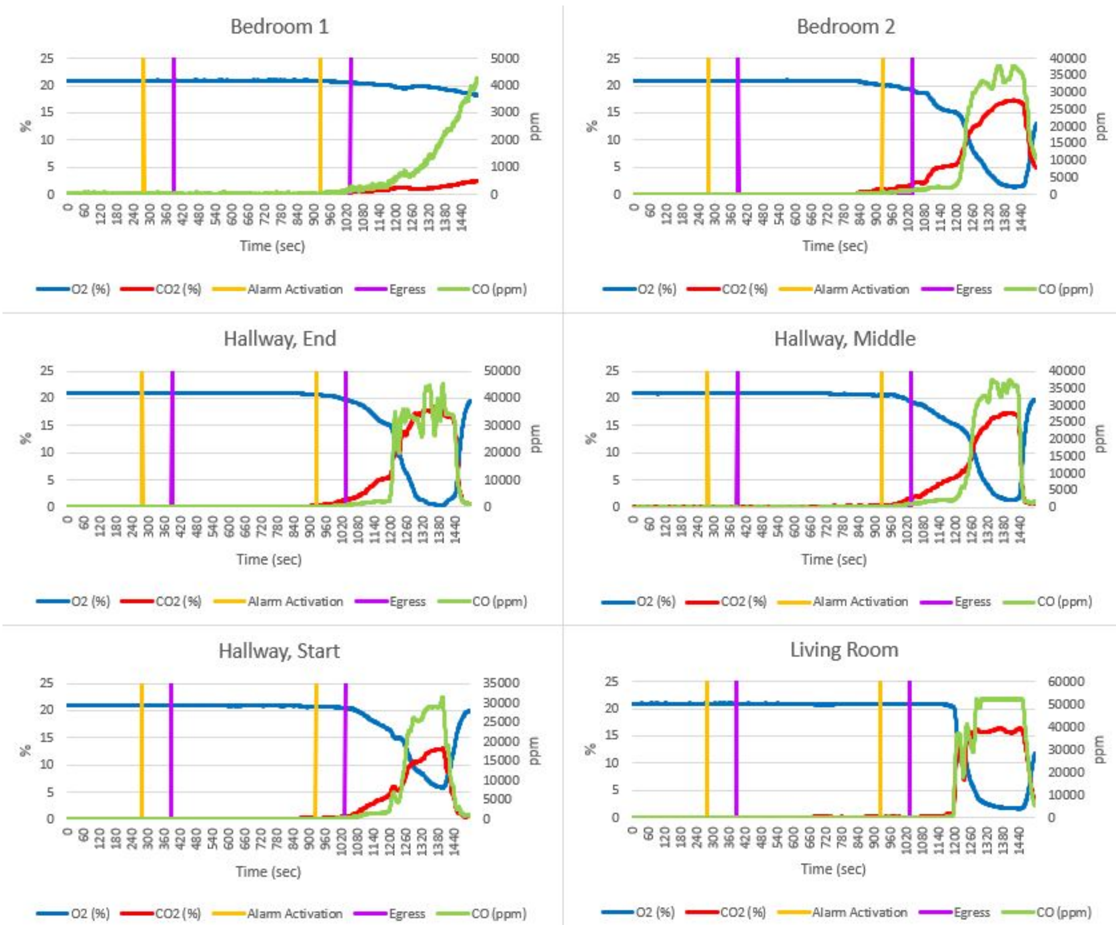

Figure B.9: Gas Concentrations v. Time for Experiment K4 in Sample Locations

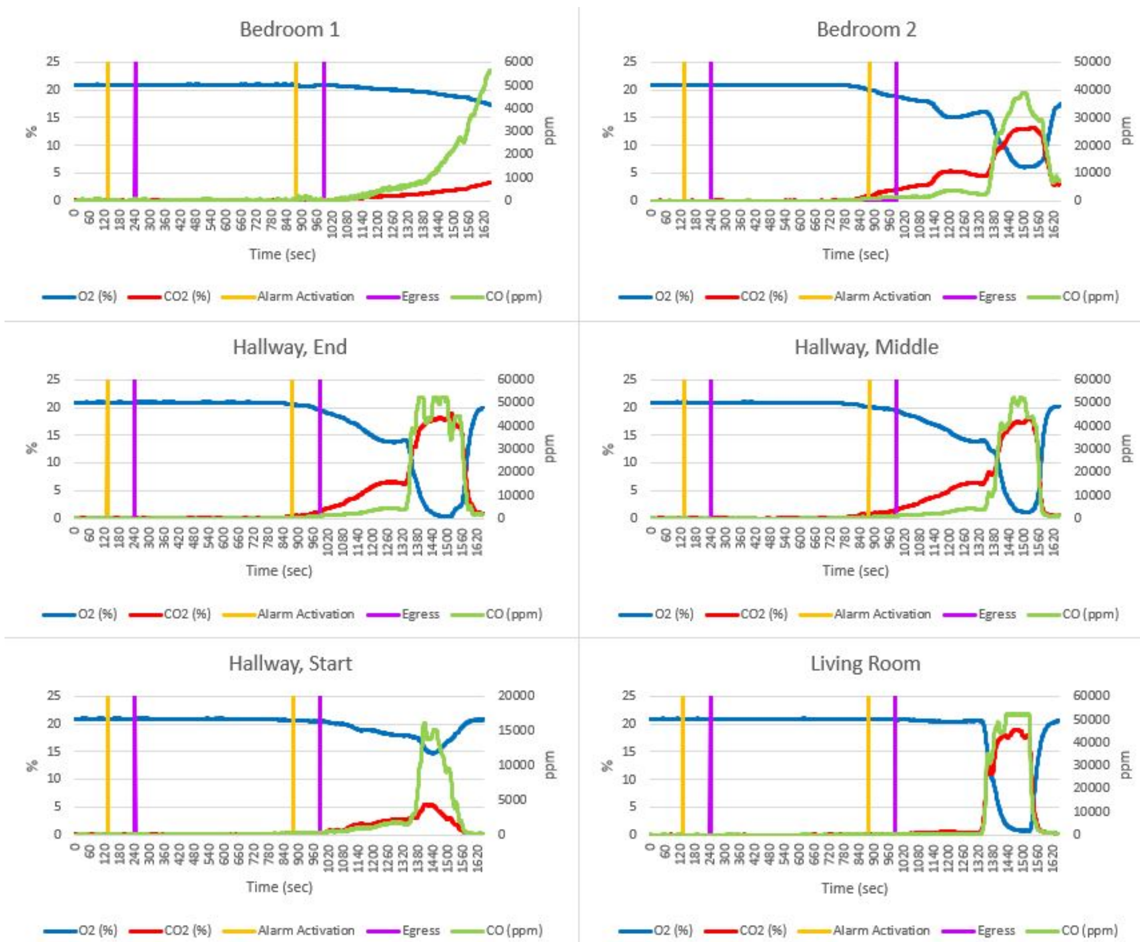

Figure B.10: Gas Concentrations v. Time for Experiment K5 in Sample Locations

Chapter C: Appendix C - Heat Flux and Temperature Data

Due to the large volume of data used in this experiment a Google Drive has been created to house the necessary spreadsheets. The drive can be accessed via the following link:

https://drive.google.com/drive/folders/1oGu5uLtcKJtvvEIqAIUxRnZbykiav58n?usp=sharing

Heat flux data for Experiment K1 is not available.

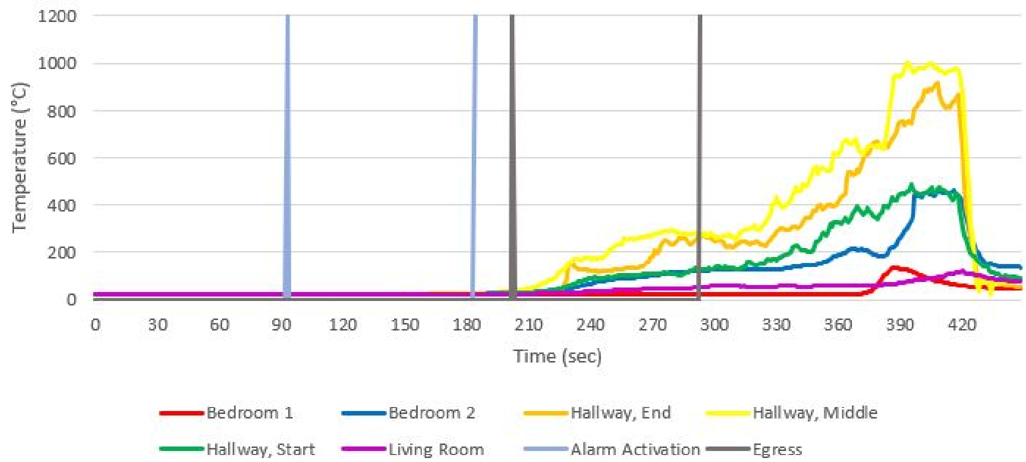

Figure C.1: Temperature at 0.9 m v. Time: Experiment B1

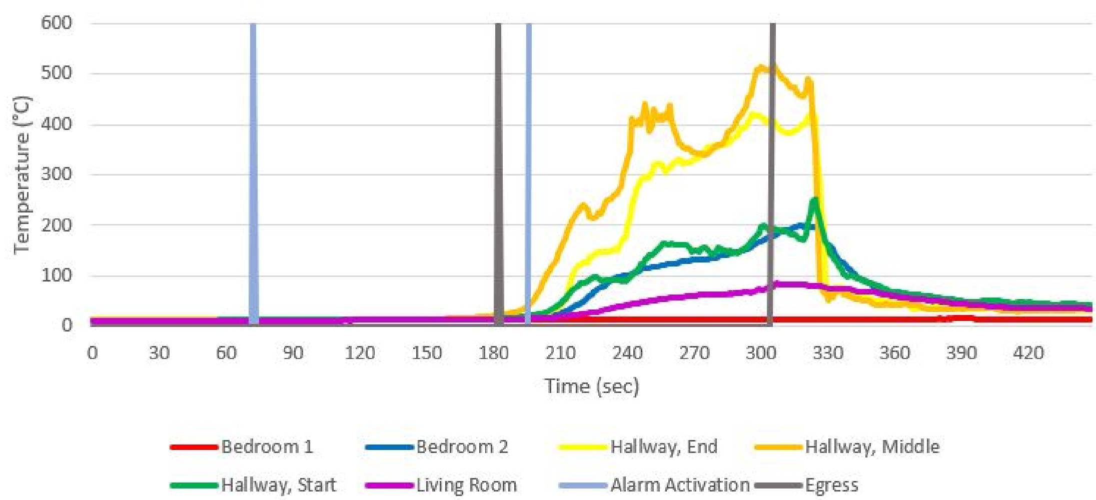

Figure C.2: Temperature at 0.9 m v. Time: Experiment B2

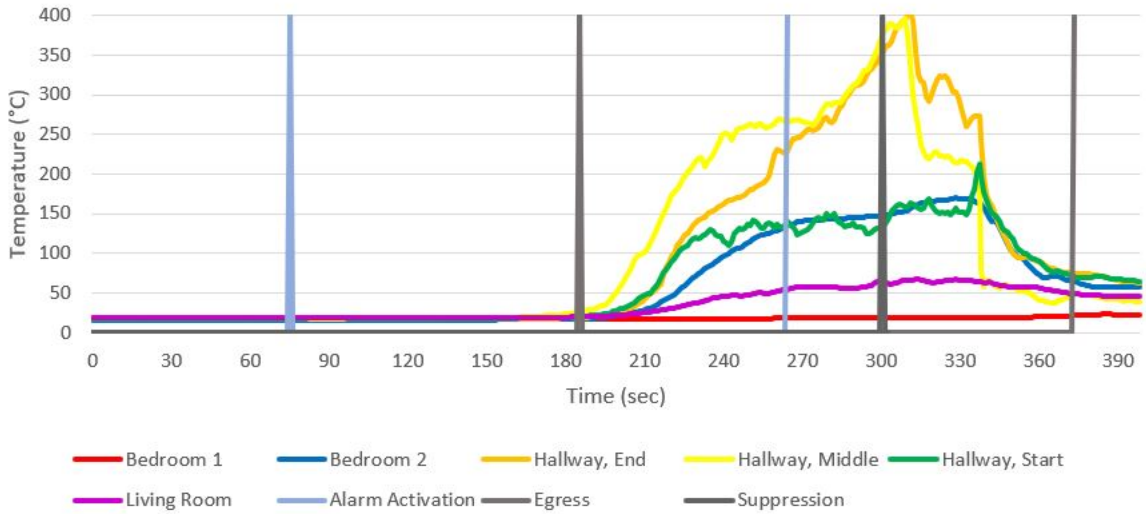

Figure C.3: Temperature at 0.9 m v. Time: Experiment B3

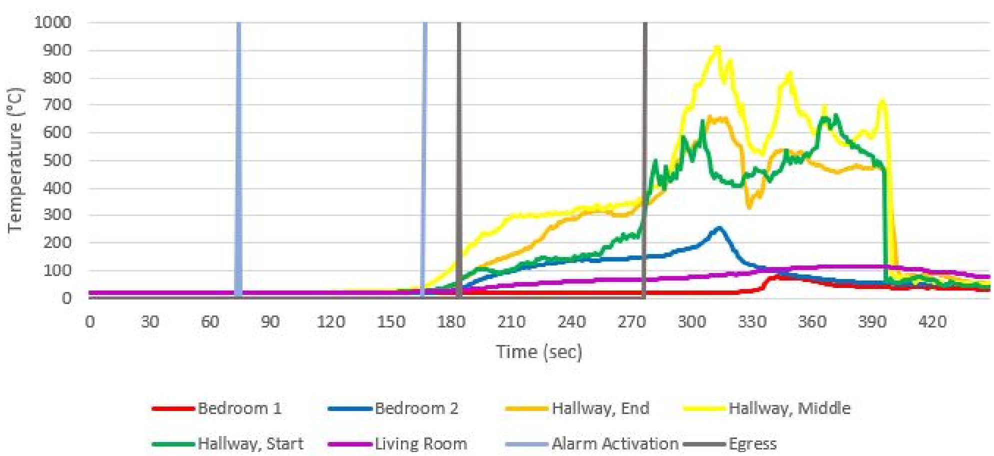

Figure C.4: Temperature at 0.9 m v. Time: Experiment B4

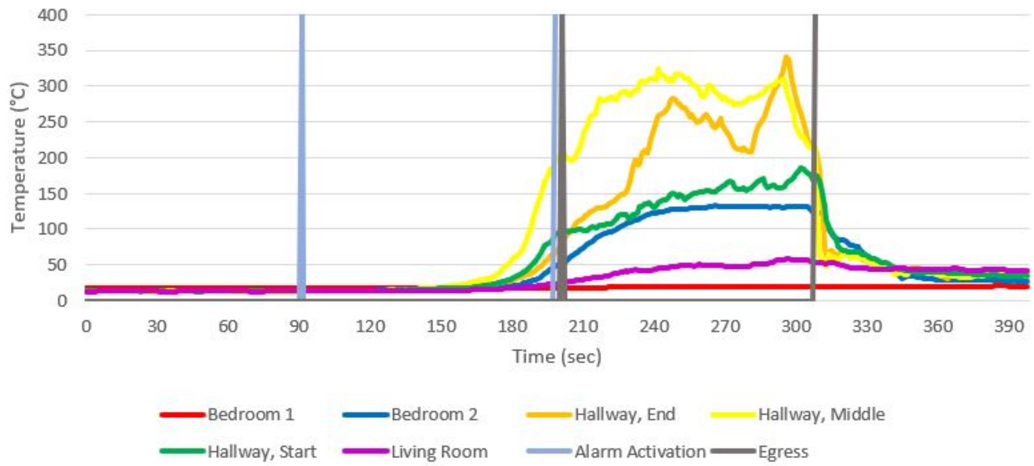

Figure C.5: Temperature at 0.9 m v. Time: Experiment B5

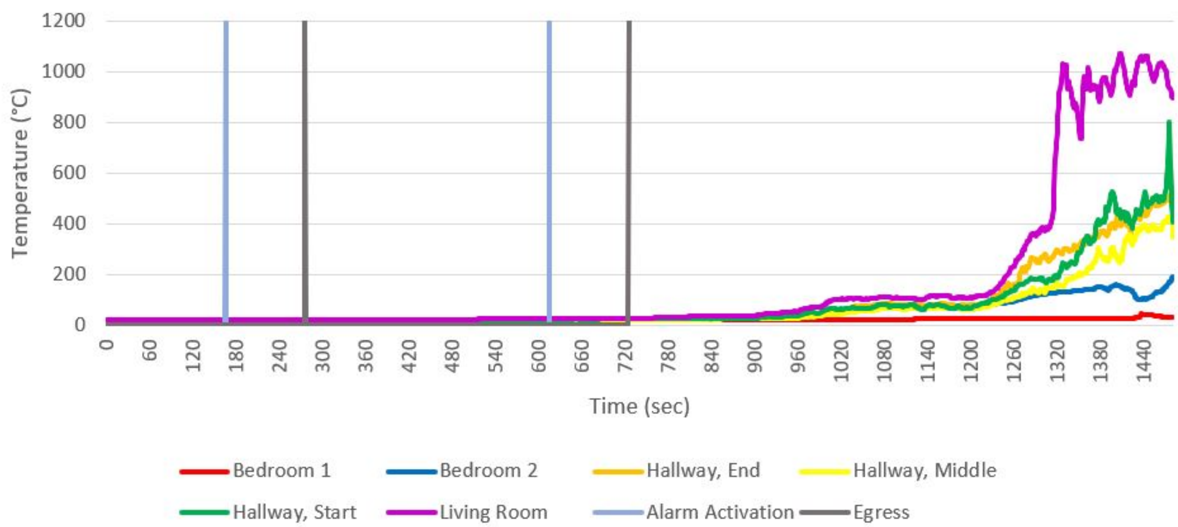

Figure C.6: Temperature at 0.9 m v. Time: Experiment K1

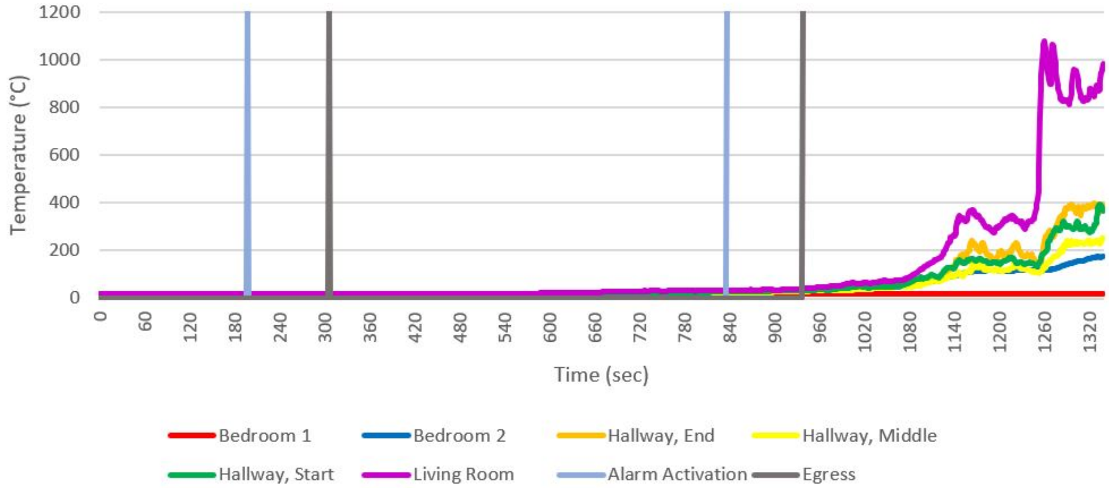

Figure C.7: Temperature at 0.9 m v. Time: Experiment K2

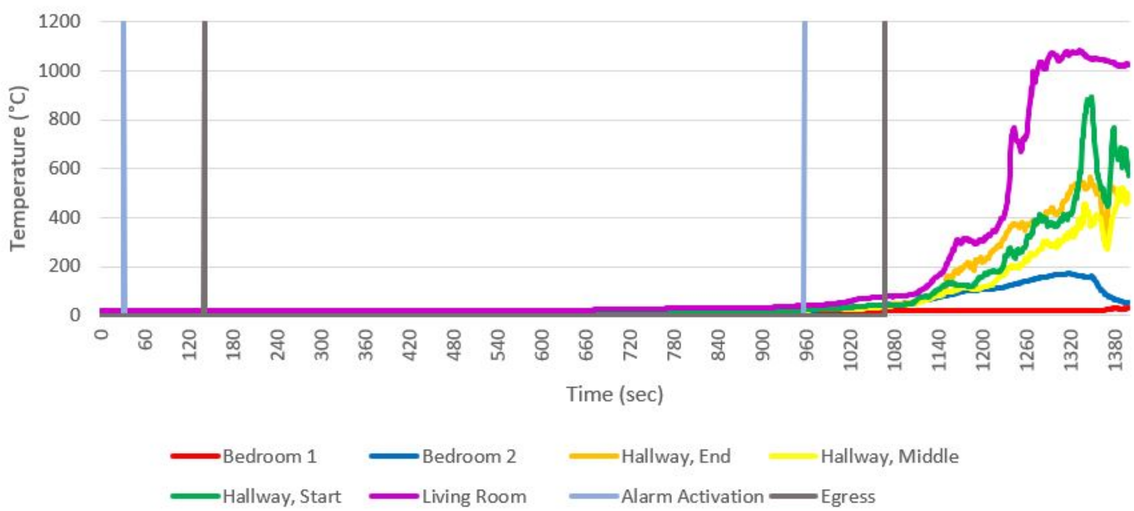

Figure C.8: Temperature at 0.9 m v. Time: Experiment K3

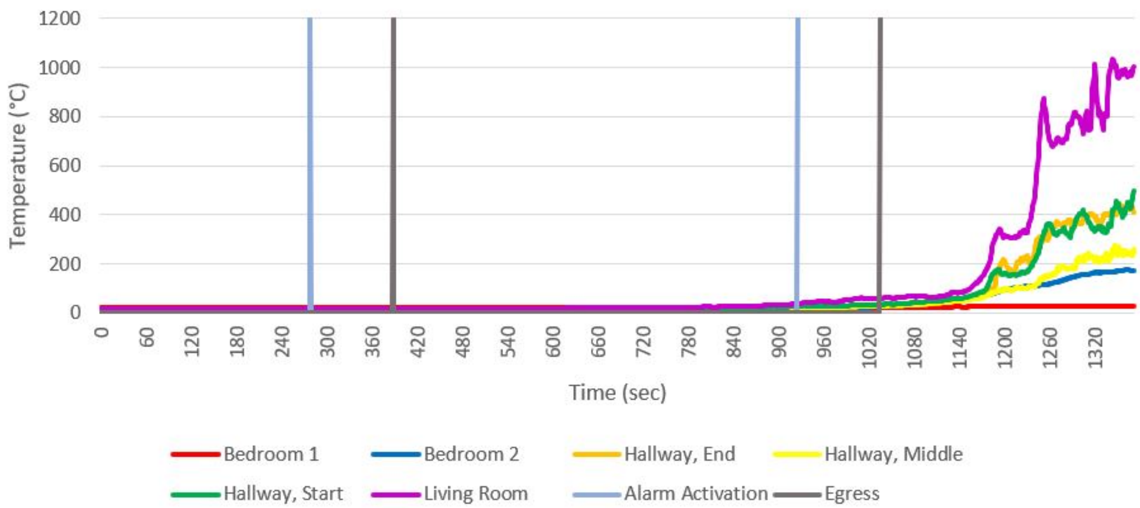

Figure C.9: Temperature at 0.9 m v. Time: Experiment K4

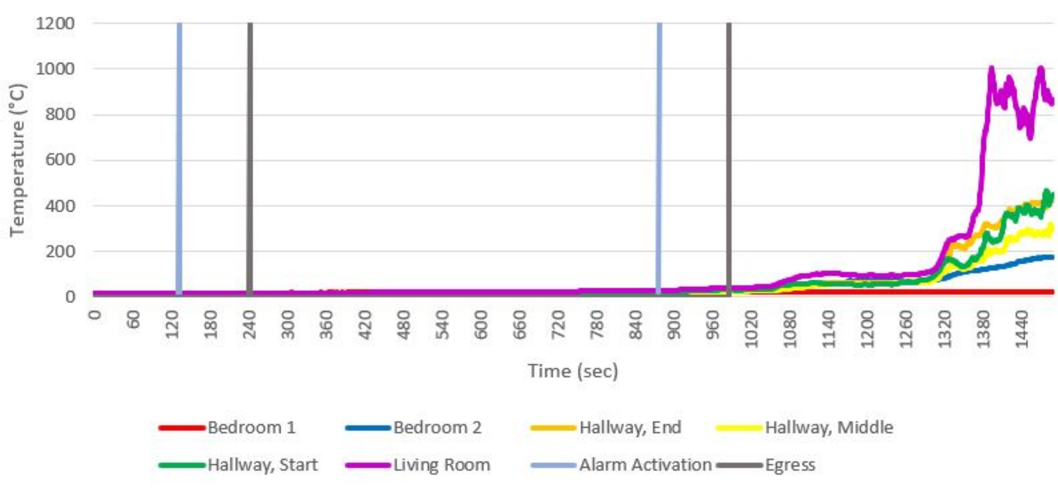

Figure C.10: Temperature at 0.9 m v. Time: Experiment K5

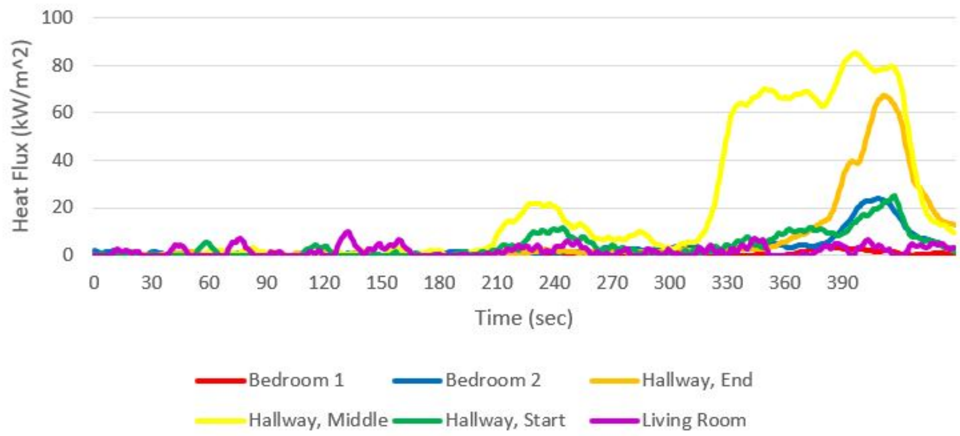

Figure C.11: Heat Flux v. Time: Experiment B1

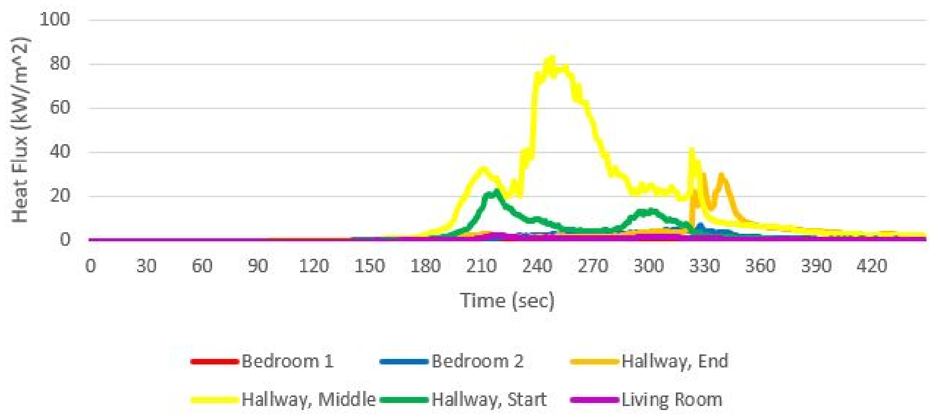

Figure C.12: Heat Flux v. Time: Experiment B2

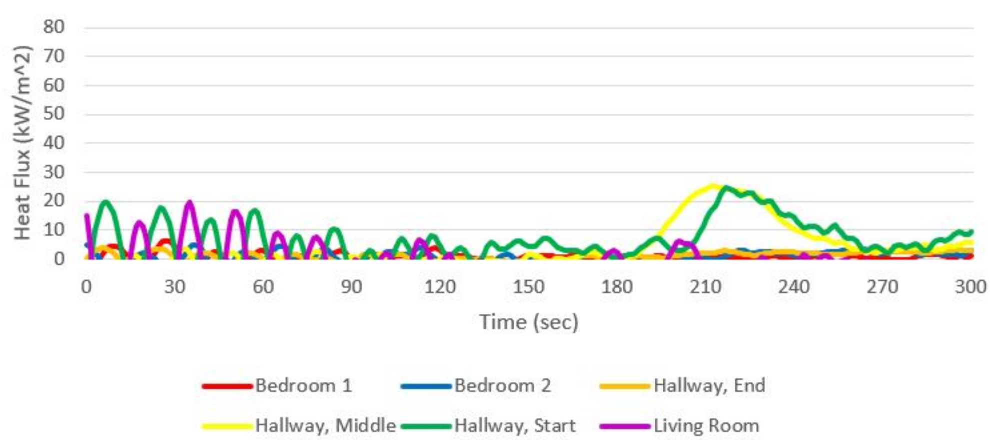

Figure C.13: Heat Flux v. Time: Experiment B3

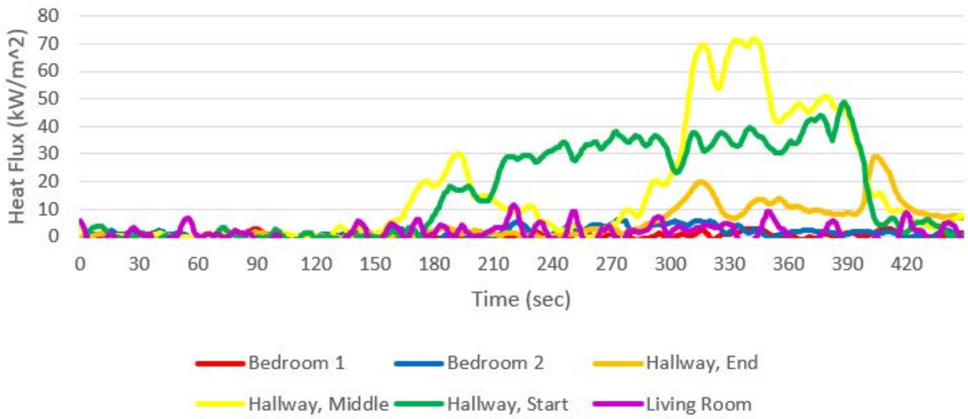

Figure C.14: Heat Flux v. Time: Experiment B4

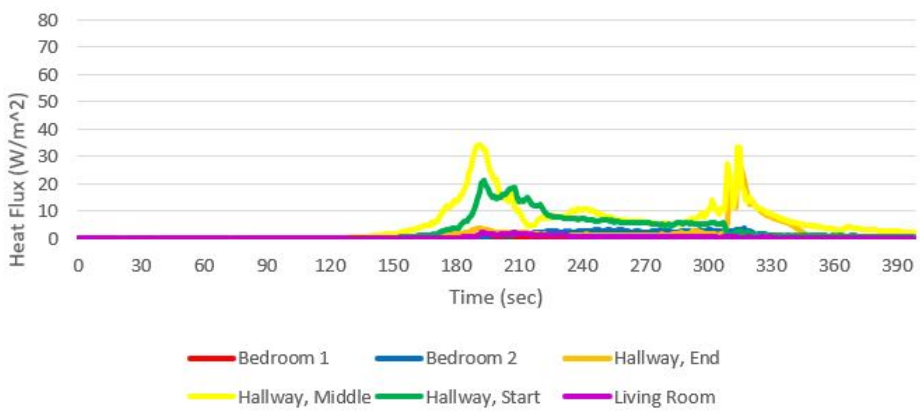

Figure C.15: Heat Flux v. Time: Experiment B5

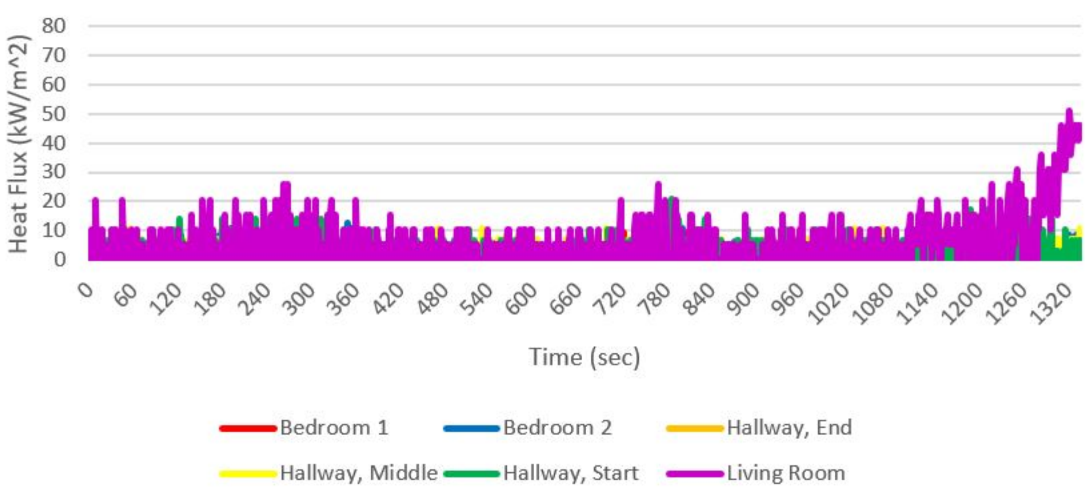

Figure C.16: Heat Flux v. Time: Experiment K2

Figure C.17: Heat Flux v. Time: Experiment K3

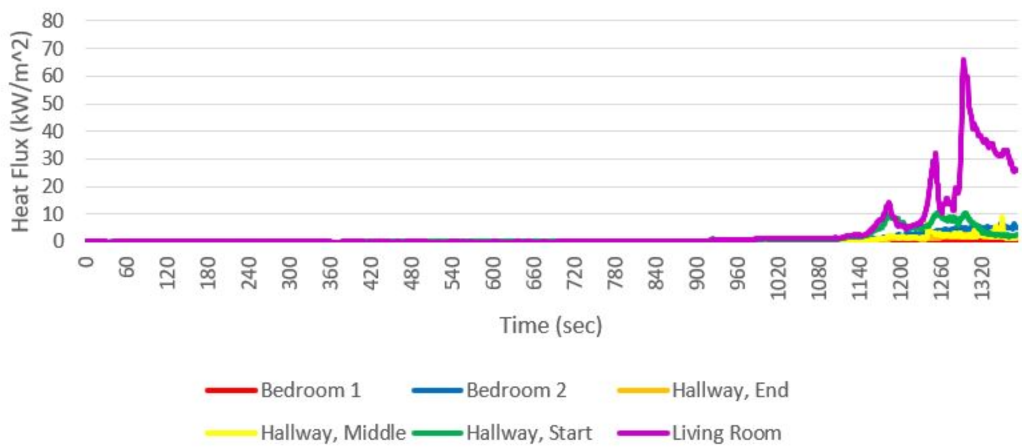

Figure C.18: Heat Flux v. Time: Experiment K4

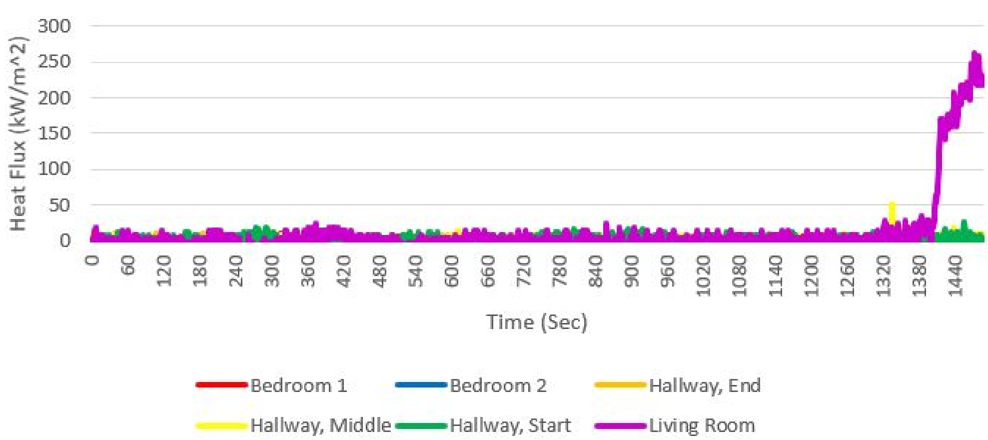

Figure C.19: Heat Flux v. Time: Experiment K5

Chapter D: Appendix D - FED Analysis Data

Due to the large volume of data used in this experiment a Google Drive has been created to house the necessary spreadsheets. The drive can be accessed via the following link:

https://drive.google.com/drive/folders/1oGu5uLtcKJtvvEIqAIUxRnZbykiav58n?usp=sharing

References

[1] Bukowski, R.W., Mullholland, G.W., *NBS TN 973 Smoke Detector Design and Smoke Properties*, National Bureau of Standards, Gaithersburg, MD., Nov 1978.

[2] Milke, J., *The History of Smoke Detection: A Profile of How the Technology and Role of Smoke Detection Has Changed*, Suppression, Detection, and Signaling Research and Applications Conference, 2011.

[3] Ahrens M., "Smoke Alarms in U.S. Home Fires", *National Fire Protection Association*, 2019.

[4] Bukowski, R.W, *NIST SP 965 Performance of Home Smoke Alarms*, National Institute of Standards and Technology, Gaithersburg, MD., 2008.

[5] Yamada, T., Akizuki, Y., *SFPE Handbook of Fire Protection Engineering: Visibility and Human Behavior in Fire Smoke*, Springer New York Volume II, Chapter 61, 2016, pp. 2181-2206.

[6] Bukowski, R.W., *NIST TN 1455-1 Performance of Home Smoke Alarms, Analysis of the Response of Several Available Technologies in Residential Fire Settings*, National Institute of Standards and Technology, Gaithersburg, MD., 2007.

[7] Alpert, R.L., "Calculation of Response Time of Ceiling-Mounted Fire Detectors" *Fire Technology*, vol. 8, 1972, pp. 181-195.

[8] NIST, *International Study of the Sublethal Effects of Fire Smoke on Survivability and Health*, National Institute of Standards and Technology, Gaithersburg, MD., 2001.

[9] Chow, C.L., et al. "Assessing Smoke Toxicity of Burning Combustibles by Four Expressions for Fractional Effective Dose.", *Fire and Materials*, vol. 44, 2020, pp. 804-813.

[10] Purser, D.A., *SFPE Handbook of Fire Protection Engineering: Combustion Toxicity*, Springer New York, Volume II, Chapter 62, 2016, pp. 2207-2307.

[11] Purser, D.A., McAllister J.L., *SFPE Handbook for Fire Protection Engineering: Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat*, Springer New York, Volume II, Chapter 63, 2016, pp. 2308-2428.

[12] NFPA, *NFPA 130, Chapter B*, National Fire Protection Association, 2014.

[13] Bukowski, R.W., Tubbs, J.S., *SFPE Handbook for Fire Protection Engineering: Egress Concepts and Design Approaches*, Springer New York, Volume II, Chapter 56, 2016, pp. 2012-2046.

[14] Kuligowski, E.D., *SFPE Handbook of Fire Protection Engineering: Human Behavior in Fire*, Springer New York, Volume II, Chapter 58, 2016, pp. 2070-2114.

[15] Underwriters Laboratories, *UL 217: Standard For Safety, Smoke Alarms*, Underwriters Laboratories Standards for Safety 8th ed, 2015.

[16] Cleary, T.,Taylor, G., *Modeling Smoke Detector Activation* Suppression, Detection, and Signaling Research and Applications Conference, 2018.

[17] Schifiliti, R.P., Custer, R.L.P., Meacham, B.J., *SFPE Handbook of Fire Protection Engineering: Design of Detection Systems*, Springer New York, Volume II, Chapter 40, 2016, pp. 1314-1377.

[18] USNRC Fire Dynamics Tools, *Estimating Sprinkler Response Time* U.S. Nuclear Regulatory Commission, Washington DC, 2013.

[19] Turns, S.R., *An Introduction to Combustion Concepts and Applications, Third Edition*, McGraw-Hill, 2012.

[20] Quintiere, J. G., *Fundamentals of Fire Phenomena*, John Wiley & Sons, Hoboken, NJ, 2006.

[21] Gwynne, S.M.V., Boyce, K.E., *SFPE Handbook of Fire Protection Engineering: Engineering Data*, Springer New York Volume II, Chapter 64, 2016, pp. 2429-2551.

[22] Residential Size-Up and Search & Rescue Experiments (To be published. Please see the UL FSRI website for details).

[23] ICC, *2018 International Residential Code, 4th Edition*, International Code Council, 2020.