ABSTRACT

Title of Thesis: FIREFIGHTER PORTABLE RADIO CARRYING METHODS: POCKET OR STRAP?

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Firefighters rely on their portable radios daily for communication. This project examines firefighter portable radios and their carrying methods. Carrying methods such as radio pockets sewn into turnout gear and radio straps are examined with respect to carrying utility, thermal protection, and decontamination ability. Information was gleaned from several firefighter line of duty death and "near miss" reports, personal interviews, empirical testing, computational fire modeling, and previous studies. Tests were conducted with radios carried in radio straps both above and below the turnout coat, as well as in the radio pocket. Radios were exposed to a radiant heat flux determined from computational fire modeling via a radiant panel until the test radio was either unable to transmit or receive messages from another radio. From this analysis, it is determined that wearing a portable radio in a radio strap under a turnout coat is the most efficient and safest way to carry a radio.

FIREFIGHTER PORTABLE RADIO CARRYING METHODS: POCKET OR STRAP?

by

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Introduction

1.1 Defining the Problem

Firefighting is an inherently dangerous profession. Working in a hazardous and strenuous environment with severely diminished senses can often result in firefighters becoming disoriented and separated from each other. If firefighters are so separated that they cannot communicate verbally with each other, they can often use their portable radios to communicate with each other inside of the building, or outside. While these radios are quite literally a lifeline for firefighters, like all components of firefighting protective equipment, these can experience catastrophic failures.

While these radios may experience signal degradation in the built environment, the hardware itself is also susceptible to failures, especially when exposed to heat. Complicating this issue, unlike most components of firefighting equipment, most portable radios that are in use in the North American fire service were not designed for use in firefighting conditions. Standards such as NFPA 1802 have been written to address this gap, but many fire departments have not been fortunate enough to adopt radios that follow this standard due to the cost of modern portable radios.

1.2 Carrying Methods

In addition to hardware itself, firefighter personal behavior can also affect a portable radio's ability to transmit. One of the main behaviors that affects a radio's ability to transmit is the way that the radio is carried. Due to the requirement for firefighters to utilize heavy equipment, firefighters need their hands free. Therefore, the options to carry these radios are limited. As many fire departments began to issue radios to each firefighter, a pocket specifically designed for a portable radio was often added. While each fire department ordering protective equipment can opt for these pockets to be placed wherever they like, these are usually located on the firefighters' chest. While this area was traditionally underused for pockets on firefighter turnout gear, it was also located closer to the firefighter's face. Therefore, while the fire environment necessitates respiratory protection, those using their portable radios can communicate more clearly. This position also allowed for the emergency button to be located closer to the firefighter's head so that in a stressful emergency, a firefighter would be able to activate this button with ease. Additionally, if a firefighter were to fall through a hole in a weakened roof or floor, their radio would not be exposed to the heat below. However, as the fire departments are more frequently responding to types of incidents such as medical emergencies, other carrying methods were developed. One of the most popular ways to carry a radio today was developed from these efforts: the radio strap.

Generally, a strip of leather or nylon, a radio strap is designed to be worn over a shoulder with the radio hanging down at the firefighter's side. This method allows firefighters to carry a radio when not wearing turnout gear, such as on medical incidents. These straps can also be worn in conjunction with the turnout ensemble, although variations do arise. Some firefighters prefer to wear their radio strap beneath their turnout coat, so that the radio and the speaker microphone cord are protected by the protective equipment. However, other firefighters prefer to wear their radio above their coat allowing for easier access to change channels and volume. Other discrepancies arise as to the height of the radio. Some firefighters prefer to wear their radio closer to their waists, allowing for the entire radio assembly to be protected by the turnout coat if worn under the coat. Other firefighters seek to wear their radios against their thighs, allowing for the speaker microphone cord to be protected by the coat while also allowing for access to the radio itself. Finally, some firefighters wear their radios facing backward, meaning that the screen and the speaker diaphragm are worn facing the firefighter rather than facing the surrounding environment.

While the radio pocket and radio straps are the most common ways to carry a radio, they are certainly not the only way radios are carried. A firefighter from Australia stated that he preferred to carry his radio in a similar location to a radio strap, but that his department would not issue a radio strap because, "it's to American." This firefighter explained that to achieve this positioning, he placed the radio in his turnout pants cargo pocket. He attaches a speaker microphone to the radio and has the cord run below his turnout coat and turnout pants. He has cut a small hole in the outer lining of the cargo pocket backing for the cord to extend up toward the collar where he allows the speaker microphone to hang unsecured.

Finally, it is important to note the actions that firefighters must complete while operating at an incident and the positions in which these actions are completed. Operations such as advancing hose lines, searching for victims and fire, and removing trapped occupants are all generally best completed with a firefighter crawling. Firefighters can use large skeletal muscles to advance hose lines and remove victims while also keeping them closer to the ground to find overcome victims. This position is also taught to firefighters as the best position to use when working in zero visibility conditions as a firefighter can possibly find a compromised floor and not fall into a hole or down a staircase. However, firefighters can often crawl in different positions. While crawling on "all-fours" may be the most common, using a "tripod" stance is growing in popularity. While different firefighters may choose one method over the other due to personal preference, it is important to note in this study as it will mean that portable radios will be in different orientations. For example, the firefighter working in a stance known as the "tall tripod," where the firefighter operates with his weight on one knee and his or her opposite foot in front of him, will have a radio in a radio pocket held with the antenna pointing straight up. However, a firefighter on "all-fours" will have his antenna pointing straight in front of him or her rather than vertically as desired by portable radio literature. The effects of these different methods will be mentioned later in this report in the fire modeling chapter of this report.

1.3 Critical Incident Study

1.3.1 1999 Cherry Road, Washington D.C.

One of the most infamous basement fires in the American fire service occurred in Washington D.C. in 1999. This fire, located on Cherry Road, resulted in the deaths of two firefighters and injured several others [12]. Seven crews and a chief responded to the fire initially before having four additional crews respond. When the fire crew arrived, they noticed smoke showing from the front of the building where they moved to attack the fire. As an additional crews arrived, a sliding glass door at the rear of the basement was opened to provide both better access as well as ventilation to the fire. However, this allowed the fire to rapidly intensify, endangering the crews who were already engaged in attempting to extinguish the fire. As another crew moved to this area, they noticed that the basement had become completely involved in fire and they moved to extinguish the fire. This crew requested permission to attack the fire, but they were denied as the incident commander did not know the locations of all the crews. However, for the crews inside, the situation had become untenable due to an extremely rapid increase in temperature. One firefighter was able to locate the nozzle of a hose line where he directed the stream of water at the ceiling. This firefighter was able to evacuate from the building, but the other two firefighters that were with him were unable to evacuate.

In the National Institute of Occupational Safety and Health (NIOSH) report on the fire, there are several recommendations to improve firefighter safety. However, several of these recommendations are in direct response to the radio communication challenges that were experienced on this fire. While the fire department's radio system was designed in accordance with NFPA guidelines, several channels were close together and radio traffic "bled through" to other channels. However, individual firefighters were not equipped with their own portable radios. The practice of equipping each firefighter with his or her own portable radio is relatively new, as many fire departments have issued a single radio to a group of two firefighters, or one radio per crew as seen in this incident. Recommendation #5 in this report states, "Fire departments should ensure that personnel equipped with a radio position the radio to receive and respond to radio transmissions." This recommendation references the times when an incident commander called interior crews who did not respond. A lack of response was the reason that the crew that had reached the rear of the basement was denied permission to attack the fire as the incident commander could not determine the location of interior crews and they did not answer his radio transmissions. In the commentary for this recommendation, the report also states, "an officer in the photograph had his radio positioned in his front bottom pocket (approximately waist level) of his turnout coat." This position is not very common in the modern United States fire service, due to the prevalence of dedicated radio pockets. This position would likely increase the exposed length of the speaker microphone cord, leaving the radio vulnerable to a failure.

Another issue with the radio system was the specific frequencies used. While the radio system was designed in accordance with the NFPA 1221 guidelines, many of the frequencies were located close together [33]. This was done to allow for a smaller footprint on the radio traffic in the national capital region. However, because the frequencies were closer together, firefighters often experienced a "bleedover" where radio traffic would be audible on a nonrelated channel. Firefighters also experienced interference from other agencies with the same problems. It is believed that one of the officers who received a message from the incident commander but did not answer it never heard the message due to this "bleedover." The report also states in this same section that firefighters should receive a portable radio that is equipped with an emergency button. This button can be found on nearly all fire service radios for the purpose of transmitting emergency radio traffic. These can be programmed to do various tasks, but generally they will open the firefighter's microphone and allow him or her to transmit without holding the push-to-talk (PTT) button as normal. Some radios are also programed to trigger emergency alarms at fire dispatch centers so that dispatchers can communicate the emergency to an incident commander who might be unable to receive the message. Finally, on modern digital radios, these buttons may be programed to allow a user to bypass a "busy" signal so that the firefighter has priority over others operating at the fire scene. This issue will be discussed later in this section.

1.3.2 2007 Meadowood Court, Leesburg, VA Fire

The first incident discussed after 2000 is the 2007 Meadowood Court Fire in Leesburg, VA [43]. Firefighters were initially dispatched to a commercial fire alarm, but while responding, some units were redirected to a residential house fire. The first arriving engine and ladder arrived and operated alone for several minutes at a two-story house with fire evident. Two firefighters entered the house with a hose line while two others entered to search for potential victims. The firefighters advanced to the second floor of the building, inadvertently passing fire burning on the first floor. When attempting to open the ceiling to expose the fire burning in the attic, the truck company firefighters exited and reentered the house with longer hooks due to the tall ceilings. While a second hose line was being brought to the crews operating in the zero visibility conditions, the crews experienced an extremely rapid temperature increase. They also noticed that the fire was extending from the first floor and onto the second floor. The crews retreated to a bedroom and began to attack the fire that was blocking their egress. While this was happening, the engine company officer attempted to notify the incident commander of the situation, but his portable radio was inoperable, possibly due to a dead or degraded battery. In addition to the possible battery issue, the department's internal investigation states, "Analysis of the radio also revealed thermal damage and a separation of the lapel microphone from the radio." [43]

Therefore, while the engine company officer was unable to transmit a MAYDAY, the truck company firefighter was able to transmit a MAYDAY message. In response, the incident commander deployed the rapid intervention team to rescue the trapped firefighters. The engine company attempted to open the hose line to cool the area, but they immediately lost water pressure due to the hose line being burned through. Therefore, the engine company abandoned the hose line and sought refuge in a bedroom. However, there was a partial collapse, separating the truck company officer from the other three firefighters. The three other firefighters were able to evacuate from the second floor via an external ground ladder. The truck company officer was also able to evacuate from a different side of the building. It is reported that his truck company officer's turnout gear was burning when he was rescued.

In response to this incident, a comprehensive review of the incident was conducted by the fire department. Part of this analysis included both the radio traffic as well as the portable radio themselves. Three of the trapped firefighters wore their radios in a radio strap while the fourth firefighter wore theirs in a radio pocket. As previously mentioned, the engine company officer's radio had failed. The speaker microphone had both separated from the radio and it had melted to the turnout coat and the radio strap had melted to the self-contained breathing apparatus harness. According to the report, the radios carried in the radio straps all suffered thermal damage while the firefighter who wore their radio in the radio pocket did not experience any thermal damage.

Obviously, with this thermal damage and the hectic nature of the incident scene, the radio traffic was analyzed. In this report, firefighters were "stepped on" or "covered," meaning that two units attempted to transmit at the same time, making at least one message unintelligible. This occurred four times during the initial confusion of which units would be responding as well as four additional ones afterward. There were five "garbled" or otherwise unintelligible messages before units arrived at the scene and ten afterward. While the volume of units arriving and the complex nature of the incident would justify these errors, there were several microphone clicks, meaning that the radio attempted to transmit, either due to an inadvertent button push by the firefighter, or as an equipment malfunction. None of these microphone clicks occurred before units arrived at the scene, but there were 74 microphone clicks while units operated at the scene. These four firefighters were luckily able to escape the building. However, one of their critical "lifelines" to their fellow firefighters on the scene failed these firefighters.

1.3.3 2007 Marsh Overlook, Woodbridge, VA Fire

In April of 2007, the Prince William County, Virginia, Fire Department responded to a two-story house fire during shift change at just after 6:00 AM [20]. When firefighters arrived, they saw fire showing from two sides of the building. The company officers of the first two arriving units began to survey the entire scene by walking to the rear of the structure before determining a plan of action and entering the structure. Firefighters assigned to the truck company entered the building and proceeded to the second floor to search for victims due to the presence of a locked door and a vehicle in the driveway. The engine company deployed a 2 ½ inch hose line into the building and called for water. While the hose line was being charged with water, the interior conditions deteriorated nearly instantaneously. The truck company firefighters on the second floor began to move to the stairs in response to these conditions. Simultaneously, an order to evacuate the building was issued by the incident commander. Due to the zero visibility conditions, the officer of the truck company stumbled across the stairs and fell down a few steps. He then directed the firefighter with him to follow him to the steps, but this firefighter was unable to do so.

Now that the 2 ½ inch hose line had been charged with water, firefighters began to direct water upward toward the second floor to protect the truck company. The truck company officer was able to exit the building but was stopped by the firefighters operating the hose lines. The officer of a company assisting the engine with their hose line called a MAYDAY for the missing firefighter. This transmission was then followed by the missing firefighter himself calling a MAYDAY. More hose lines were deployed to flow more water into the area to provide refuge to the missing firefighter as well as other firefighters engaged in rescue efforts. However, due to the intense heat, these firefighters were driven back. The missing firefighter therefore could not be rescued despite numerous attempts. The firefighter succumbed to his injuries at the scene.

In response to this incident, the Prince William County Fire Department diligently researched the incident. Numerous recommendations were made regarding staffing and policies. However, research was also conducted with third parties. The truck company officer's and the deceased firefighter's turnout gear were both analyzed by a third party, as were their self-contained breathing apparatus. However, of particular interest to this study was an analysis of the portable radios carried by the firefighters.

During this incident, many firefighters, including the incident commander, stated that they were unable to communicate effectively through the duration of the incident. While a complete radio transcript was not provided with this report, a timeline referencing several key messages is provided as an appendix to the referenced report. During this incident, firefighters were "stepped on" or "covered" three times. Transmissions that did not have to contend with these challenges also became garbled, unintelligible, or unclear in some way. According to the fire department's internal investigation, 26 transmissions were at least partially unintelligible. However, most dramatic would appear to be what are shown as "mic clicks," in the transcript. These could have been a firefighter who inadvertently pressed the PTT button, or it could be that the wires in the radio contacted one another, allowing the radio to transmit. There were 87 distinct reports of "mic clicks," with many relaying, "several mic clicks," likely leading to over 100 of these incidents. Several firefighters also experienced a radio prohibit, or a "busy" signal. This signal is also colloquially known as a "bonk," and will be discussed in several of the following incidents. Furthermore, the report states, "Numerous personnel reported operations problems with their portable radios." Six problems were stated including Transmission and Receiving failures, an "out of range" radio, self-transmitting radios, dead batteries, and an "inoperable radio." The report also states that nine firefighters experienced radio failures, with most of these firefighters either involved in the rescue efforts or in the hose line operations.

Another radio problem mentioned in this report states, "Portable radios are extremely vulnerable to poor environmental conditions and interference of digital noise from ambient sources which negatively impact the ability of emergency personnel to effectively communicate." [20] The report states that this finding is mainly linked to water damage, which was the inspiration for the radio test conducted in conjunction with this report.

An appendix of this report describes the process of firefighters exposing their radios to water simulating a heavy rain. The firefighters wore their radios in a radio strap over their coat, limiting the radios' protection from the water. These radios were coupled with various speaker microphones. The speaker microphone, due to their unshielded positions at the firefighters' shoulder appear to have been most effected by the water deposits. The testing evaluated if the emergency button would work as designed and programmed, despite the damaged speaker microphone. This was largely confirmed to operate on all operations channels. However, the open microphone feature, designed to keep the firefighter's radio in the transmitting mode without any additional input for a set duration, could not operate once the transmission capabilities were eliminated. It was also determined that the radios operated effectively with an untested speaker microphone. Partially developed from this study, more advanced and more modern radios generally have better water resistance than older radios.

As a final note of interest from this incident, the firefighters' protective equipment was examined. While the truck company officer was able to evacuate relatively quickly after the emergency evacuation order, his gear was damaged. However, the deceased firefighter's gear was far more damaged. However, the statements in the appendix of the referenced report states that much of this damage likely occurred after the firefighter's passing. Therefore, if the firefighters' protective equipment could have received such significant damage, it is reasonable to state that the radio would need to be protected, either in the bunker coat pocket or in a radio strap worn under the firefighter's turnout coat.

1.3.4 2007 Deutsch Bank Building, New York, NY, Fire

In 2007, the Deutsch Bank Building fire in the Manhattan borough of New York City experienced a fire while it was undergoing demolition resulting from the damage inflicted by the September 11th attacks. [7] While responding to this fire, two firefighters were trapped and succumbed to their injuries. In addition to these two firefighters, 115 others were injured. While many building fire protection systems were in various states of disrepair, firefighters also had significant communication challenges, leading to these injuries and fatalities.

When firefighters arrived, there was a miscommunication as to which fire department connection would supply the building's standpipe system. Unfortunately, the building's standpipe system was inoperable due to the demolition efforts. When the first companies ascended the building, they found that the stairwells had been blocked with hatches. Firefighters worked to remove these hatches, and after a significant effort to remove these obstructions, firefighters encountered an intense fire. Numerous other resources were summoned to attack the fire, which spread downward via plastic sheeting designed to separate portions of the building. These obstructions made the building into a labyrinth for the firefighters. Firefighters were also cut off by the downward spread of the fire. As conditions deteriorated, firefighters worked to establish a water supply via a hose line on the building's exterior. Once firefighters were able to secure a water supply using this method, a fire attack commenced. However, the firefighters who were operating this hose line ran out of air. While these firefighters called a MAYDAY for assistance, others were called due to crews being separated. Additionally, firefighters also declared MAYDAYs due to difficulties navigating around the obstructions in the building. The firefighters who ran out of air were eventually removed from the building and transported to hospitals where they were pronounced dead.

While high-rise fires pose immense logistical challenges, the conditions in this building complicated this incident further beyond high-rise fires. Overall, there were 13 MAYDAYs declared during the first hour and forty-five minutes of this incident. Many of these were unique incidents, but some of these calls resulted from reports not being acknowledged. Also, there were several urgent communications regarding missing firefighters. Unfortunately, an incident with this many emergency messages would be extremely challenging for the best prepared and best equipped fire departments. While these radio communication challenges were not related to radios failing, they do show how logistical challenges can dramatically complicate a fire response. Had these firefighters not been able to communicate these emergency messages, more catastrophic consequences would have surely followed. Furthermore, high-rises typically pose immense communication challenges, solely due to building construction features. Therefore, these challenges will be dramatically complicated by the increased traffic resulting from similar emergencies.

1.3.5 2008 North Carolina Incident

During this incident, two firefighters were killed and one severely injured [8]. Firefighters arrived at a commercial millwork facility to find a large fire. Multiple crews entered the building to extinguish the fire, but they were evacuated from the building due to the deteriorating conditions. However, crews soon reentered the building to contain the fire within the building to the office area rather than the production area. However, while these firefighters were working, they experienced a radio failure. When the group did not answer multiple radio messages from the officers outside, a rapid intervention team was dispatched to find and rescue the potentially trapped firefighters. However, the group was not in danger, so the firefighter in charge of the interior team, a captain, sent another firefighter out of the building to report the position and recall the rapid intervention team. The chiefs and the firefighter sent outside met before the firefighter reentered the building to rendezvous with the group. However, while the chief was instructing the rapid intervention team that they were not needed, the firefighters inside noted that the fire was spreading extremely rapidly. During this period, there were numerous unintelligible radio messages. These messages could have been the interior crew requesting help, but this cannot be determined.

The two firefighters realized that they could not control the fire and they decided to evacuate the building. However, the firefighters became disoriented and returned to the nozzle to use its water for protection from the intense fire. While this was happening the captain again attempted to call for assistance, but he could not determine if anyone heard his message. One firefighter who had reentered the building attempted to call the captain over the radio, but he could not reach the captain. The captain who was attempting to release kinks in the hose line previously called for the firefighter at the nozzle to follow him and exit the building. The captain also called a MAYDAY requesting assistance again, but he did not receive a response to either transmission. The captain began to evacuate the building where he found that the hose line had begun to leak. Due to the intense heat, the captain laid down next to the hose line so that the leaking water could cool him and provide protection from this intense heat.

Luckily, one of these MAYDAYs was heard and one of the rapid intervention teams was able to enter the building and rescue the captain. However, the intense heat prevented them from advancing further along the hose line to rescue the other firefighters. One of the firefighters was rescued in subsequent efforts, but the intense heat caused a substantial delay to reach the second firefighter. Both firefighters were pronounced dead.

While there were several factors that lead to the untimely deaths of these two firefighters, the first factor mentioned in the NIOSH report of this incident is, “intermittent radio communication problems (unintelligible transmissions in and out of the fire structure)…” [8] In response to this factor, the report recommends that radio manufacturers should develop and refine radio systems working with firefighter protective equipment.

1.3.6 2008 Ohio Incident

In a 2008 incident in Ohio, two firefighters were killed when they were trapped in a basement while attacking a fire [9]. The firefighters arrived and found a homeowner who informed the firefighters that the house was on fire. In response to this information, the firefighters advanced a 1 ¾ inch hose line into the building to combat the fire. When one of the firefighters called for water, his message was not heard by the firefighter at the engine. However, after multiple attempts, another firefighter was heard. When the captain and another firefighter reached the basement, they began to apply water to the fire while another firefighter assisted them moving the hose line. Two other captains believed that they needed to reposition the hose line, but despite a radio call and one of the captains yelling to the crew inside, they did not receive a response. Inside of the building, one firefighter saw the captain attempting to call a MAYDAY due to the intense fire, but despite 3 efforts, the radio gave a "busy" signal, preventing her from transmitting her messages. The captain then instructed the firefighter to evacuate from the building, and that she and the second firefighter would follow. However, they did not. The firefighter who had evacuated attempted to rescue his crew, but he was unable to reach their position due to the heat. He then reported the situation to his incident commander who attempted to reach the interior crew but could not. Crews brought two hose lines with them to control and extinguish the fire, and when another crew arrived, another attempt was made to rescue the trapped firefighters. This crew advised the commander that they believed that the fire was being fueled by the house's natural gas and that the hose line that the crew had been using had burned about 18 inches near the nozzle. These crews were able to remove the debris from both victims, who were both pronounced dead at the scene.

While this incident had far fewer contributing factors than many of the aforementioned incidents, one of the issues listed is the radio communication problems. To address this factor, the

NIOSH report makes a few key recommendations. One is that, “fire departments should ensure that radio operability guidelines follow best practices recommended by the International Association of Fire Chiefs.” The report also states, “The communications network must integrate the equipment and procedures with the dynamics of the incident site, especially in terms of the environment and the human factors affecting its use.” [9] The report also gives the same recommendation that radio manufacturers must work with fire departments to improve radio capabilities and designs.

This specific incident was also referenced in an article from FireFightingNews.com. This article, published in 2011, discussed how several fire departments have experienced radio failures with digital radios that were new at the time. These radios had been developed in the aftermath of the September 11th attacks with the goal of allowing several public safety agencies to communicate with each other. However, the article states that firefighters are skeptical of the new technology and even states, “Digital radio failures contributed to the deaths of at least five firefighters, the disabling of a sixth and scores of close calls.” [13]. While several incidents are discussed in this article, many discuss incidents that occurred due to, “bonking.” These busy signals, named for the distinctive sound emitted from the radios, have been observed in numerous incidents. Specifically referring to this incident, the article states, “the trunked system rejected at least 43 attempted communications by firefighters.”

1.3.7 2010 Connecticut Incident

Two firefighters were killed in a fire in a two and half story multiple family dwelling in 2010 in Connecticut [10]. Firefighters arrived to find a building with a fire burning in a room on the second floor. Firefighters quickly extinguished the fire in the room, but quickly noted that the fire had spread into the eves and into the attic space. Due to the difficult to extinguish fire and outside temperatures above 90ºF, many firefighters quickly exhausted their air supply. As firefighters replenished their air, they reentered the building and resumed their firefighting duties, often with firefighters from other companies. The fire, strengthened by the wind, eventually caused interior conditions to deteriorate. Despite efforts to ventilate the building, visibility reduced, and the heat built up in the building. Firefighters working at the building's rear stairs became trapped and called a MAYDAY. However, this message was not acknowledged by the incident commander or by the dispatch center. More than three minutes after this message was broadcast, another firefighter encountered one of the firefighters who called the MAYDAY message. This firefighter called his own MAYDAY for help to remove the endangered firefighter. This message was received by the incident commander, but not by the fire dispatch center. While the rescuing firefighter eventually did receive assistance from other firefighters, it was quickly determined that a second firefighter was missing. Another firefighter found his missing coworker and called a MAYDAY. This message was not acknowledged, so he called for a second MAYDAY. This third overall message was acknowledged by the dispatch center and this second injured firefighter was removed from the structure. However, both firefighters were both pronounced dead at the hospital.

While radio failures were not a factor in the deaths of these two firefighters, the failure to receive their messages likely did lead to their deaths. The NIOSH report does not contain a comprehensive radio transcript, but rather summarizes important radio transmissions rounded to the nearest minute to construct an incident timeline. This timeline provides a minimum of 29 messages that were either partially unintelligible or were not acknowledged. While the fluid and hectic incident scene would certainly justify these missed messages, this problem will be greatly magnified by damaged radios. Therefore, while radio failures may not be responsible for the deaths of the firefighters, this incident highlights how important radio communications can be and how significant a failure in communications can be.

1.3.8 2011 San Francisco, CA Fire

Firefighters responded to a four-story residential structure with two levels below grade and two above at the front of the building [11]. When firefighters arrived, they found light smoke coming from the first visible floor. The first engine company deployed a 1 ¾ inch hose line into the building to the "first floor." This floor would be the third overall floor. One of the chiefs arrived and had a face-to-face conversation with the engine company officer. The two officers both believed that the fire was on the floor below them in the basement. The chief stated that crews would attack the fire from a different side of the building before he retreated from the building. The two firefighters on the hose line did not follow the chief. It was believed that the crews advanced to the basement stairs, but after a basement sliding glass door was breached, the fire rapidly intensified, and overcame the crew on the hose line. The two firefighters were transported to a hospital, but both were pronounced dead.

The building's structure and the fire department tactics played a large role in this incident. However, the fire communication methods complicated the issue. The NIOSH report issued in the wake of this incident provides a recommendation that fire departments and radio manufacturers need to work together to improve radio systems for firefighters. The report states, "During this incident, several issues occurred involving the radio, such as: garbled and unintelligible radio transmissions heard by the IC; the Mayday from BC6 being walked on by the dispatch; and the Victims' remote microphones being damaged by thermal environments." [11] The report did not state the way the firefighters were carrying their radios, but regardless of carrying method, the speaker microphone cord will be exposed to the fire environment. While the radio pocket method exposes less of the speaker microphone cord to the environment than carrying the radio completely unprotected, it exposes far more of the cord than the radio strap arrangement.

1.3.9 2012 Riverdale Heights, MD Fire

Firefighters responded and arrived to find a two-story single-family house [44]. An engine and two firefighters from a truck company entered the house. However, due to the wind-driven basement fire, the firefighters on the engine company were forced out of the building. However, the firefighters on the truck company did not know that they were left alone in the building. These two firefighters attempted to return to the door, but they were unable to open the front door. One of the two firefighters found a window and they attempted to climb through the window. However, the first firefighter was unable to exit the window. While the two trapped firefighters had called for the engine company several times, they called for a MAYDAY at the window [17]. To transmit this message through the large volume of radio traffic, the two firefighters activated the emergency features of their radios to override any other radio traffic. The two firefighters sheltered in place for a short time, waiting for assistance to come from the firefighters outside the building. However, when the message was not acknowledged, the second firefighter was able to climb through the window and get help from the building's exterior. The firefighter who remained trapped inside was able to move toward the front door. Eventually the second firefighter, who had removed his respiratory protection to summon help in the front of the building, was able to force the front door open and rescue the still trapped firefighter. Overall, seven firefighters were injured during this incident, and while two of the firefighters suffered near fatal injuries, all the firefighters were able to recover.

While the extreme heat in the building and the miscommunication between the truck and engine companies were two of the main causes of the injuries, there were also complications with the firefighter's portable radios. During the incident, there was a significant amount of radio traffic. While there were numerous "stealth rejects," there were numerous radio messages that were garbled or otherwise ineffective. In the transcripts of one radio channel used during the incident, there were 50 electronic garbles and other failed messages. It should also be noted that despite the recording of the emergency activations, the MAYDAY and the requests for the hose line are not reflected in the transcripts.

A second radio channel was also needed due to the emergency activations. In addition to this complication, one of the trapped firefighters had the sheathing on his speaker microphone melt and the wires fuse together. This caused an open transmitter, meaning that other firefighters could not transmit on this channel. This firefighter as well as the other trapped truck company firefighter wore their radios in a radio strap over their coat. In response to this finding, the report references the National Institute of Standards and Technology (NIST) report entitled *Testing of Portable Radios in a Fire Fighting Environment* [48] which guides firefighters to wear their radios in the radio pocket sewn into the turnout gear. This report will be reviewed in detail in a following section of this report.

1.3.10 2014 Southwest Inn, Houston, TX Fire

One of the most notable fires for radio traffic complications is the 2014 Southwest Inn fire in Houston, Texas [45]. This fire in a hotel caused the deaths of four firefighters at the scene, with a fifth succumbing to injury complications a few years later. Firefighters arrived to find smoke showing from the front of the main hotel building. The crews progressed into the building with a 2 ½ inch hose line. They then requested that the next arriving engine company secure a water supply while they fought the fire. As more crews arrived, they entered the building to support the first crew on the hose line. One crew was also designed as a rapid intervention team while the crews worked inside. The first challenge to the radio system documented in this report was that one of the firefighters working to attack the fire had a stuck microphone. However, just after the incident commander attempted to contact the firefighter to alert them of the situation, there was a significant building collapse. One of the crews inside called a MAYDAY for the now trapped crew. Initially, there was confusion as to who the endangered crew were, as the crew that transmitted the MAYDAY message was not the crew that was now trapped. The rapid intervention team was activated to find the missing firefighters while other crews were used to form a secondary rescue team. As other crews arrived on scene, some were used to rotate with the crews who had been operating since the early portion of the incident while others were used to assist in the rescue efforts. As firefighters worked to rescue their trapped comrades, one of the radios of the missing firefighters was activated. This radio activated several more times, for a total of nine times. This number is reflected in the transcripts, but the report later states that this sole radio activated over twenty times. Due to this number of activations, it was believed that the firefighter had found an area of refuge, so firefighters continued to search for this firefighter. However, after this firefighter was located and extricated from the building, the decision was made to shift from a rescue to a recovery mode. Overall, four firefighters were killed and twelve were initially injured. It is likely that had the errant radio activations not occurred, that there would have been fewer injuries to the firefighters involved in the rescue effort.

In response to this incident, the Houston Fire Department launched a rigorous investigation into several aspects of the incident, including the firefighters' radios. The radio system that the fire department was using was new to the fire department and had only been operational for a few months. Firefighters reported that they often experienced radio coverage issues, especially in commercial buildings and those built with large amounts of concrete and steel. In response to the individual issues seen at the Southwest Inn fire specifically, “Bonks” are addressed first. The report states that there were 83 such incidents in the fifteen and a half minutes before the collapse and 496 in the first hour of the incident. Overall, the report states that, “During the Southwest Inn fire there were a total of 761 ‘Transmission Bonks’ signals on the Southwest Talk Group assigned to this incident.” [45]. The next issue that was mentioned was a Digital Delay. Essentially, when a user completes a transmission, there may be a one to one and a half second delay before other users hear this traffic. Therefore, when multiple personnel try to key their radios during this delay, the number of “Bonks” is dramatically increased. The report next addresses Quick Keys, which are a short, and often inadvertent, activation of the PTT button. While the activation of the button is short and no voice message is transmitted, each incident can tie up the Talk Group for three to four seconds. To explain the significance of these activations, the report states, “During the first 60 minutes of the Southwest Inn fire, there were approximately 96 ‘Quick Keys’ which totaled 6 minutes and 24 seconds of possible usable talk time. This equates to approximately 11% loss of air time in the first hour. These 96 ‘Quick Keys’ also led to 111 transmission ‘Bonks’ which is also estimated to be 19% of the total transmission ‘Bonks’ that occurred at this fire.” [45]. The next issue mentioned regarded open and stuck microphones. To address these issues, the department transitioned from a 60 second to only a 30 second maximum message length, with only 10 seconds if there is no voice or verbal transmission. Another interesting solution posed by the incident reviewers is that of removing a “stuck” open radio and moving it to another monitored channel. This would prevent other users from switching to a different channel while also clearing that same channel. In addition, the monitoring also means that the radio can be monitored by dispatchers rather than the incident command staff. Finally, discussion was given to if certain radios should be given preference over other radios.

In addition to the radio components themselves, the reviewers also examined the system linking the radios to the SCBA mounted microphone. It was determined that one of the reasons that the individual radio that activated twenty times was that the wires in this system had been damaged by the radiant heat. The report then states, "Once the internal hard wires are exposed, radio problems such as 'Quick Keys can occur." [45]. However, the ability to operate a portable radio once a firefighter has removed his or her gear was also examined. The report states that Houston firefighters generally wear their radios in their radio pockets on their turnout coats and that this SCBA integrated radio system dramatically improves communications. However, when the firefighter's turnout gear is removed, both the radio and the microphone are integrated into the turnout gear. The report states that when not wearing their turnout gear, "Most firefighters 'clip' the radio to their side using the belt-clip attached to the radio." [45]. As a response to this issue and to assist firefighter communications while the SCBA integrated radio system was being repaired, the department would purchase a speaker microphone for all radios. For short term fixes, the report also mentioned that when a radio malfunctioned, the incident commander can call for a "radio-man" to fix the radio or to provide replacement equipment. The report also states, "During the Southwest Inn fire, requests for a 'radio-man' were made six (6) separate times." [45]

As a final note, several changes were made to the Houston radio system. Specifics relating to the carrying methods for radios will be discussed in a later subsection.

1.3.11 2017 Texas Strip Mall Fire

The final and most recent incident to be examined is a wind driven fire that occurred in a strip mall in Texas [3]. Firefighters arrived and found smoke emitting from the front of the building. The crews entered the building, with the truck company moving to find the fire in front of the engine company. When the fire was found, the truck company firefighters called for the engine company to advance the hose line to their position. However, one of the truck company firefighters then transmitted a MAYDAY message. Firefighters attempted to rescue this firefighter by deploying the rapid intervention team into the building. However, shortly after the firefighter who had initially called the MAYDAY was rescued from the building, one of the rapid intervention firefighters was lost. It was not recognized that this firefighter was lost until he was discovered in the building. When it was recognized that this second rescued firefighter was not the missing firefighter from the original truck company who had entered the building, efforts to recover this firefighter were initiated. The firefighter was removed from the building and was pronounced dead at the scene.

While some of the main factors contributing to the loss of this firefighter was the wind and the application of somewhat outdated firefighting tactics, radios partially contributed to the confusion on this incident. The only MAYDAY message or indication that the firefighters were missing came from the truck company's firefighter mentioned above. However, this firefighter experienced his own radio issues. The report lists six distinct times that his radio is keyed, but two of these entries to the timeline mentioned that the radio was keyed multiple times. A definitive timeline is not provided in the report. This firefighter also possibly inadvertently changed the channel on his radio. This change also could have been made to reach someone on a different channel due to the radio traffic at the scene and the firefighter knew that his radio was no longer transmitting his voice. In response to this issue, the report states, "Radios should be designed and positioned to allow the fire fighter to monitor and transmit a clear message." [3]

1.3.12 Other Near Miss Incidents

While there is a plethora of information available on the incidents above, there are numerous more incidents that occur daily. Some of these have been reported to a website known as firefighternearmiss.com for various reasons. The first of interest discusses an incident when a new firefighter experienced his radio fall from his pocket. This is a well-known problem with radios worn in a radio pocket and is documented in one of the definitive studies shown below. In response to the incident, the self-reporting firefighter stated, "I had just put the radio in my front/chest pocket of my bunker coat when it fell out as I was crawling over the bed. This happened in the first 2 minutes of being in the fire." [41]

The second of these incidents occurred when a firefighter's speaker microphone cord became entangled in debris. The firefighter stated that he was holding his speaker microphone in his hand while his radio remained in a radio pocket. The report states that the cord was entangled in a dining room chair, and in the zero visibility, the firefighter was unable to free himself. Like the previous incident, this report goes on to state, "After a while, the radio actually pulled out of my pocket and fell to the floor, and I was able to drag the chair and radio to an area with better visibility and get untangled." [24]. The report concludes stating that if the speaker microphone had been secured either to an integral loop sewn to the turnout coat or to the SCBA shoulder strap, this entanglement would likely not have occurred.

The third incident occurred in 2009 when a firefighter fell from a stairwell. This fall was witnessed by the firefighters working in proximity who attempted to call a MAYDAY for this firefighter. However, this message was not transmitted, so the company officer calling the MAYDAY message activated his radio's emergency button. Unfortunately, this did not remedy the problem, forcing the officer to press the PTT button again. This action turned off the radio. The report states that the department has experienced similar failures, especially when the radio is wet. As a recommendation, the report goes on to state, "The portable radio manufacturer [name deleted] should investigate the issue with the portable radios and create a radio that will hold up in the condition’s firefighters face. Even in routine situations. A radio that turns itself off because of minor wetness is unsafe and unacceptable.” [39]. It is also possible that this issue would be remedied by carrying the radio in the turnout coat pocket, or under the coat in a radio strap.

The final near miss incident of interest occurred only a month after the previous incident when two radios failed while the incident commander was transmitting an emergency evacuation order [42]. The report states that as the firefighters were moving to combat the fire on the third floor after extinguishing the second-floor fire, they were ordered to evacuate. However, the two firefighters operating the hose line stated that they did not hear the evacuation order. Other firefighters behind them began to help remove the hose line from the building and the firefighters were luckily able to evacuate. In response to this incident, the report provides several possible recommendations. The first of these recommendations states that when an emergency evacuation order is given, another source of alert must be given, such as sounding the apparatus airhorns. Furthermore, the report includes the sentence, “Everyone should have noticed a lack of communications on their radios and left immediately.” [41]. Therefore, while not directly stating it, other firefighters operating at the scene appear to have endured radio failures. While a carrying method may not completely prevent an incident of this type from occurring, it would greatly reduce the chance of these failures resulting to the heat firefighters endure while operating inside of the building.

1.4 Current Regulatory Standards

1.4.1 Introduction

There are relatively few standards governing fire service portable radios. Most portable radios on the market are designed and built to military specifications. However, the new National

Fire Protection Association (NFPA) 1802 standard sets requirements for fire department communications [35]. A discussion of each of these standards is included below.

1.4.2 *NFPA 1802: Standard on Two-Way, Portable RF Voice Communications Devices for Use by Emergency Services Personnel in the Hazard Zone*

The 2021 edition of NFPA 1802 contains numerous comments on the design of fire service portable radios and the criteria that these radios must be tested to meet [35]. This standard is relatively new, with the only edition being published in 2021, one year before the release of this document. For any device, including both portable radios and speaker microphones to be compliant with this standard, it must be tested by an independent third party. Twenty-one samples of each device need to be tested for the device to be certified under this standard. Portable radios must pass tests in speech quality, heat and immersion leakage resistance, vibration, impact acceleration resistance, corrosion, display surface abrasion, high-temperature functionality, heat and flame, product label durability, cable pullout, case integrity, water drainage, tumble — vibration, TIA transmit power, TIA carrier frequency stability, TIA receiver sensitivity, power source performance, electronic temperature stress, and antenna VSWR swept frequency. Speaker microphones must also pass many of the tests above. These tests include speech quality, vibration, impact acceleration resistance, corrosion, high-temperature functionality, product label durability, cable pullout, case integrity, water drainage, tumble — vibration, and power source performance. However, the standard is written that only "new" portable radios and speaker microphones are to be tested.

In the chapter six of the standard, the design standard, there are specific requirements as to the service life of the radio, as well as the requirement that the radio must be designed to be operated with a gloved hand. Furthermore, section 6.1.6 states, "All controls shall be designed to prevent unintentional activation, deactivation, and change of operation." [35] Later in this chapter, the document states that the timer must be set to one minute, as they were for the Houston Fire Department during the Southwest Inn fire. The standard also states that if the speaker microphone fails, the portable radio must make an audible announcement that the device has failed.

Regarding internal temperature, the radio must be able to determine and indicate when it is over temperature. This critical temperature is set by the manufacturer and will likely vary between different models of radios. The announcements must be made visually on the device's display as well as audibly once every five minutes until reset by a maintenance technician. These incidents must be logged by the device, and after ten minutes of continuous exposure, the radio must audibly indicate that it, or an attached speaker microphone, has been over temperature for a longer period.

Regarding durability, portable radios and speaker microphones must not melt. While it will be expanded upon in a later chapter of this document, several radios experienced some degree of melting so severely that their internal components could be handled through the case.

Finally, the document outlines testing requirements. In the interest of brevity, this document will only discuss the quantities of interest to this study, namely temperature. The elevated temperature conditioning procedure states that the device must be exposed to a temperature of 71ºC, or 160ºF for four hours. The heat immersion test states that the radio must be inserted into an oven kept at 22ºC, or 72ºF at the center of the oven. The oven will then be heated to 177ºC, or 350ºC for fifteen minutes before being removed and inserted into a 22ºC or 72ºF water bath for fifteen minutes. This cycle is to be repeated six times and the water leakage into the power compartment is to be tested. If this test is passed, then the speech quality is to be measured again. The next test of interest is the high temperature functionality test. This test requires four replicates to be placed into an oven heated to 260ºC, or 500ºF with the radios mounted, “as worn”. The devices are then tested for five minutes with the speech quality measured after the device is removed. Finally, the heat and flame test is discussed. The device is placed on a mannequin over the protective clothing. The radio is then to be exposed to direct flame impingement for ten seconds in the apparatus.

It should also be noted that NFPA 1802 speaks on portable radio specifics, but it is not the only NFPA standard to speak on radio communications. NFPA 1221 contains guidance on communications center [33]. While these locations can be vital during firefighting operations due to their responsibilities during the initial dispatch phase of an incident as well as MAYDAY incidents, portable radios are not discussed in this standard. Rather, the document focuses on the design and staffing of these locations.

1.4.3 MIL-STD-810H

This standard is a set of military testing specifications regulating the temperatures that equipment must meet to be used by the United States military [6]. There are no provisions for portable radios or for firefighters. This policy was originally published in 1962 but has been updated to its current version that was published in 2019. While this family of standards includes guidance on numerous other quantities such as impact and water resistance. In terms of temperature, this standard requires equipment to be heated to 160ºF, an equivalent of 71ºC.

Many of the quantities mentioned in the NFPA 1802 standard were copied from this family of military specifications. This decision was preferable for radio manufacturers as products can be dual certified, meaning that a product can be sold both to the fire service as well as to the military. This consideration means that manufacturers can save design, production, certification, and overhead costs by streamlining their product lining while also meeting the demands of the fire service.

While the NFPA 1802 standard captures a great deal of the quantities of interest in this family of specifications, older radios were not designed in accordance with the NFPA 1802 standard. Currently, most firefighters worldwide use radios that were not designed in accordance with NFPA 1802. Many manufacturers are still selling portable radios that do not meet the NFPA 1802 standard to fire departments, meaning that fire departments will likely continue to use non-compliant radios for several years to come.

1.5 Fire Department Policies

While portable radio carrying methods are largely a personal choice and can vary from firefighter to firefighter, some fire departments have issued policies on how firefighters are to wear their radios. While this was centralized to the national capital region, it has spread to several other jurisdictions. However, it should be noted that many fire departments do not have such requirements in place.

The city of Annapolis, Maryland, provided instruction to wear their radios in a radio strap beneath the turnout coat to all their firefighters. This instruction is despite the inclusion of a radio pocket on the issued turnout gear [29]. According to a department member, the policy was developed to maintain better accountability of radios. The officer stated that portable radios were not always taken on "routine" calls such as medical responses. This development was due to a research study conducted by a fire department in the same region. This study, conducted by the Fairfax County (VA) Department of Fire and Rescue will be discussed in detail in a following section [38].

The Anne Arundel County (MD) Fire Department occupies the same county as the Annapolis Fire Department and has a similar policy. However, this policy stops short from requiring firefighters to wear their radio in one particular manner. Firefighters are issued turnout gear with sewn in radio pockets as well as radio straps. The policy simply states that firefighters must use gear that meets or exceeds the same standards. This policy is enforced with personnel protective equipment, but not with radios.

Firefighters in Montgomery County, Maryland, must wear their radios in a radio pocket. Fire Chief's General Order 11-05 states, "When firefighter PPE is worn during all firefighting operations, the portable radio <u>must</u> be carried inside the sewn-on breast pocket of the turnout coat." [40]. The policy includes a link to the NIST study on this topic and states that the study is the reason for this policy. Originally issued on February 23, 2011, the policy was rescinded on July 22nd, 2015. However, after speaking with a member of the department, this policy has yet to be replaced and therefore firefighters do follow this guidance [26]. The same firefighter also stated that the department issues the firefighters radio straps for responding to medical emergencies and other incidents.

The city of Ocoee, Florida, maintains a policy that their firefighters must wear their radios on department issued radio straps. A firefighter for the department stated that most of the firefighters on the department regularly respond to medical emergencies and find it much easier to wear their radios on radio straps anyway. The firefighter was new to the agency and could not provide a justification for the policy. [2]

The Pasco County, Florida, Fire Department also requires their firefighters to wear a radio strap. While the department's policy lists seven other ways to carry their radios, the statement, "If supplied with a commercial radio holsters [sic] [radio strap]." [37] A firefighter for the agency stated that each of the department radios are equipped with a radio strap, requiring firefighters to wear their radios in a radio strap [31]. Finally, regardless of carrying method, the policy also states that the lapel microphones should not be removed from the radio.

The final fire department that has a radio policy that will be examined in this report is the Houston Fire Department. As mentioned above during the discussion of the Southwest Inn fire, the department has endured significant challenges with its radio system. According to a firefighter with the department, there is not a set policy on how firefighters are to wear their radios. The same firefighter mentioned that the department did issue radio straps a few years after the Southwest Inn incident, but that the department membership did not find the straps comfortable or practical. The firefighter also stated that the chiefs collected the radio straps and, "they are probably in some garage somewhere." [30]. However, this firefighter stated that the department has a provision for radios within its "Two Minute Drill." This drill, common to the fire service, requires a firefighter to be able to don their turnout gear and respiratory protection from his or her station uniform within two minutes. The Houston Fire Department has gone a step further and requires firefighters to have their radios turned to the correct channel and on the maximum power setting. For the purposes of this drill, the radio is to be worn in the radio pocket. The firefighter could not provide the department's justification for this positioning, other than the absence of other equipment to carry a radio.

1.6 Review of Previous Studies

1.6.1 Introduction

This report is far from the first research into this topic. While most research on firefighter radio communications is mainly geared to the portable radio or the system itself, there are a few that consider carrying methods. These will be examined below.

1.6.2 NIOSH/Tri-Data Report

This report is referenced numerous times in the NIOSH reports that were referenced above. This study, the *Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems*, is dated as September 2003 and therefore predates numerous upgrades in radio technology [36]. However, while the report mainly focuses on the radio systems, it does contain information on specific fire departments as well as some behaviors that can affect radio communications. While a carrying method is not one of the behaviors examined in this report, the report does mention that having the radio too far or too close to the mouth or mask mounted voice amplifier can reduce the quality of a transmission. It also mentions the difficulties of operating a radio while wearing full protective equipment, especially gloves. The final two factors mentioned in this report is potential inadequate training on radio features as well as the fire service cultural reluctance to declare a MAYDAY and other emergency traffic.

Regarding the specific challenges found by individual fire departments, most of the departments mentioned had either recently or were in the process of upgrading to an 800 MHz radio system. None of the fire departments specifically mentioned radio carrying methods.

1.6.3 NIST TN 1477

There are two documents published by NIST relating to firefighting portable radios. The first, titled *Testing Firefighting Portable Radios in a Fire Fighting Environment* consisted of seven radios tested in an apparatus specifically designed for this test [48]. The radios were positioned both inside a turnout coat radio pocket and they were left exposed. No other carrying method, including radio straps, were tested. The radios had their signals analyzed without an antenna. Only the portable radios themselves were tested initially. Some damage was noted to the antenna when tests including it were conducted. However, these tests did not have their signals examined.

The document first states that the tests were conducted in a Class III thermal environment, with a maximum temperature of 260ºC and a 10 $kW/_{m^2}$ maximum heat flux. These thermal classes were defined in *Thermal Environment for Electronic Equipment Used by Firefighters*, a previous NIST study [22]. However, they are summarized in the early stages of this report and are shown in Table 1.1 below.

Table 0.1: Thermal Classes as Reproduced from NIST TN 1474 and NIST TN 1477

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

Radios were obtained from three different manufacturers for this study, all of which stated that their maximum operating temperature was 60ºC, as seen in the military specification referenced above.

The report also outlines the specialized testing apparatus assembled for this test. Named in the report as the Fire Equipment Evaluator, this device, "is a closed-loop, recirculating wind tunnel designed to simulate thermal conditions up to Thermal Class III." The device can produce air temperatures up to 300ºC and flow velocities from 0.5 $m/_s$ to 2.0 $m/_s$. A diagram of the apparatus is provided in Figure 1.1.

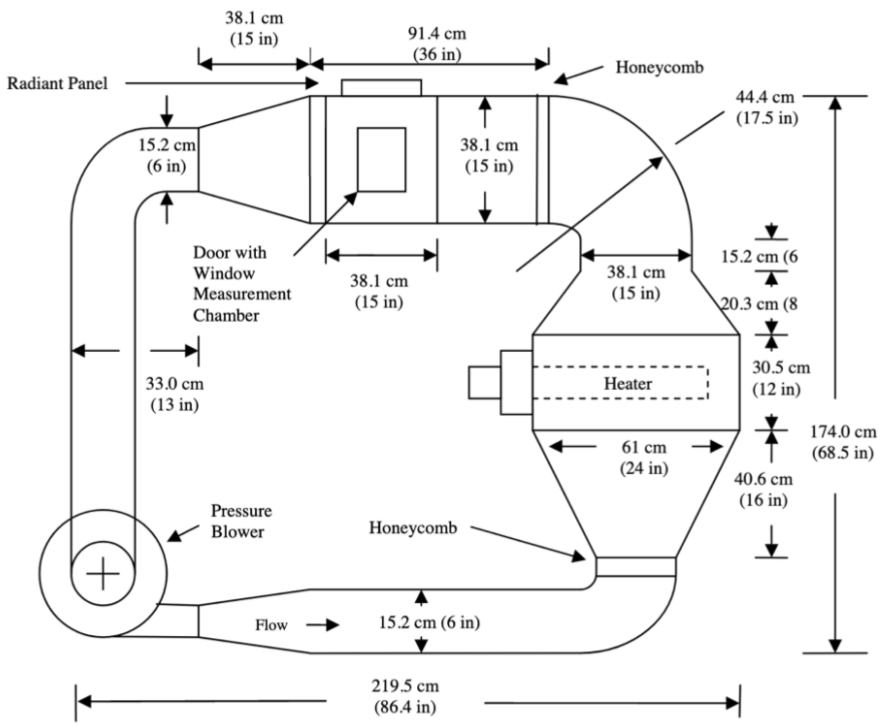

Figure 0.1: Fire Equipment Evaluator (FEE) Schematic from NIST TN 1477

The radios tested in the simulated turnout coat pocket experienced temperatures inside of the pocket on average of 75 ºC lower than the ambient temperatures when the radio was subjected to a forced flow of 0.9 $^{m}/_{s}$ and 57 ºC with a 2 $^{m}/_{s}$. While not stated in the report, it is assumed that the ambient temperature was 20ºC. The study found that the radio protected by the turnout coat pocket could survive the Class III thermal conditions listed earlier, but the seven of the exposed radios all failed at various points during the Class II thermal condition tests. Three of these damaged radios did not return to their normal functioning after returning to the ambient temperature. The results shown as Table 5 in the report are also shown here as Table 1.2.

Table 0.2: NIST TN 1477 Class III Thermal Soak Results

Radio	Survive Soak	Notes
A	No	9.5 min – no transmit or receive
A	No	8.5 min – no transmit or receive
B	No	Transmission signal shift, increased noise
B	No	Transmission signal shift, power loss and increased noise
C	No	Transmission signal shift, no transmission on cool down
C	No	Transmission signal shift, no transmit or receive on cool down

This study also examined the speaker microphones designed for each of these radios. Two of the three microphones could not survive a 26ºC temperature while the third experienced melting and visual deformation while also exhibiting a volume decrease.

Included in the conclusions section of the report is the statement, "Since firefighter turnout gear is designed to protect firefighters exposed to Thermal Class III conditions, handheld radios should be constructed to handle these conditions." [22]. The report concludes by stating that the "next step" would be for NFPA to develop a standard regarding the thermal environment that radios should be designed to meet as this 2006 report far predated the NFPA 1802 standard. Only NFPA 1221 had been published which did not provide these requirements.

1.6.4 NIST TN 1474

The information from the study above was included in the NIST study known as *Thermal Environment for Electronic Equipment Used by Firefighters* which was published just prior to the previously presented study [22]. This study mainly examined firefighter Personal Alert Safety Systems (PASS), but radios were also examined. The document outlines the apparatus that is used in the 1477 study as well as the thermal classes to which the radios were tested.

An interesting note in this study is the decibel reduction of PASS devices in different thermal classes. As mentioned with one of the speaker microphones in the above study, as temperatures increase, the volume tends to decrease. This result can be attributed to multiple effects, but the thermal damage to internal components would be significant. PASS devices from two different manufacturers were tested, and in the Class III thermal environment outlined above, decibel reductions from 13 dB to 17 dB were observed. While a PASS device is simply designed to make a distinctive and loud sound, portable radios are designed to transmit intelligible traffic. Therefore, while these reductions might be acceptable for PASS devices, reductions of this severity in portable radios can be catastrophic to a portable radio.

1.6.5 Fairfax County (VA) Fire and Rescue Department Study

The most recent study examined in this report is one that is published from the Fairfax County Fire and Rescue Department in Northern Virginia [38]. In contrast to the NIST study, this report did not consider portable radios themselves, but rather it only examined the radio pocket in comparison to the radio strap. While the previously referenced studies focused on the thermal environment and the radios themselves, this study focuses more on firefighter specific behaviors. This study is also written from the point of view of a single, large fire department. Therefore, manufacturer names are listed in the report and mention is given to department specific equipment and locations. These will be omitted for this report.

The Portable Radio Placement in the IDLH [Immediately Dangerous to Life and Health], begins by stating that some fire departments, including the authoring agency, issued policies that radios can only be worn in the turnout coat pocket. The document states that this policy was written in 2009 while also making mention that Montgomery County, Maryland, has a similar policy. Based on the dates of publication, this policy is the one examined earlier in this report.

The study then offers the section, “Three Critical Reasons why the Radio Pocket is Unsafe.” In this section, radio signal degradation, ejection from the radio pocket, and melting of the speaker microphone are the three reasons that are listed in this section.

The signal degradation of a radio pocket exceeds all other carrying methods according to testing conducted with the department’s radio manufacturer’s engineers. The report states that this reduction could be as much as 30 dB, reducing the radio’s power substantially. As one of the main purposes of the Tri-Data report discussed earlier, underpowered radios may be unable to transmit through obstructions such as walls [36]. Therefore, with only 0.01 W as the document states, a firefighter may have significant difficulties, or even be prevented from, transmitting messages to other firefighters on an incident. The reduction was likely due to the positioning explained earlier with the firefighter crawling on “all-fours.” The radio strap decibel loss is listed as only 15 dB for a crawling firefighter a few pages later. The report goes on to state that a firefighter can expect to experience a 11 dB loss while standing with the radio worn in the radio pocket with only a 7 dB loss when worn in a radio strap.

Next, the report discusses a portable radio ejection as a reason to not use a radio pocket. While these pockets are closed by a hook and loop style closure, this material can melt or be degraded with the introduction of water. These closures also degrade with multiple openings and closings. The report states that due to the weight of the radio, this closure cannot be trusted to contain a radio, making it possible that it will be ejected from a pocket. A radio ejection would equate to the exposed radio mentioned above in the NIST 1477 report.

The final justification for the shift away from the radio pocket is the melting of the speaker microphone cord. This issue has been mentioned in the critical incidents above, and the report also states that this is the weakest and least protected portion of the radio assembly. The report states that the safest way to wear the shoulder microphone is under the turnout coat.

In addition to removing these deficiencies, the report also states that the speaker microphone will generally be in approximately the same position as seen with the radio pocket, with the added benefit of placing a second PTT button, the one on the portable radio, located near waist level. This is seen as a benefit as it may allow a firefighter to request assistance if he or she is entrapped and unable to access the device at his or her chest. The radio knobs were also measured, and it was found that the radio strap moved the critical knobs nearly two feet lower on a standing, six foot tall, firefighter.

The report also goes further than just stating that the radio strap is the preferred way to wear a portable radio. The report states that the radio strap should be worn under the coat to protect the speaker microphone cord with the radio exposed below the coat line. This consideration is made to allow the firefighter to access the knobs and to interact with the radio with only one hand. Wearing the radio above the coat line would mean that the firefighter would need to move the coat with one hand and interact with his or her portable radio with the other. The same can be said for the radio pocket.

Comparing the thermal protection directly, the report states, "The reality in the NIST report is that while the radio pocket provided some level of protection, the pocket is not designed with the same thermal protection found on most of the coat. The same level of thermal protection, if not more, can be gained when the radio is covered with leather." [38] The report also states that when a speaker microphone is melted in such a way that a short circuit is created, the radio can be "locked" open, prohibiting other firefighters at the scene from broadcasting any radio messages. The report states that the best way to prevent an incident of this nature is to wear the cord beneath the coat, rather than being prepared to remove the speaker microphone and using the portable radio. The report states that the Washington D.C. Fire Department was in the process of evaluating a sheath to protect the shoulder microphone cord, but that wearing the radio under the coat would still be the preferred method. The report states, “However, the other issues associated with wearing the strap over the coat include: entanglement, less protection than wearing it under the coat, and the antenna does not cant away from the body in the same manner as when you wear the radio strap under the coat.” [38]. This report also mentions the study conducted by the Prince William County (VA) Department of Fire and Rescue in the wake of the Marsh Overlook incident mentioned earlier in this report. The Fairfax study mentions that Prince William’s agency does not have a policy on radio strap carrying method, but that firefighters are instructed to wear their radios on a radio strap beneath their coat with the radio exposed.

As a final note, the report describes a set of training exercises that Fairfax County firefighters complete, including an exercise designed to train a firefighter to rapidly evacuate from a room that is approaching flashover. The firefighters must breach a wall and crawl into a second room. However, the report states that multiple recruits experience their radios being caught on the wood stud and prohibiting them from exiting the room. Another exercise trains firefighters to self-extricate from a wire entanglement. However, instructors found that when a radio is worn in the radio strap, recruits operating in simulated zero visibility conditions could not distinguish between the wires and their radio components.

As a final note on the discussion of this report, it should be noted that the report itself mentions that radio straps of any material were not tested during the NIST evaluation. It is therefore the goal of this study to evaluate the radio strap versus the radio pocket to determine the optimal way for firefighters to wear their portable radios.

Radio Strap Solutions

1.7 Introduction

Before comparing a specific carrying method, it is important to provide some more information on radio straps. Again, as previously mentioned, radio straps have dramatically increased in popularity in the last decade and a half. With this rise in popularity, there have been many updates and advancements in radio straps. This section will discuss many of these advancements and some of the typical ways that different firefighters wear their radios.

1.8 Radio Strap Carrying Configurations

While some fire departments require their firefighters to wear their radios on radio straps in specific ways, many firefighters are allowed to wear their radios in their preferred method. Also, even fire departments that require their firefighters to wear their radios on a radio strap may allow their firefighters to choose the height and orientation of their radios.

One of the main decisions that firefighters must make is the location where they will wear their radios. Some firefighters may choose to leave their radios exposed, as seen in the Fairfax study, while others may choose to wear their radios beneath their coats. Some firefighters may choose this location as the radio will be closer to the firefighter's waist. This position may be preferred when the firefighter is responding to medical emergencies or other incidents when the firefighter is not wearing a full complement of protective equipment.

Firefighters are also allowed to choose the side where they choose to wear their radios. This is generally a personal choice made based on the firefighter's handedness. The decision can also be made based on the preference when a firefighter is crawling. Firefighters are often taught that in the case of a wire entanglement that they should crawl on their left side. Therefore, a firefighter may choose to wear his or her radio on the right side so that they are not lying on their radios. However, firefighters who are commonly driving fire apparatus may choose to wear their radios on their left so that it does not get tangled with the seatbelt or the radio console inside of the apparatus.

Another choice that firefighters can make is to wear their radios forward or backward. Depending on the radio model, this will change the orientation of the speaker microphone and the radio's graphical display. However, for one of the most common new models of radio, the display is located at the rear of the radio. Firefighters may also choose to wear their radios "backwards" with the intention of moving the portable radio's PTT button.

As mentioned earlier, choosing to wear the radio strap above or below the coat is also a choice that firefighters must make. For firefighters to wear their radio straps under the coat they must put the radio strap on before leaving the station and putting on his or her turnout coat. However, firefighters who wear radio straps above their coats can put the radio strap on while responding to the emergency or after arriving at the scene. Some firefighters prefer to wear their radios over the coat so that they will have access to the entire radio assembly. With complete access, firefighters will be able to turn their radio to the correct radio channel and be ensured that they are monitoring and transmitting on the correct channel. Other firefighters may choose to wear their radios below their coat to provide the speaker mic with the additional protection as mentioned in the previous chapter.

1.9 Commercial Off the Shelf Solutions

While firefighters can often decide their preferred locations for their radios, firefighters and fire departments have choices when it comes to radio straps. While there are numerous vendors in the industry, a principal difference is the material of the strap. The main two materials on the market are leather and nylon. Leather radio straps still hold a large majority of the market, but many agencies that are providing all their firefighters with radio straps are choosing to purchase nylon radio straps [32] [28].

First, for leather straps, there are numerous suppliers. Both commercially made and handcrafted straps are made and in use across the country. While some fire departments may purchase personalized radio straps for their firefighters for fire scene accountability purposes, many departments simply purchase the commercially available products due to the lower cost. Personalized radio straps are often purchased by individual firefighters. Also, much of the handcrafted market is produced by firefighters themselves. Leather has been used for various pieces of ancillary protective equipment such as glove retaining straps, suspenders, flashlight holders, and even helmets. The reason for the widespread use of leather is both its durability and its history. Many firefighters may work an entire career with the same leather helmet, with some even passing it down to their children when they become firefighters. As leather is also a natural material, it chars rather than melts. Therefore, it has often been perceived as a "safer" material to use for fire protective equipment. However, leather has been challenged in recent years on two key aspects. Leather radio straps, especially handcrafted ones, are generally heavier than nylon straps. In a quick test conducted with a nylon strap, a commercially produced leather strap, and a personalized strap, the nylon strap was the lightest with a mass of 337.3 grams. The commercially produced leather strap followed with a 360.5-gram mass and with the personalized strap finishing with a 641-gram mass. Figures 2.1 shows a comparison of the nylon strap on the left, a handcrafted leather strap in the center, and a commercially made strap to the right. Figures 2.2, 2.3, and 2.4 show the masses of these three straps as discussed earlier.

Figure 0.1: Radio Strap Comparison

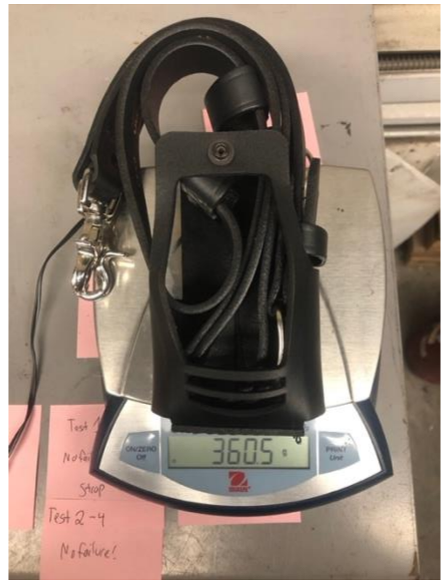

Figure 0.2: Commercially Produced Leather Radio Strap Mass

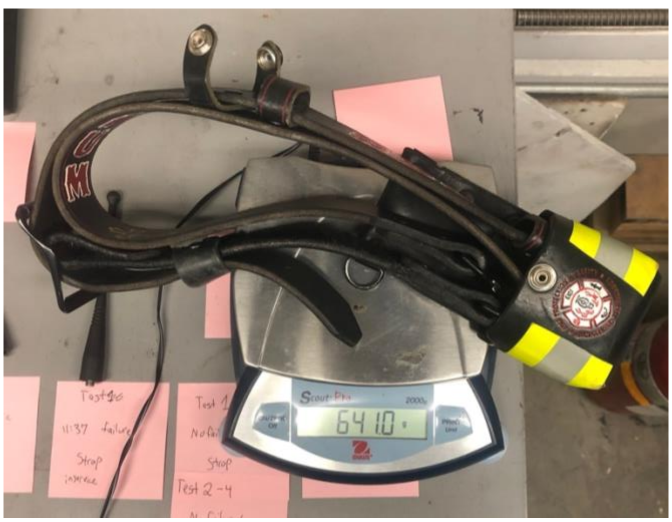

Figure 0.3: Handcrafted Leather Radio Strap Mass

Figure 0.4: Nylon Radio Strap Mass

However, while the weight of a radio strap is negligible when compared to the weight of other protective equipment, synthetic straps still have one large advantage over their leather challengers. Synthetic radio straps can be decontaminated simply by inserting them into a turnout gear extractor. Because the radio straps are made from fabrics, they can be cleaned with a firefighter's turnout gear. Leather radio straps can only be cleaned with a manual soap and water scrub. Therefore, as cancer prevention efforts increased in the fire service, nylon radio straps have grown increasingly popular. However, the synthetic radio strap industry is predominantly controlled by a few companies. Yet, the costs for these devices are competitive to their leather counterparts. However, these synthetic straps, often made from nylon or plastic, do melt, rather than char. This possibility has often steered firefighters away from these devices due to the belief that the strap will melt when exposed to high heat.

While each of the materials has its own benefits, one of the main practical justifications for each radio strap is its cost. While most radio strap vendors will provide discounts to fire departments for bulk orders, a single commercially made leather radio strap can be found for $50.00 from at least one source. Handcrafted leather and nylon straps can be found within the range of $100 to $150 generally.

Computational Fire Dynamics Modeling

1.10 Introduction to FDS

Developed by NIST, Fire Dynamics Simulator, or FDS, is the preemptive fire modeling software used by Fire Protection Engineers [23]. These models allow for the evaluation of various fire scenarios without spending large sums of money on physical testing. Parameters such as room size, heat release rate, fuel packages, and more can all be altered with a few keystrokes. A series of calculations are conducted at certain time stamps for a particular region of space. Each of the regions constitutes a grid-like arrangement known as a "mesh." In this case, a mesh of 0.1 meters was used for each simulation, regardless of the size of the modeled compartment.

Full-scale testing has already been conducted to verify and validate the veracity of the FDS calculations. Information regarding these validation efforts can be found in the FDS Verification Guide. These calculations are forms of the Navier-Stokes equations and are mainly focused on the movement of fluids, especially heat and smoke. More information on these calculations can be found in the FDS Technical Reference Guide [18].

In this study, FDS Version 6.7.5 and Smokeview Version 6.7.15 were used. While not mentioned above, Smokeview is the program used to create a graphical representation of the modeled environment. This program is used to show visualizations of the model geometry as well as the smoke movement. Instrumentation used in these simulations included virtual heat flux gages placed into the model to determine the heat flux that each radio would receive when worn in a certain position. Assuming a "worst case" scenario, a firefighter was left approximately five feet from the fuel package with the firefighter not entering or exiting the space. Therefore, the firefighter remained in a constant location and was not subject to different flow or temperature gradients. In addition to the heat flux gage, thermocouples were also placed in the same locations to evaluate the temperature that the radios would receive so that the results could be compared to the NFPA 1802 and NIST TN 1477 studies. Finally, it should also be noted that while fire modeling is an invaluable tool, emphasis is also placed on the empirical testing of multiple radios. These results are presented in the following chapter.

1.11 Radio Positions

1.11.1 Pocket versus Strap

Multiple firefighters were surveyed to determine a variety of quantities. Firefighters were asked their preferred method to wear their radios so that emphasis could be placed in the appropriate areas. Next, the heights of these radios were measured to determine the location of the virtual heat flux and virtual thermocouples in the models. These heights were taken for a standing and for a crawling firefighter. The positions in which firefighters crawled were also evaluated. These results are listed in Table 3.1. As a note, the names and fire departments of those surveyed were removed.

Table 0.1:Radio Positioning Survey

Firefighter	Preferred Carrying Method (Strap vs. Pocket)	Crawling Position (All 4's vs. Tripod vs. One Knee)	Crawling Height (m)	Standing Height (m)

Firefighter 1	Strap with Radio Over Coat	Tripod	0.25	0.89
Firefighter 2	Strap with Radio Under Coat	All 4's	0.51	0.91
Firefighter 3	Pocket	One Knee	0.73	1.30
Firefighter 4	Strap with Radio Under Coat	All 4's	0.33	0.94
Firefighter 5	Strap with Radio Under Coat	Tripod	0.51	0.86
Firefighter 6	Strap with Radio Under Coat	All 4's	0.53	0.97
Firefighter 7	Strap with Radio Over Coat	Tripod	0.25	0.97
Firefighter 8	Pocket	All 4's	0.81	1.04

1.12 Fire Scenarios

Four fire scenarios were conducted to best simulate a firefighting environment. Previous experiments conducted measuring the heat release rates of various target fuels were used to choose these vital quantities. Both studies can be found in the University of Maryland's Burning Item Database. Each of these are summarized below.

It is also important to note that these scenarios were not conducted for any of the case studies outlined in the previous chapter. These scenarios were deemed to be specific to the incidents. Also, the specifics of the structure interior, such as the fuel packages and their locations, have proven to be indiscernible. Additionally, several of the incidents such as the 1999 Cherry Road [21] and 2007 Marsh Overlook [20] fires have already undergone a thorough FDS analysis. Finally, as the focus of this report was not on the compartment fire dynamics that lead to the deaths of these firefighters, but rather only to provide a heat flux that a firefighter could expect to experience, the FDS simulations were kept as brief as possible.

1.12.1 Living Room

The first simulation that was completed was a fire in a living room. This small room only contained a couch which served as the target fuel. As this simulation was based on the example file packaged with FDS entitled "couch," the heat release rate curve presented below is produced from an unedited simulation consisting of the target fuel package without any ventilation as Figure 3.1.

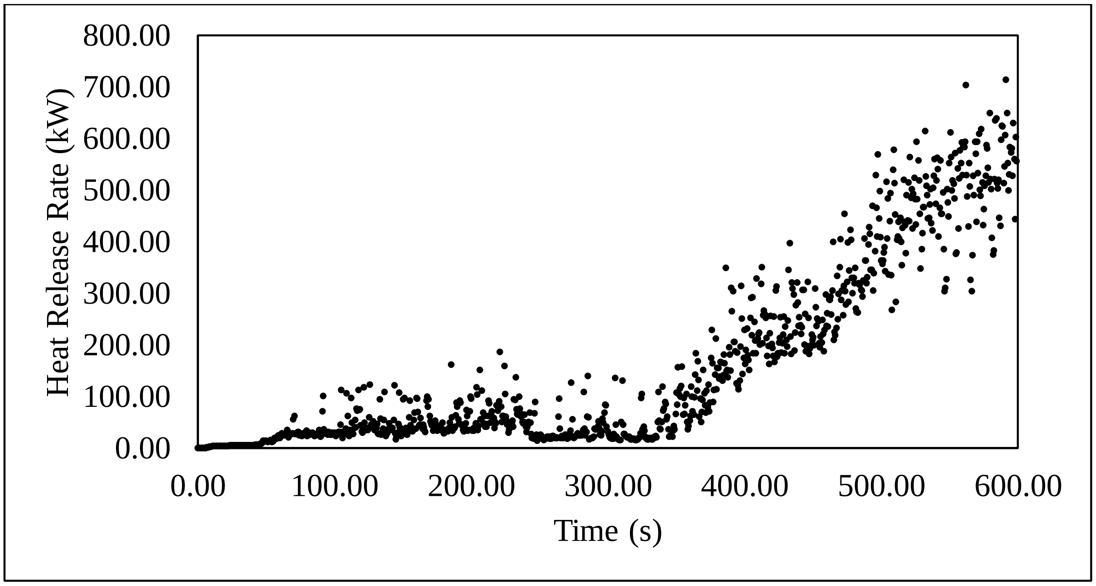

Figure 0.1: Couch Example Simulation Heat Release Rate Curve

A couch was chosen as modern couches are often composed of synthetic materials such as polyurethane foam, which often equate to higher heat release rates. While these more volatile fuels have often proved challenging for firefighters, they are quite prevalent in the United States. Therefore, because most modern homes contain at least one couch, generally of these synthetic materials, a simulation containing a couch was analyzed. The firefighter was placed so that the radios would be 1.6 meters away from the couch when the firefighter was positioned in the tripod position, approximately 1.35 meters away when the firefighter preferred to crawl on one knee, and approximately 1.1 meters away when the firefighter used the all-fours position. These positions were only in the x-plane, with all the radios being positioned in the same y-plane. The heights presented above were used as the z-plane.

The room and fuel arrangement can be seen below in Figures 3.2 and 3.3 while Figure 3.4 shows the overhead view of the compartment.

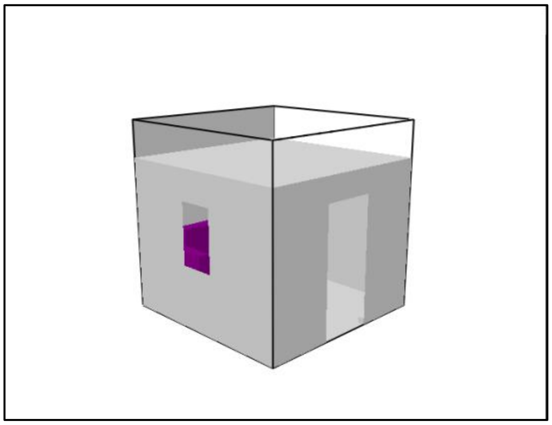

Figure 0.2: Living Room Exterior Corner View

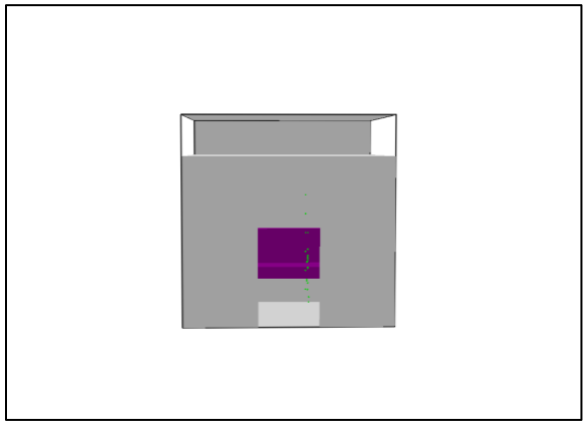

Figure 0.3: Living Room Door View

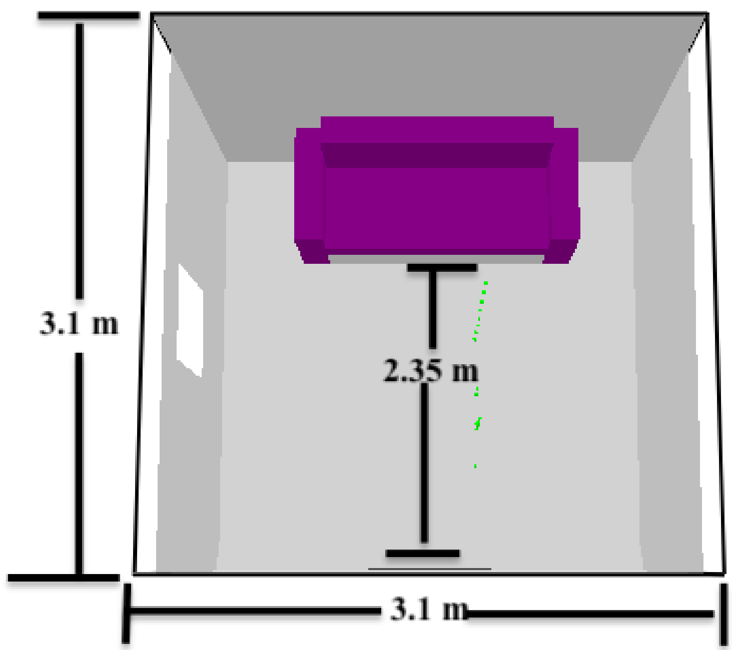

Figure 0.4: Dimensioned Living Room Simulation Overhead View

A single door and window were inserted into the room with the room only containing the couch. No curtains or floor coverings were included, with the walls, ceiling, and floor made of gypsum plaster. While this is a common material found on walls and ceilings, gypsum plaster was also used for the flooring material for simplicity. The simulations were also based on the example FDS simulation packaged with FDS entitled “couch”. Also, this determination was made as the wall material was not of particular interest, and neither was the spread of combustion byproducts. Table 3.2 below shows several of the material properties used in this simulation.

Table 0.2: Living Room Simulation Important Material Properties

Material	Specific Heat $({}^{kJ}/_{kg*K})$	Conductivity $({}^{W}/_{m*K})$	Heat of Combustion $({}^{kJ}/_{kg})$
Fabric	1.0	0.1	20,000
Foam	1.0	0.05	30,000
Gypsum Plaster	0.84	0.48	N/A

While many homes may have larger living rooms, a smaller room was chosen as an example where conditions would develop more rapidly than in a large room. Also, because the main goal of this modeling was to evaluate the conditions a radio would be exposed to a short distance from the target fuel, a simulation of a smaller room provides the vital information.

Images of the simulation are presented below. Screenshots were taken of the simulation in Smokeview at 30 second intervals, beginning 30 seconds into the simulation. These are presented below as Figures 3.5 through 3.24.

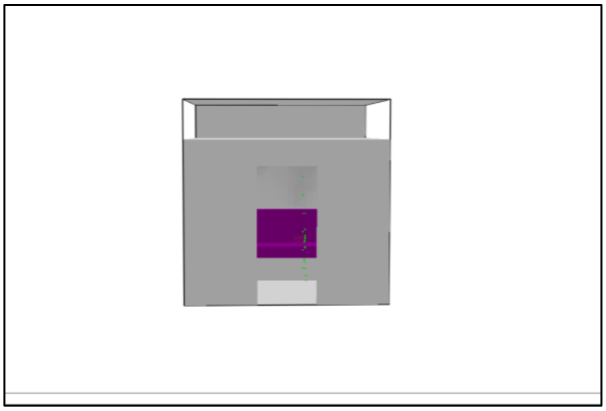

Figure 0.5: Living Room Simulation 30 Seconds

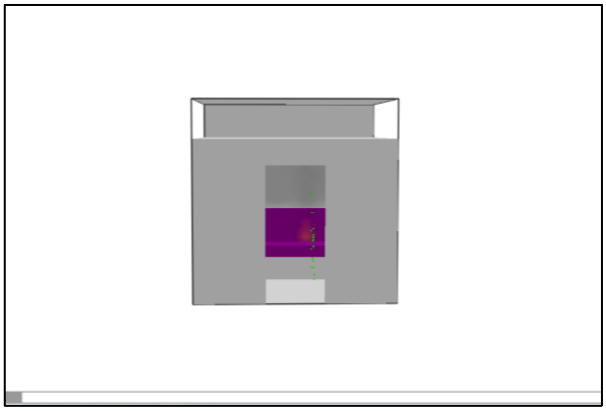

Figure 0.6: Living Room Simulation 60 Seconds

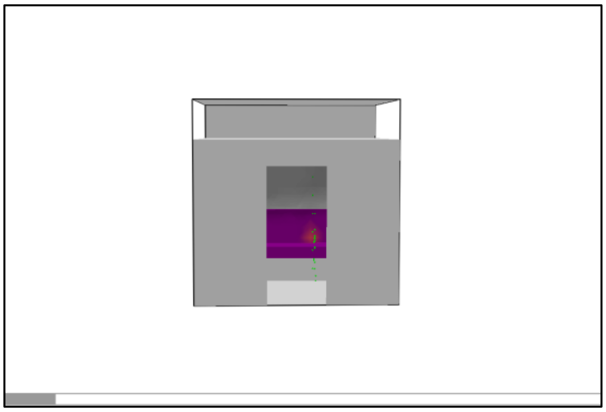

Figure 0.7: Living Room Simulation 90 Seconds

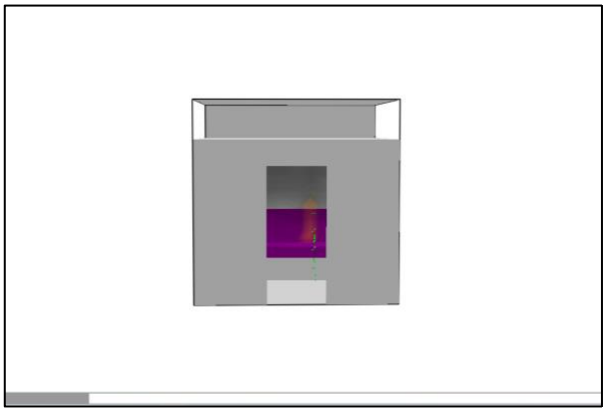

Figure 0.8: Living Room Simulation 120 Seconds

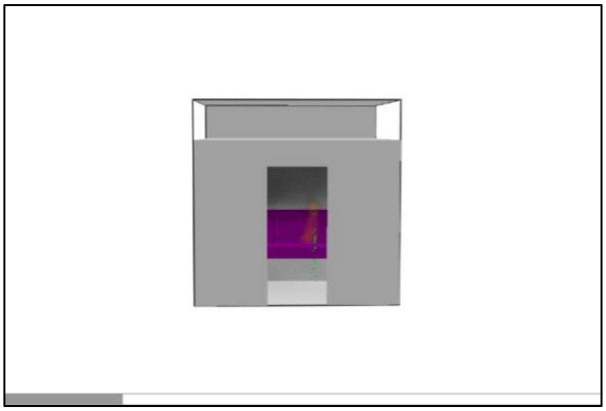

Figure 0.9: Living Room Simulation 150 Seconds

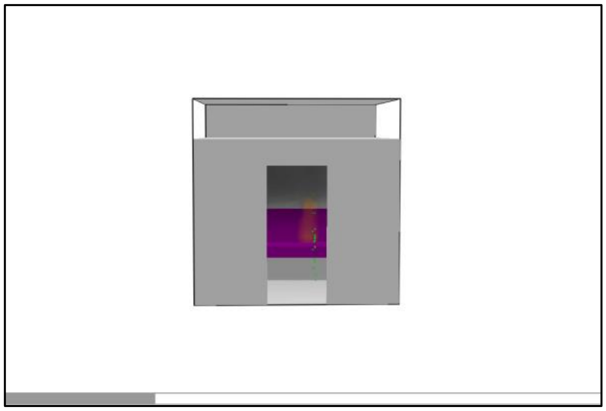

Figure 0.10: Living Room Simulation 180 Seconds

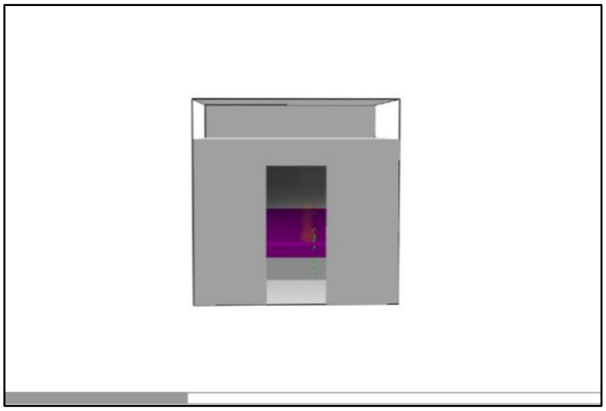

Figure 0.11: Living Room Simulation 210 Seconds

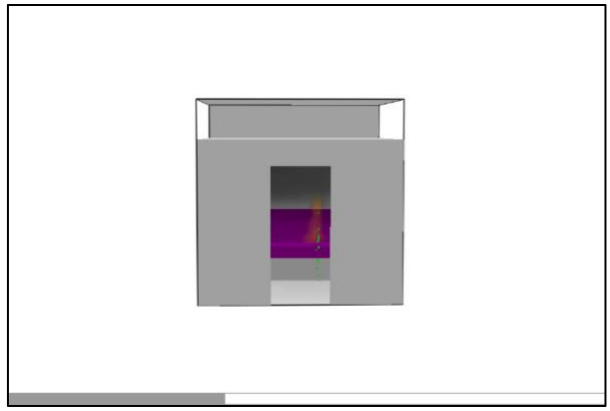

Figure 0.12: Living Room Simulation 240 Seconds

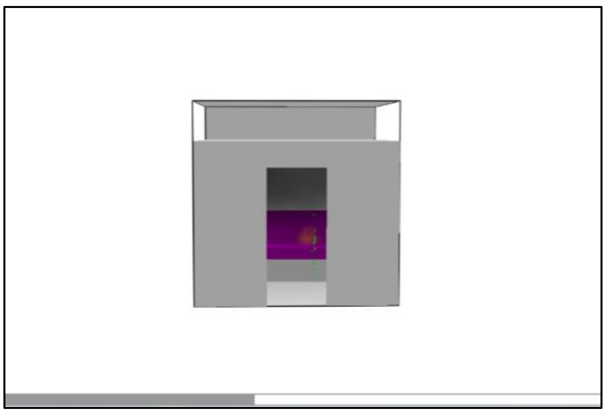

Figure 0.13: Living Room Simulation 270 Seconds

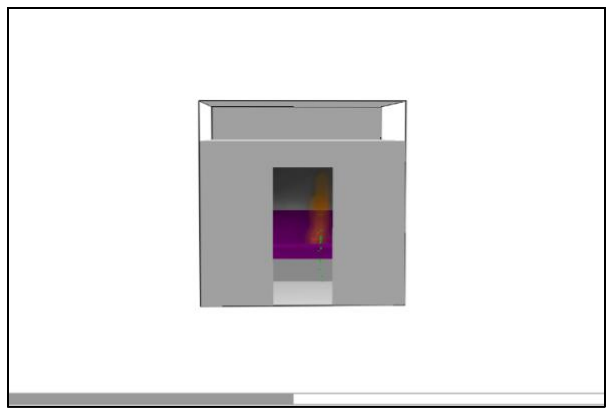

Figure 0.14: Living Room Simulation 300 Seconds

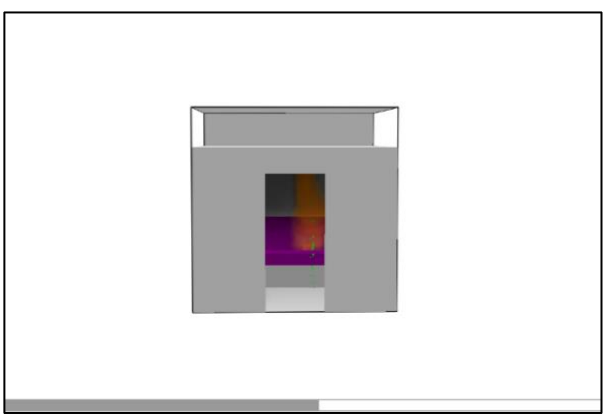

Figure 0.15: Living Room Simulation 330 Seconds

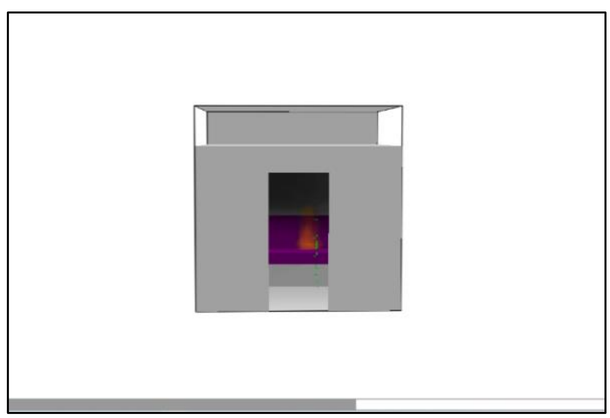

Figure 0.16: Living Room Simulation 360 Seconds

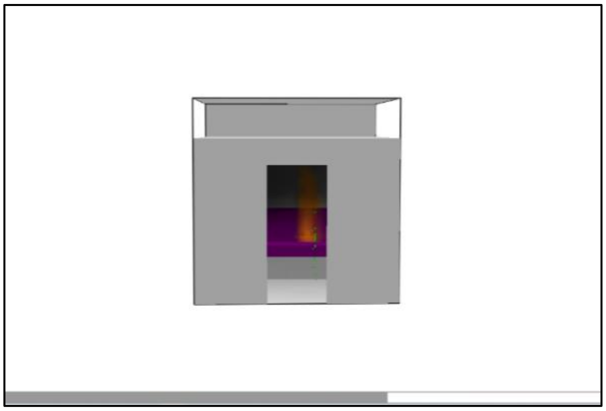

Figure 0.17: Living Room Simulation 390 Seconds

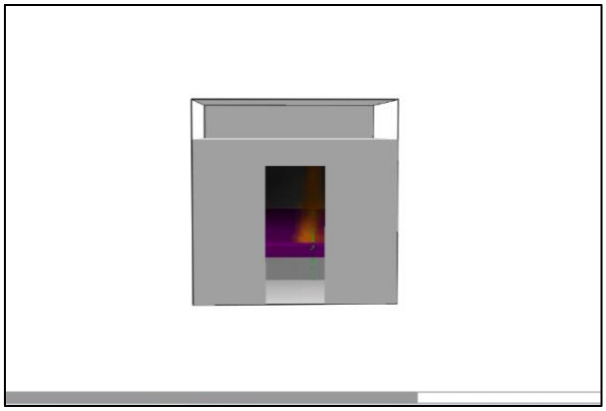

Figure 0.18: Living Room Simulation 420 Seconds

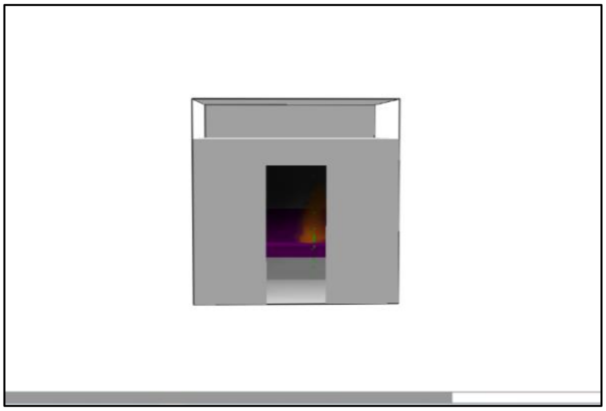

Figure 0.19: Living Room Simulation 450 Seconds

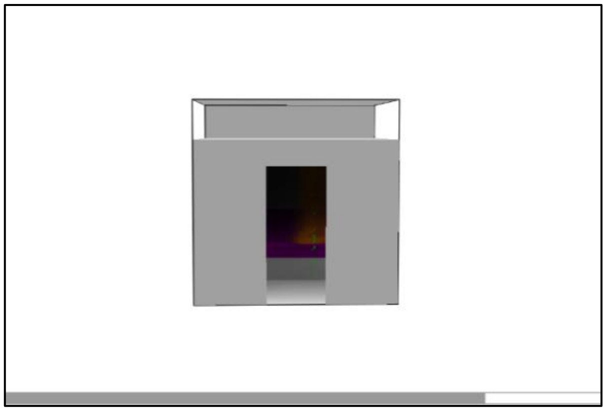

Figure 0.20: Living Room Simulation 480 Seconds

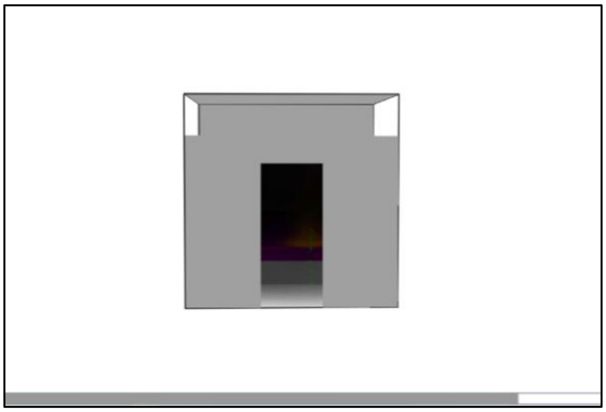

Figure 0.21: Living Room Simulation 510 Seconds

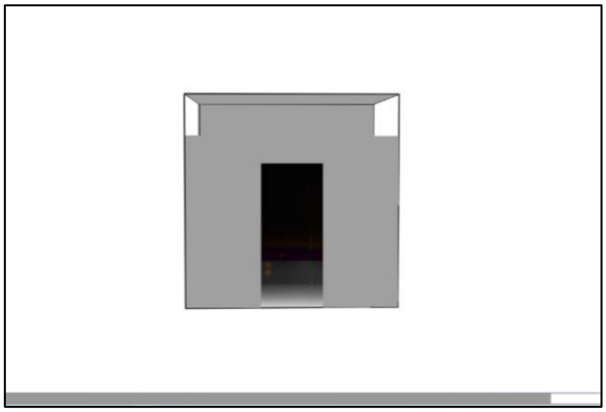

Figure 0.22: Living Room Simulation 540 Seconds

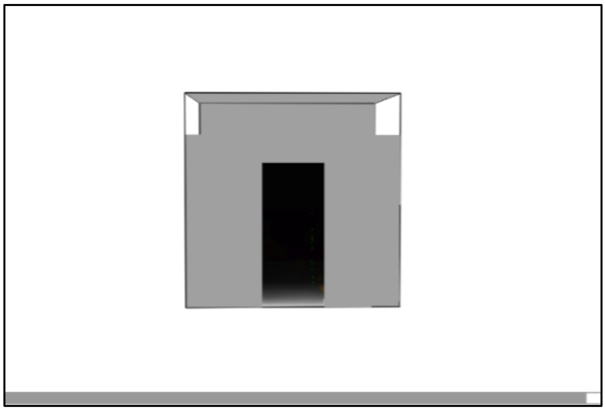

Figure 0.23: Living Room Simulation 570 Seconds

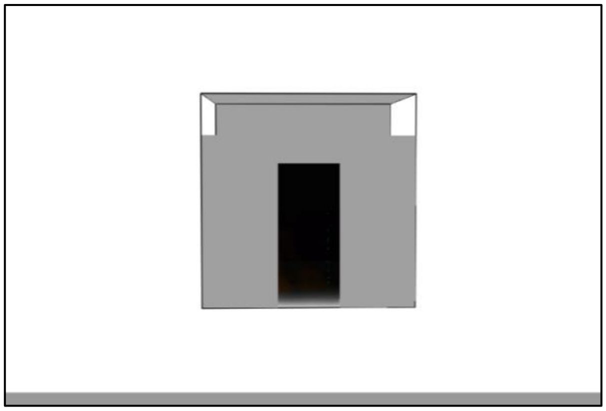

Figure 0.24: Living Room Simulation 600 Seconds

Before the radio positions are analyzed, a virtual thermocouple tree was installed in the room to track the temperature throughout the space. In addition, the smoke layer height can also be tracked through these devices. Thermocouples were placed at 0.30-meter increments from the floor to the ceiling. Figure 3.25 shows the temperature versus time curve for all the thermocouples in this simulation.

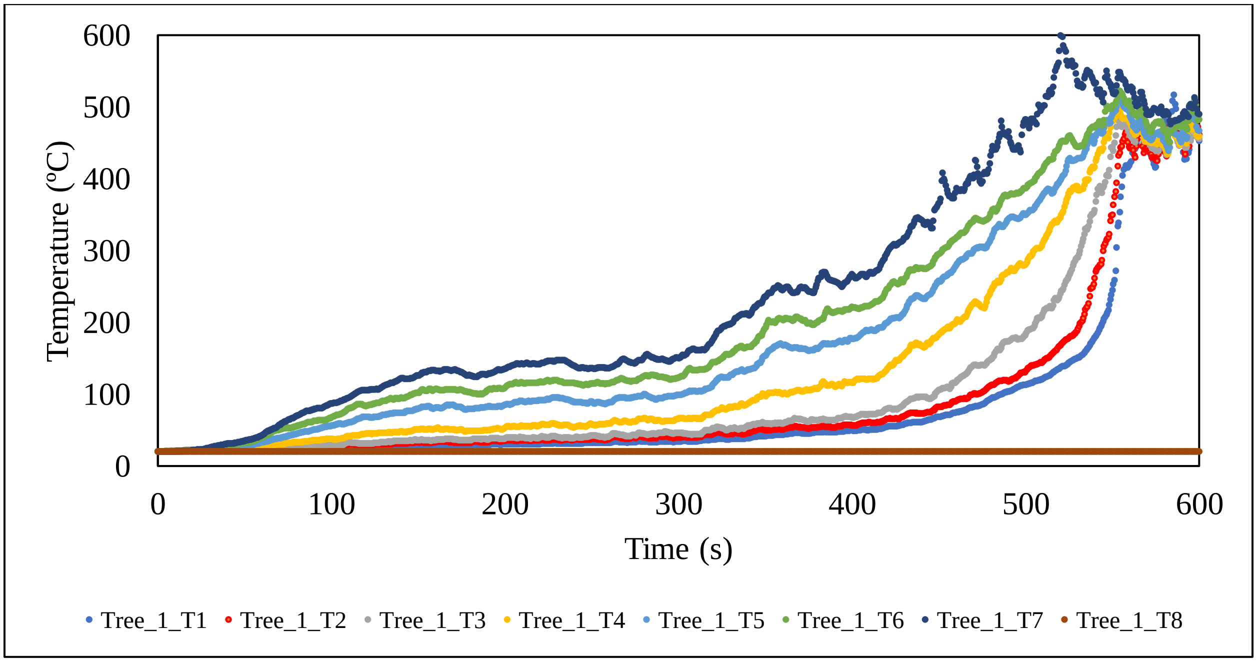

Figure 0.25: Living Room Thermocouple Tree Temperature versus Time Curves

While not labeled in the graph, T1 represents the thermocouple 0.30 meters above the floor, T2 measures 0.61 meters above the floor, and so forth.

From this analysis, the smoke layer depth versus time can be measured. To determine this value from the temperatures obtained from the thermocouple data, some equations will first need to be solved. More information can be found in the referenced Atrium Smoke Control Thesis [1]. First, the convective portion of the heat release rate is needed. This value can be found in the FDS generated HRR [Heat Release Rate] file as is shown below as $\dot{Q}_c$. This quantity can be plugged into Equation 1 below to determine the limiting elevation, shown below as z_1. Figure 3.26 is also below showing this calculated quantity.

$$z_1 = 0.166\dot{Q}_c^{2/5} \tag{1}$$

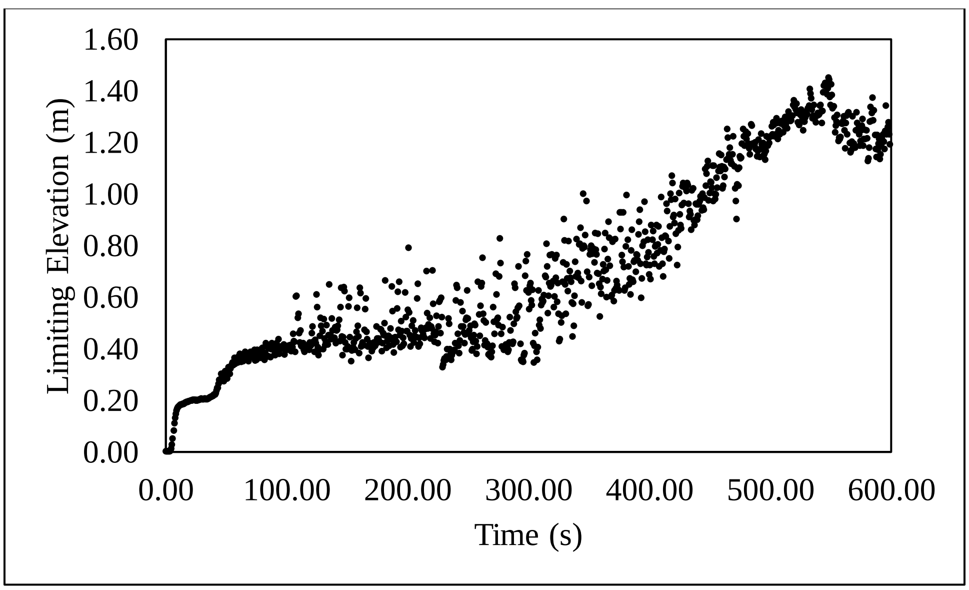

Figure 0.26: Living Room Simulation Limiting Elevation

With this limiting elevation, the axisymmetric mass flow rate can be calculated using Equation 2 below. While there are two possible equations that can be used to calculate this quantity, Equation 2 is presented below as the height to the base of the smoke layer exceeds the limiting elevation for much of the simulation. However, near the end of the smoke layer descent, the limiting elevation exceeds the smoke layer height. Therefore, Equation 3 is presented below to chronicle the mass flow rate after this time. This point was identified as 164 seconds. Figure 3.27 below also shows these variations with time and the equation alteration.

$$\dot{m}_p = 0.071\dot{Q}_c^{1/3}z^{5/3} + 0.0018\dot{Q}_c \tag{2}$$

$$\dot{m}_p = 0.032\,\dot{Q}_c^{1/3}z \tag{3}$$

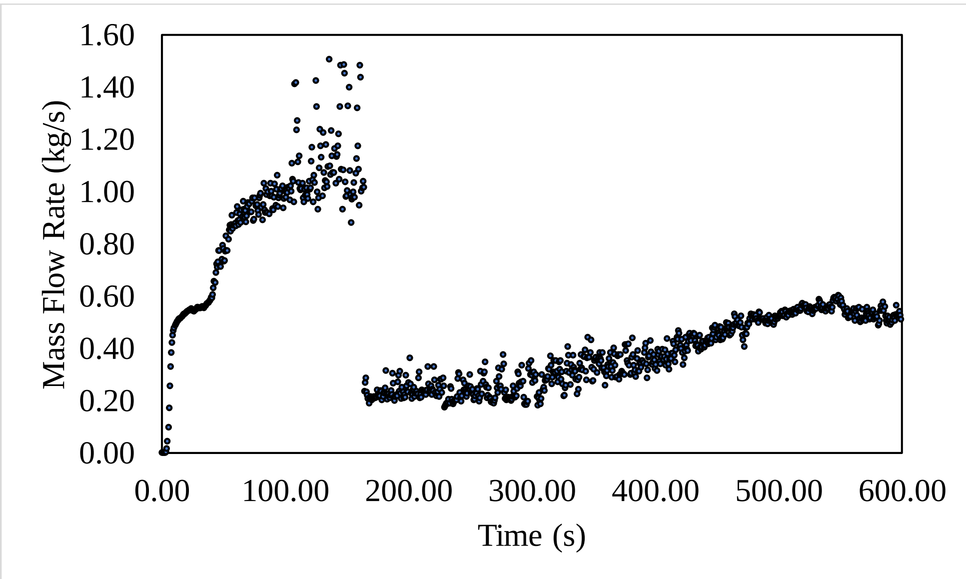

Figure 0.27: Living Room Plume Mass Flow Rate

The final equation that must be solved is to determine the smoke layer temperature. The equation to calculate this value is shown below as Equation 4. Assuming the ambient temperature of 20ºC, Figure 3.28 below shows this smoke layer temperature graph.

$$T_s = T_0 + \frac{K\dot{Q}_c}{\dot{m}_p c_p} \tag{4}$$

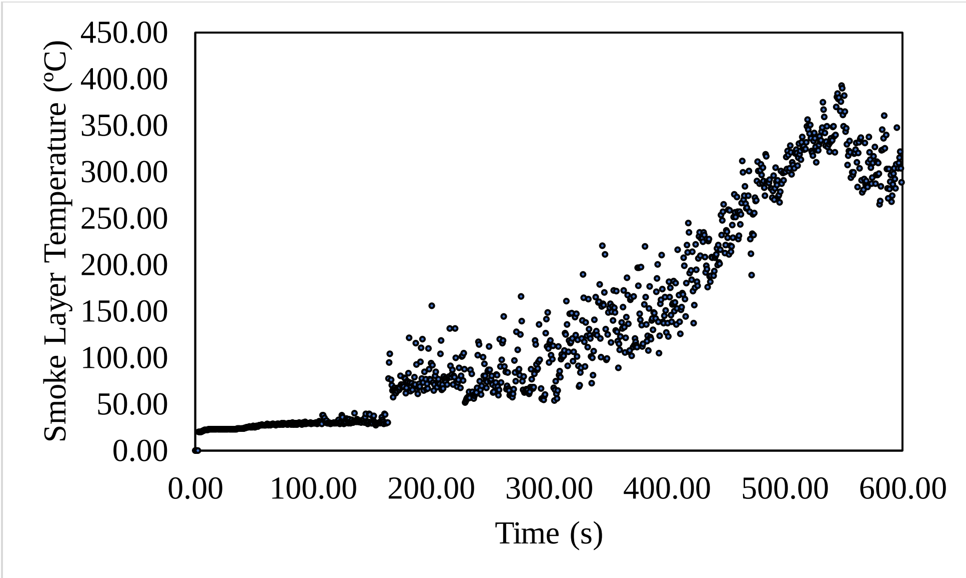

Figure 0.28: Living Room Smoke Layer Temperature

With this temperature, the smoke layer interface temperature can now be calculated. Equation 5 below calculates for this interface temperature and Figure 3.29 below shows a graph of this analysis.

$$T_n = C_n(T_{max} - T_b) + T_b \tag{5}$$

Where:

T_n= Smoke layer Interface Height Temperature (ºC)

T_{max}= Smoke Layer Temperature (ºC)

C_n= Smoke Layer Interface Constant (0.85)

T_b= Lower Layer Temperature (ºC)

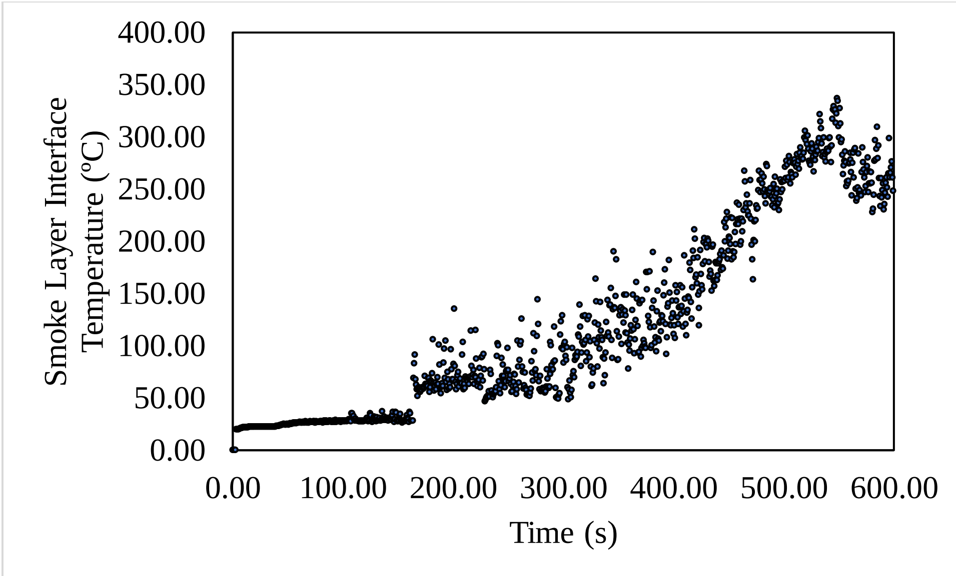

Figure 0.29: Bedroom Simulation Smoke Layer Interface Temperature

Finally, the smoke layer height can be calculated. Because both the smoke layer and the measured thermocouple temperatures changed, an effort was made to decrease the sensitivity of each individual measurement. Therefore, to determine the smoke layer height, five consecutive thermocouple measurements had to exceed this interface height. These findings are shown below as Figure 3.30.

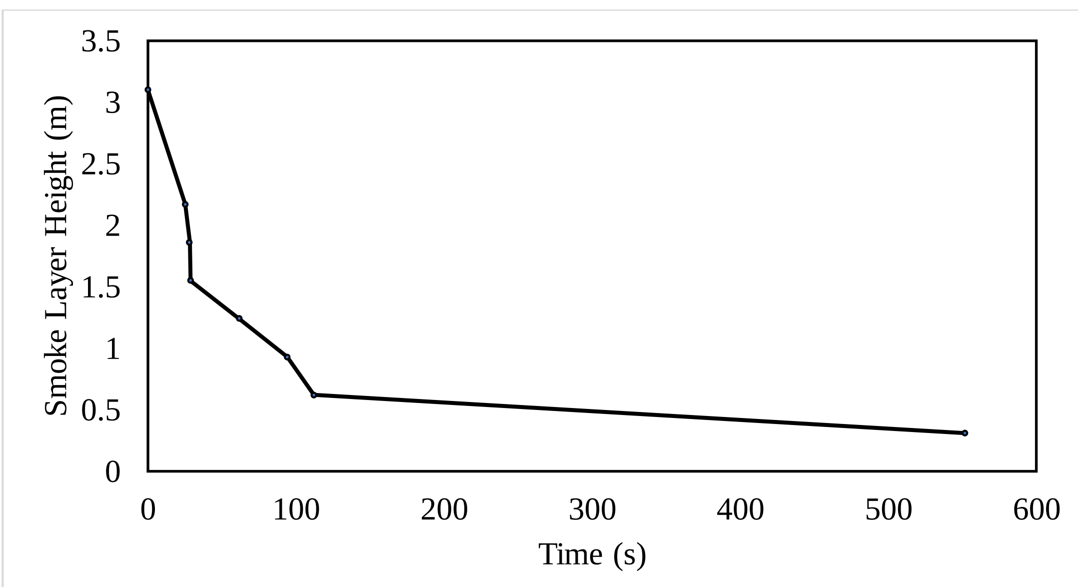

Figure 0.30: Living Room Smoke Layer Height

The final analysis conducted before reaching the heat flux for each individual firefighter is the heat release rate of the couch. While the couch presented at the beginning of this section was for the example case without any ventilation, the heat release rate curve presented below as Figure 3.31 is for the room that was modeled for this analysis. This graph also shows the heat release rate from the example simulation. The curves report similar curves, but the heat release rate data decreases at the end of the curve presented below. This is likely due to the decreased ventilation available in the compartment as it moves closer to flashover.

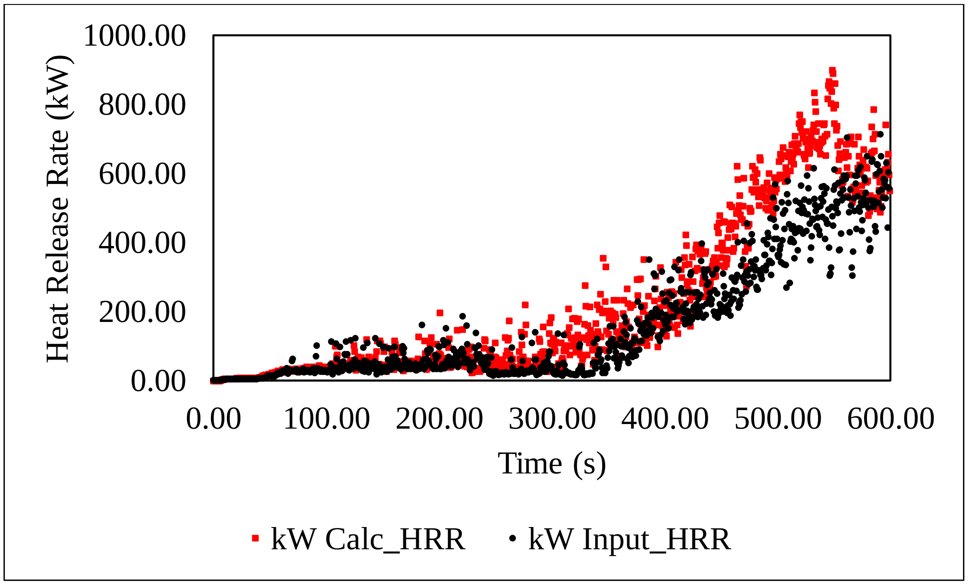

Figure 0.31: Living Room Simulation Heat Release Rate Curve

The heat flux versus time graphs for each of the firefighters is presented in Figures 3.32 through 3.34. Figure 3.27 shows the differences between a crawling and a standing Firefighter 1, Figure 3.39 shows the difference between a crawling and a standing Firefighter 2, and so forth. Again, the measurements for each of these firefighters can be found above in Table 3.1.

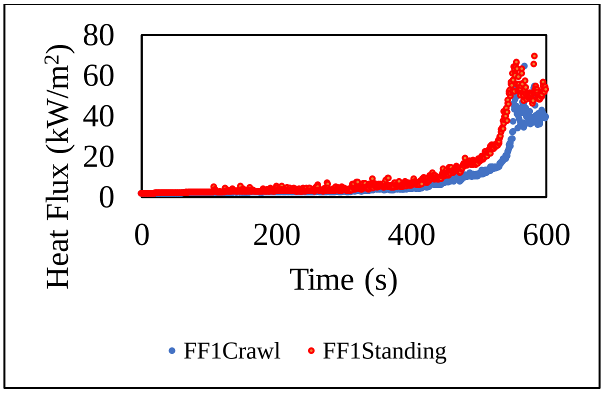

Figure 0.32: Living Room Heat Flux for Firefighter 1

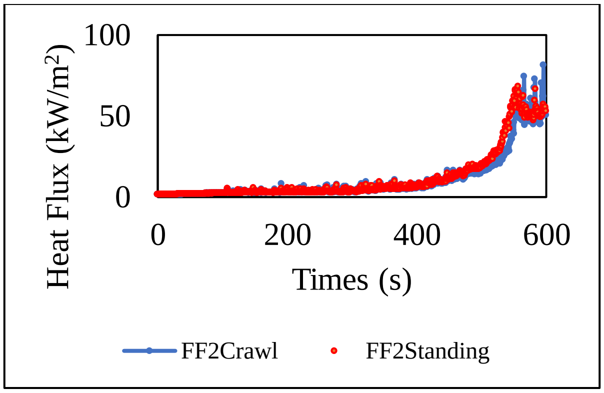

Figure 0.33: Living Room Heat Flux for Firefighter 2

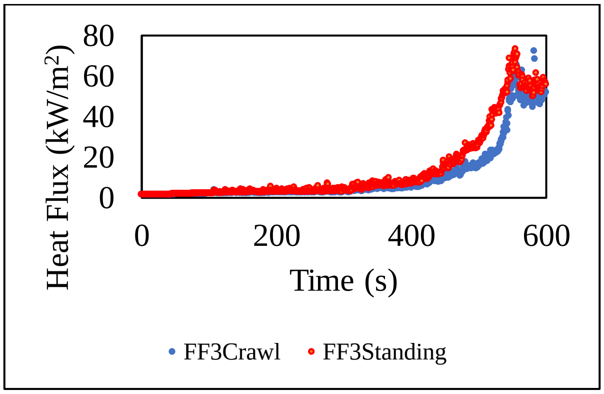

Figure 0.34: Living Room Heat Flux for Firefighter 3

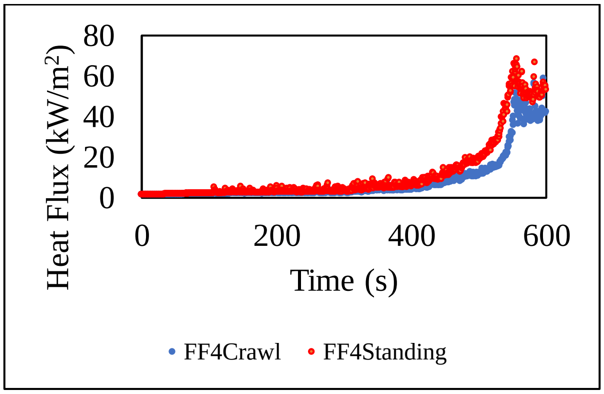

Figure 0.35: Living Room Heat Flux for Firefighter 4

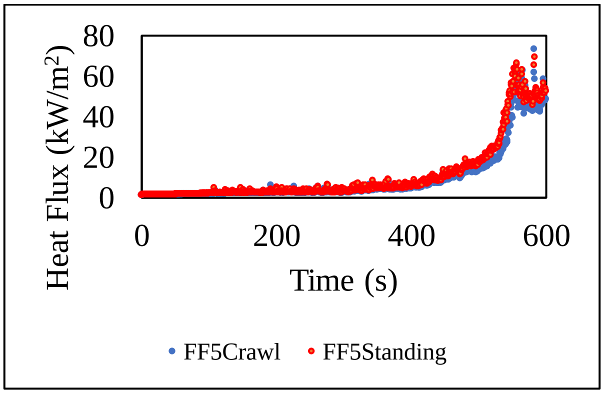

Figure 0.36: Living Room Heat Flux for Firefighter 5

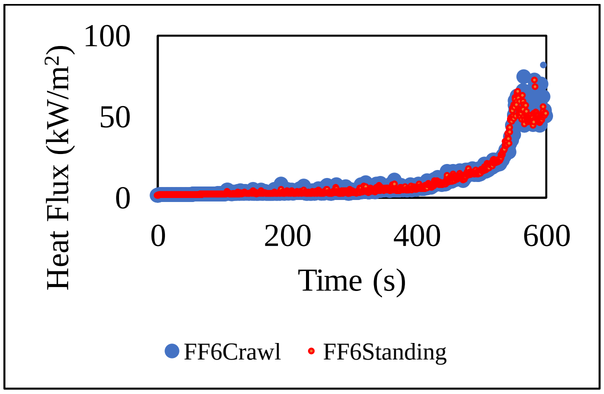

Figure 0.37: Living Room Heat Flux for Firefighter 6

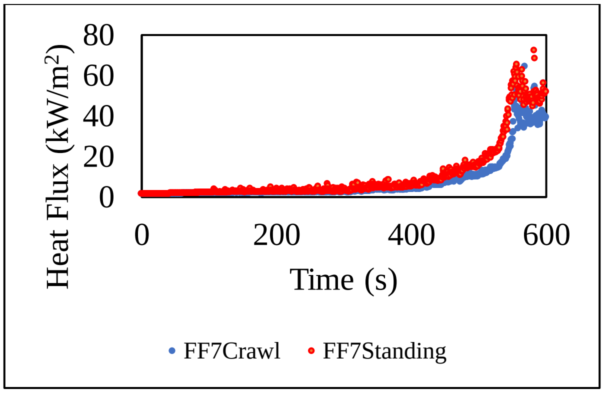

Figure 0.38: Living Room Heat Flux for Firefighter 7

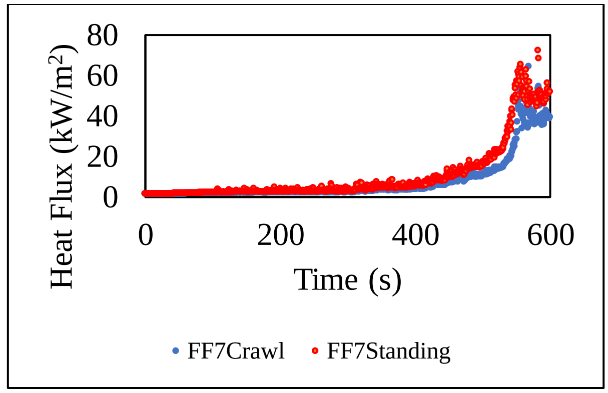

Figure 0.39: Living Room Heat Flux for Firefighter 8

Also, to approximate the heat fluxes that would be used for testing, efforts were taken to conduct hand calculations using previously determined equations. While many of these equations were designed for pool fires, an analysis was also conducted for both simulations. Also, because the cases are much simpler than the analysis for a solid fuel package, a simplified equation could be drawn. These equations can all be found in both the *SFPE Handbook of Fire Protection Engineering*'s Fifth Edition [16] and in *Fire Dynamics*'s Second Edition [14]. Both references can be found in the References Section of this report for further information. Starting with an empirical equation, Equation 6 was used.

$$\dot{q}'' = 15.4(\frac{D_t+0.5D_p}{D_p})^{-1.59} \quad (6)$$

Where:

D_t is the distance from the fire to the source (m) D_p is the pool diameter (m)

Also, before Equation 6, Equation 7 is used to determine the applicability of this test.

$$0.7 < \frac{(D_t+0.5D_p)}{D_p} \quad (7)$$

Using the firefighters' distances from the couch in the FDS input file as the D_t value, and the width of the couch as the D_p value, equation 2 was calculated. All calculations were found to be within this suitable range. From this data, Equation 1 was calculated. The findings for this living room analysis can be found below in Table 3.3. However, it is important to note that before the final heat fluxes can be determined, a safety factor of 2.0 is to be applied [14]. Therefore, the final heat fluxes are determined in the farthest right column of the table.

Table 0.3: Living Room Simulation Equation 6 Analysis for Radiative Heat Flux

Simulation Firefighter	Distance to Fire (D_t) (m)	Calculated Heat Flux ($^{kW}/_{m^2}$)	Calculated Heat Flux with Safety Factor ($^{kW}/_{m^2}$)
Crawling Firefighter 1	1.60	3.6	7.2
Crawling Firefighter 2	1.10	5.7	11.3
Crawling Firefighter 3	1.35	4.4	8.9
Crawling Firefighter 4	1.60	3.6	7.2
Crawling Firefighter 5	1.35	4.4	8.9
Crawling Firefighter 6	1.10	5.7	11.3
Crawling Firefighter 7	1.60	3.6	7.2
Crawling Firefighter 8	1.10	5.7	11.3
Standing Firefighters	1.35	4.4	8.9

The standing firefighter heat fluxes would appear to be a bit lower than expected with the crawling firefighter's heat flux would appear to be a bit higher. This is due to the firefighter's proximity to the burning fuel package. Firefighters wearing a radio strap were positioned further from the fire than those wearing their radios in the turnout gear pocket. This is also based on the wearer's preferred method of crawling. Firefighters who prefer to crawl in a tripod stance will have their radios lower to the ground, which is not accounted for in these calculations.

The next hand calculation analysis that was conducted is the point source radiation model. Again, many of the same parameters from Equation 6 above are presented again here, but this model does account for the heat release rate of the fuel package. Therefore, the peak heat release rate was used. The same pool diameter, taken as the width of the couch, was used in this analysis. This equation is presented below as Equation 8.

$$\dot{q}''_{rad} = \frac{X_r \dot{Q}}{4\pi(D_t + 0.5D_p)^2} \quad (8)$$

Where:

X_r is the Radiative Fraction of the Fire

$\dot{Q}$ is the Peak Heat Release Rate (kW)

However, as with the previous equation set, Equation 8 cannot be used before calculations are conducted for the X_r value. The calculation provided for this equation is shown below as Equation 4.

$$X_r = 0.21 - (0.0034D_p) \quad (9)$$

Using the same pool diameter, the 0.8m couch diameter, the X_r value is found to be 0.207. Additionally, the peak heat release rate is calculated through the heat of combustion. The heat of combustion from the input file, multiplied by the density found in the input file, divided by the total simulation time, and multiplied by the volume of the couch produced a value of 1568 kW. Now, using these values to determine the Equation 8 calculations, Table 3.4 is produced.

Table 0.4: Living Room Simulation Equation 8 Analysis for Radiative Heat Flux

Simulation Firefighter	Distance to Fire (D_t) (m)	Calculated Heat Flux (kW/m^2)
Crawling Firefighter 1	1.6	6.5
Crawling Firefighter 2	1.1	11.5
Crawling Firefighter 3	1.4	8.4

Crawling Firefighter 4	1.6	6.5
Crawling Firefighter 5	1.4	8.4
Crawling Firefighter 6	1.1	11.5
Crawling Firefighter 7	1.6	6.5
Crawling Firefighter 8	1.1	11.5

From this analysis, the standing heat flux is $8.43\ {}^{kW}/_{m^2}$ while the average heat flux for crawling firefighters is $8.84 \pm 0.83\,{}^{kW}/_{m^2}$. Again, these values would appear to be more appropriate. Additionally, because this equation uses a heat release rate in its determinations, it should be considered more accurate than the previous equation.

An analysis was also made of the temperatures received at the radio via the virtual thermocouples. This analysis was undertaken to equate the modeled environment with the NIST 1477 and NFPA 1802 processes. As shown with the heat flux versus time graphs above, the temperatures were also measured for each firefighter. Figure 3.40 shows this data for Firefighter 1, Figure 3.41 for Firefighter 2, and so forth. Again, it should be noted that these temperatures were the air temperatures where the radios would be worn as no protective equipment was prescribed for this experiment.

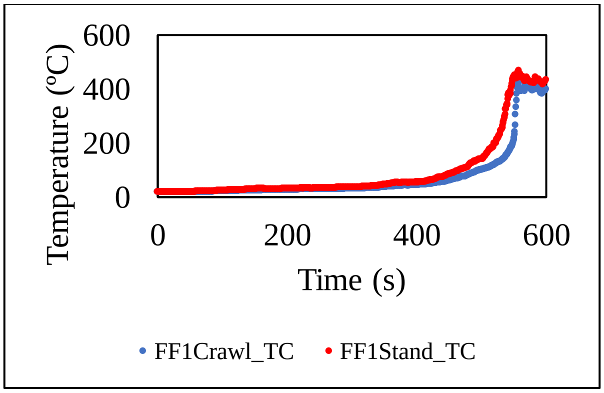

Figure 0.40: Living Room Temperature versus Time for Firefighter 1

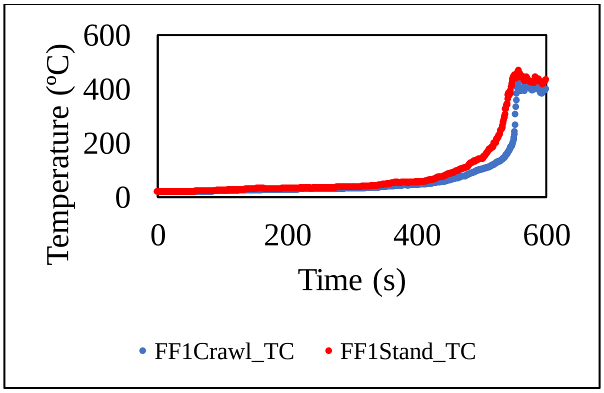

Figure 0.41: Living Room Temperature versus Time for Firefighter 1

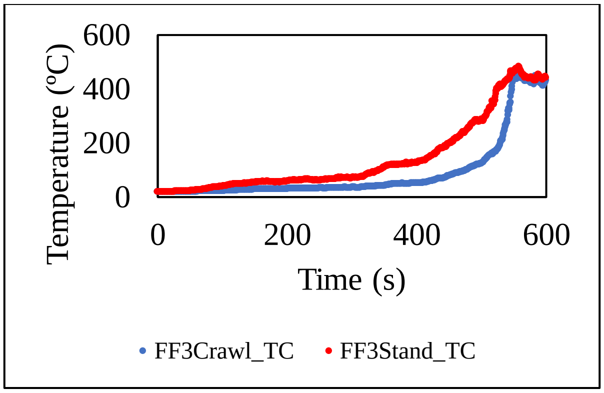

Figure 0.42: Living Room Temperature versus Time for Firefighter 3

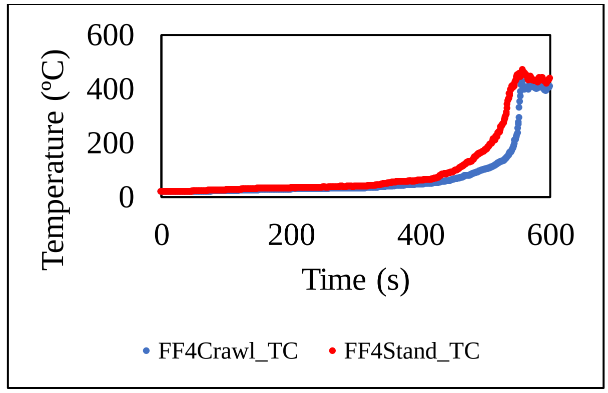

Figure 0.43: Living Room Temperature versus Time for Firefighter 4

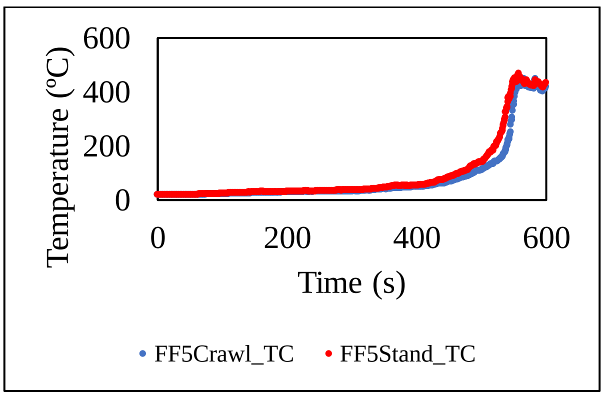

Figure 0.44: Living Room Temperature versus Time for Firefighter 5

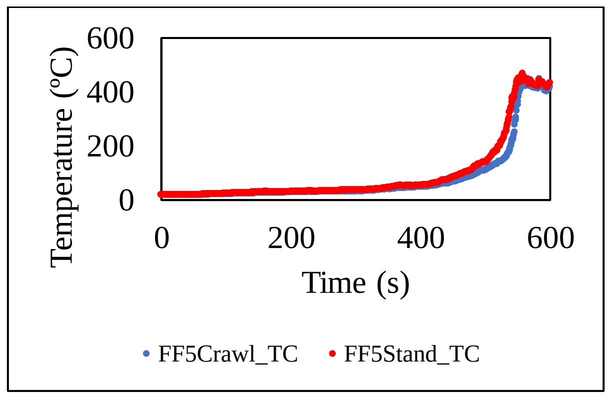

Figure 0.45: Living Room Temperature versus Time for Firefighter 6

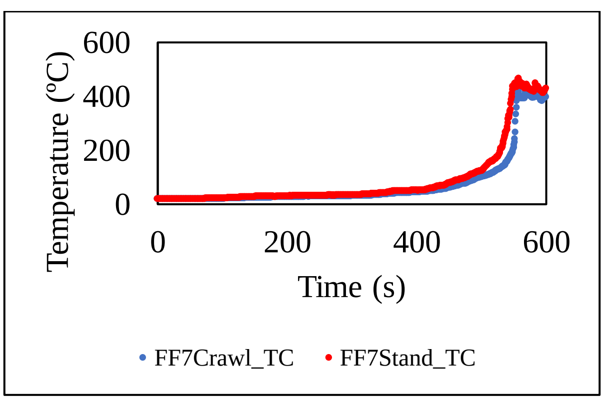

Figure 0.46: Living Room Temperature versus Time for Firefighter 7

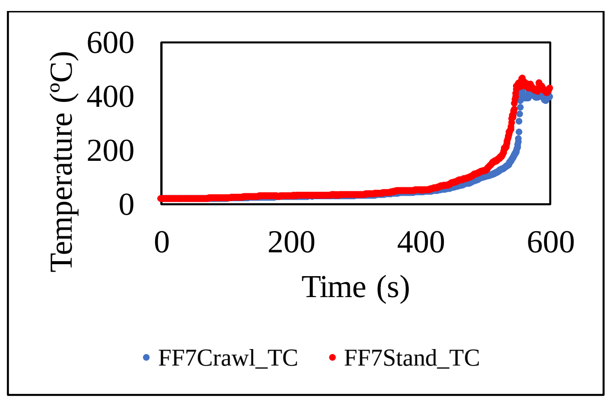

Figure 0.47: Living Room Temperature versus Time for Firefighter 8

Figures 3.48 and 3.49 below show the temperature comparison between a radio strap and radio pocket position.

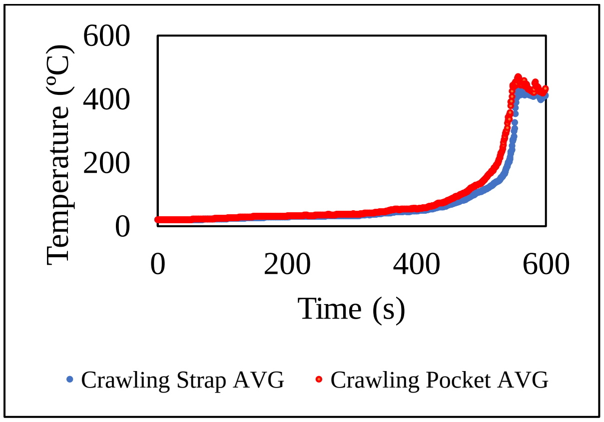

Figure 0.48: Temperatures when Crawling with a Pocket and with a Strap

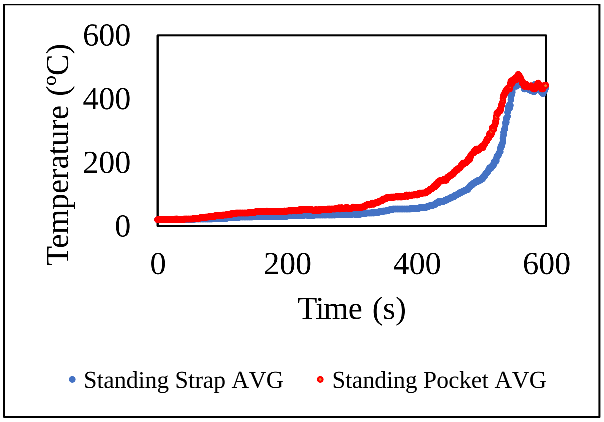

Figure 0.49: Temperatures when Standing with a Pocket and with a Strap

As with the heat flux cases presented above, Figures 3.50 through 3.51 show the comparison of the temperature experienced by a firefighter crawling versus a standing firefighter.

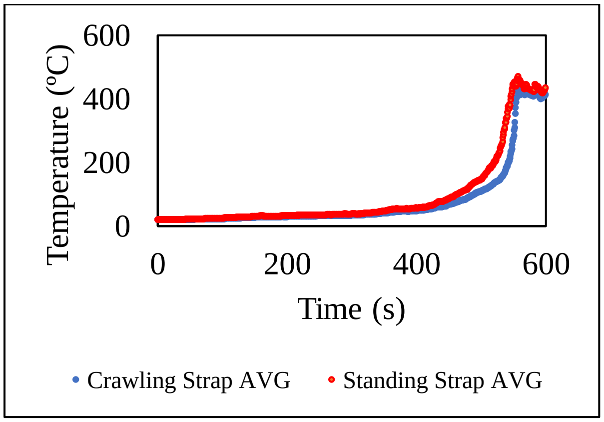

Figure 0.50: Crawling and Standing Temperatures with a Strap

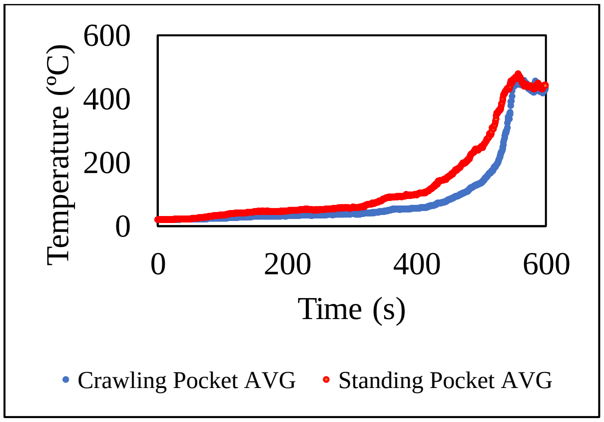

Figure 0.51: Crawling and Standing Temperatures with a Pocket

For this analysis, it can be noted that the temperatures remained relatively close regardless of positioning. This can be attributed to the lack of thermal insulation. While radios worn in the radio pocket are less protected than those worn under the turnout coat, this was not evaluated in this report. Fire departments often specify and purchase turnout gear through a variety of sources and in a variety of styles. Fire departments may have radio pockets sewn in various positions. Generally, the radio pocket is only a layer of the turnout coat outer shell, but some fire departments do have a layer of insulation as well.

1.12.2 Bedroom

The same methodology was conducted as above for a bedroom. A room with a window and a door, as was the case above, was designed with a king-sized mattress. No other furniture or flammable materials were placed in the room. The King-sized mattress was used again as a "worst case" scenario, with a large fuel in the room. Again, the heat flux and temperature that a firefighter could be expected to receive was the focus of this analysis, and therefore the room was left to be just large enough to contain the fuel package as well as the firefighter. The mattress used in this simulation comes from the referenced Boras 2004 Swedish National Testing and Research Institute test that can be found in the University of Maryland Burning Item Database [47], which provided the heat of combustion, which is used to determine the heat release rate, and by extension the heat flux. The heat release rate curve reproduced from this test can be found below as Figure 3.52.

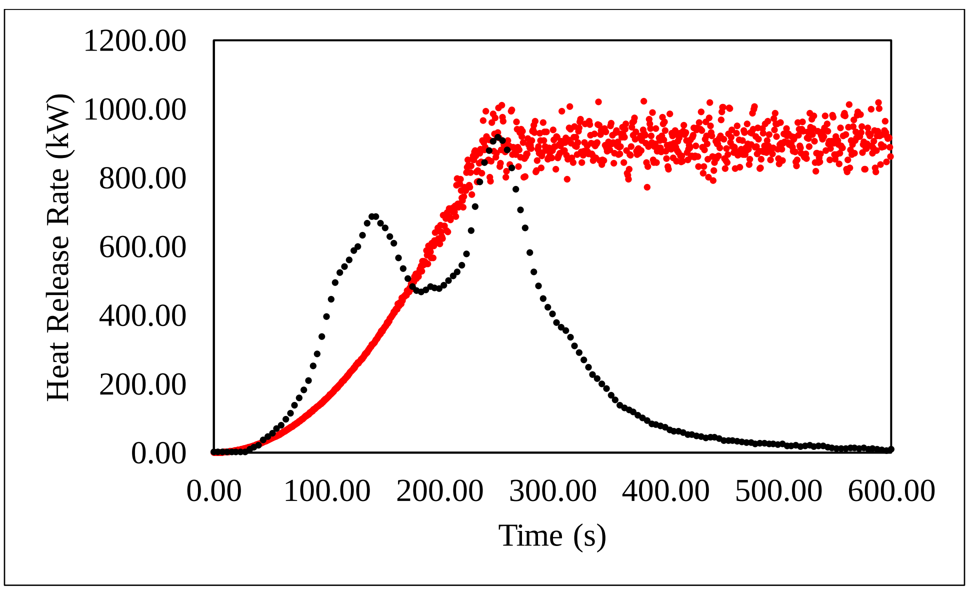

Figure 0.52: Reproduced Heat Release Rate Curve with Simulation Heat Release Rate

While the ventilation arrangement was like the living room simulation, an additional window was added. This window was included to allow for more ventilation, and therefore a higher heat release rate. The inclusion of this additional window was made so that combustion across the larger fuel surface would be possible. Furthermore, a burner was inserted into the simulation, rather than a fuel package symbolic of the mattress itself. This inclusion was made so that heat release rate could be maintained at the levels depicted in the test. Finally, the size of the room was changed to accommodate the larger fuel. Therefore, Figures 3.53 through 3.56 show the external arrangement of the compartment, a view through the door, and an overhead view as with the living room simulation above.

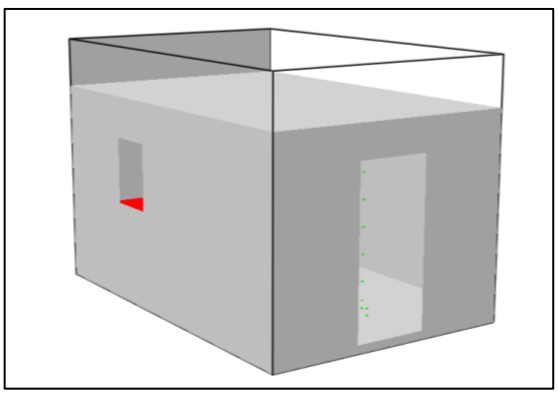

Figure 0.53: Bedroom Simulation Exterior Left Corner View

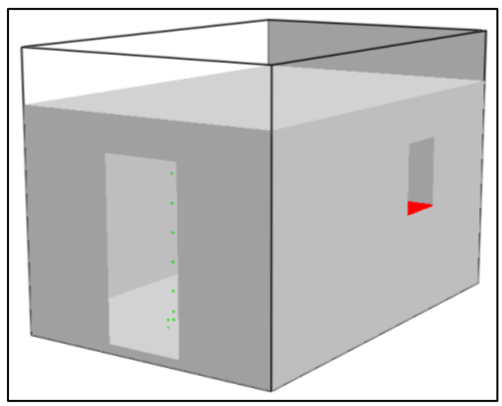

Figure 0.54: Bedroom Exterior Right Corner View

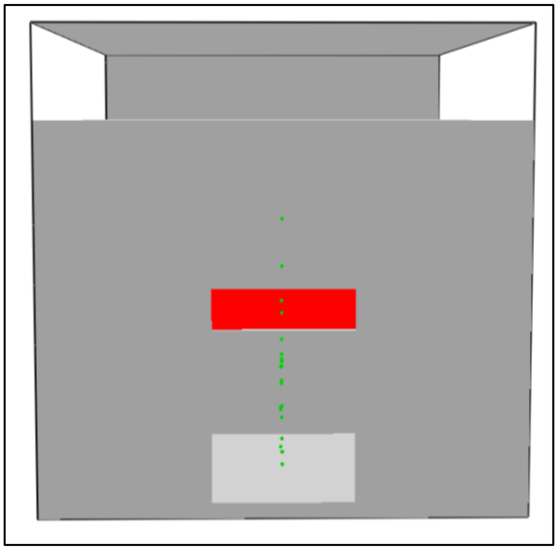

Figure 0.55: Bedroom Door View

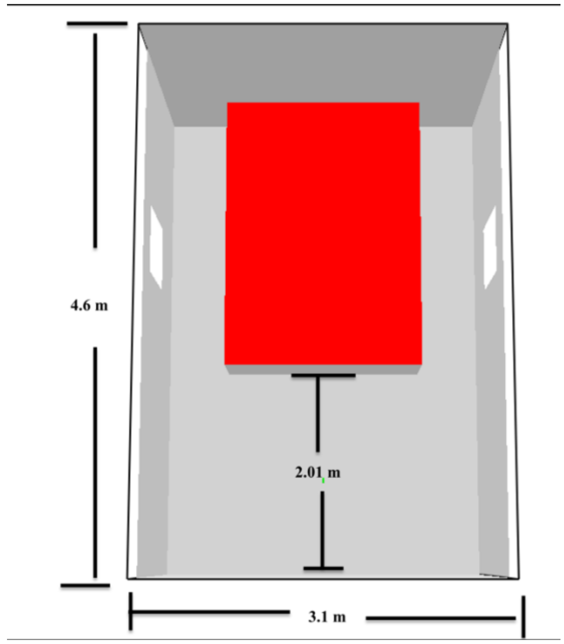

Figure 0.56: Dimensioned Bedroom Simulation Overhead View

As with the examples before, the important material properties used in this simulation are listed below in Table 3.5.

Table 0.5: Bedroom Simulation Important Material Properties

Material	Conductivity $(W/_{m*K})$	Heat of Combustion $(kJ/_{kg})$	Specific Heat $(kJ/_{kg*K})$
Gypsum Plaster	0.84	0.48	N/A

In addition to the screenshots above, screenshots are included below to show the virtual heat and smoke. These begin with Figure 3.57 below at 30 seconds and continue to Figure 3.76 at 600 seconds. These views are shown through the front door, as with the living room simulation above.

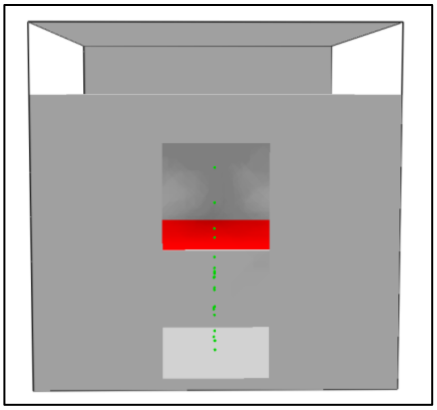

Figure 0.57: Bedroom Simulation 30 Seconds

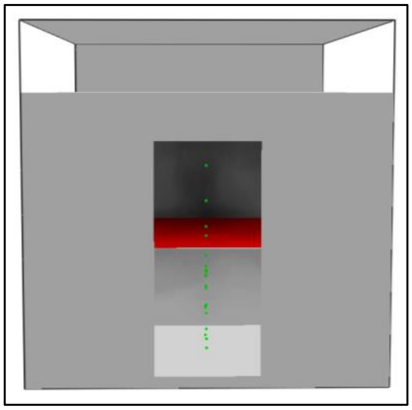

Figure 0.58: Bedroom Simulation 60 Seconds

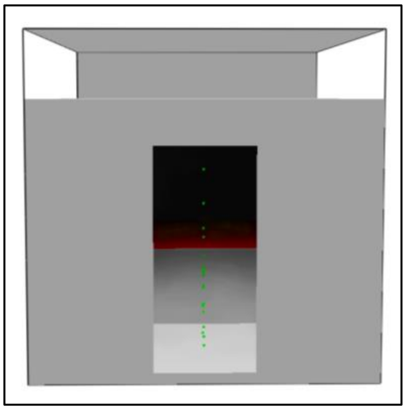

Figure 0.59: Bedroom Simulation 90 Seconds

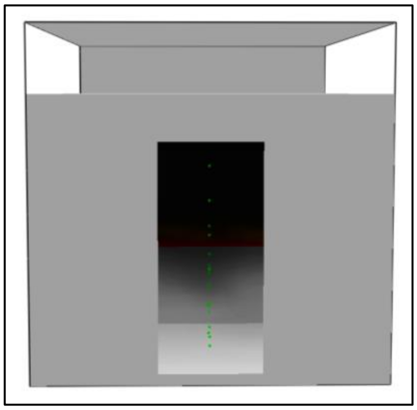

Figure 0.60: Bedroom Simulation 120 Seconds

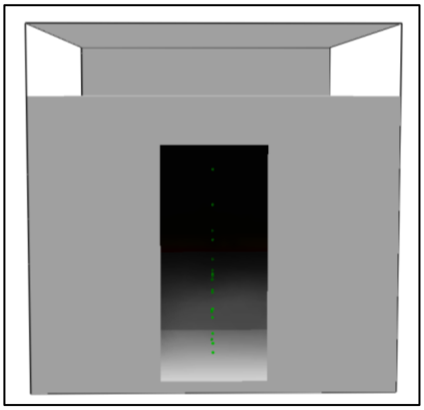

Figure 0.61: Bedroom Simulation 150 Seconds

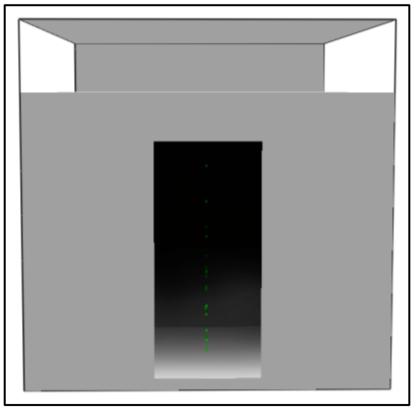

Figure 0.62: Bedroom Simulation 180 Seconds

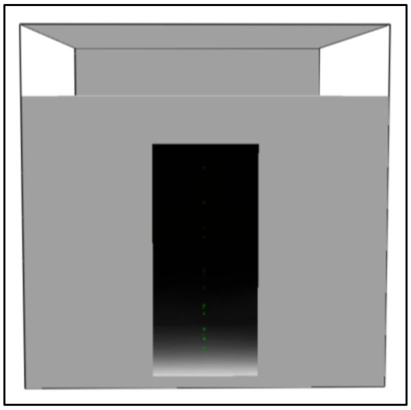

Figure 0.63: Bedroom Simulation 210 Seconds

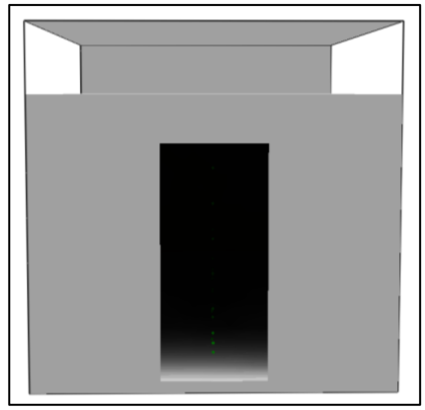

Figure 0.64: Bedroom Simulation 240 Seconds

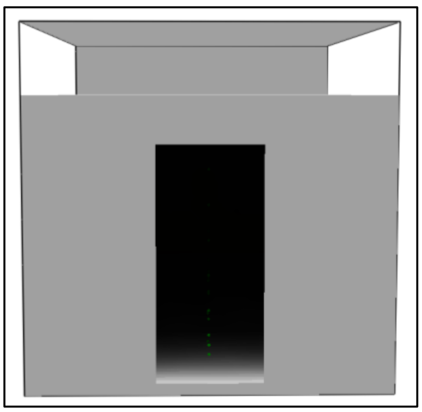

Figure 0.65: Bedroom Simulation 270 Seconds

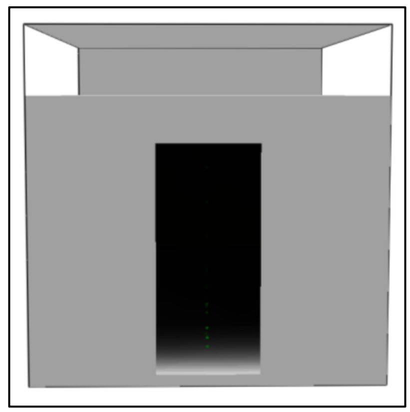

Figure 0.66: Bedroom Simulation 300 Seconds

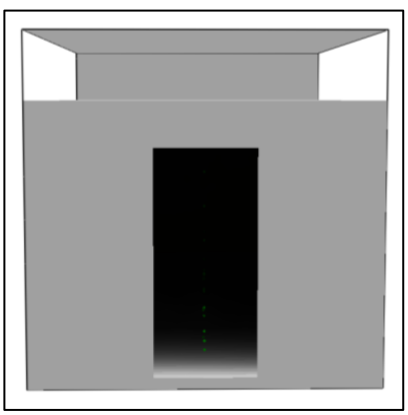

Figure 0.67: Bedroom Simulation 330 Seconds

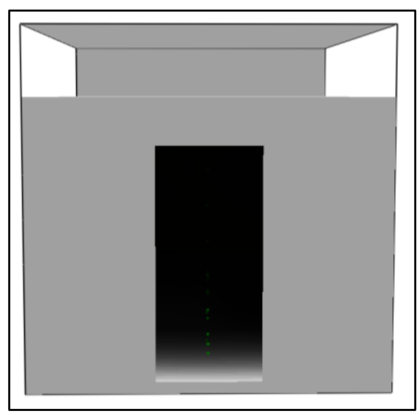

Figure 0.68: Bedroom Simulation 360 Seconds

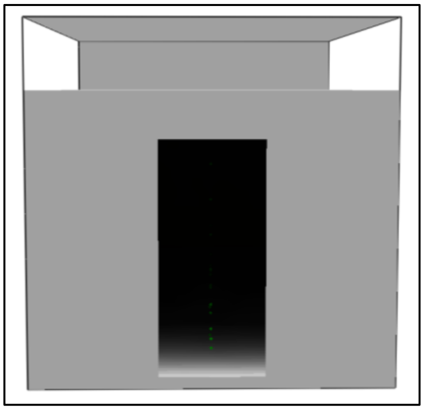

Figure 0.69: Bedroom Simulation 390 Seconds

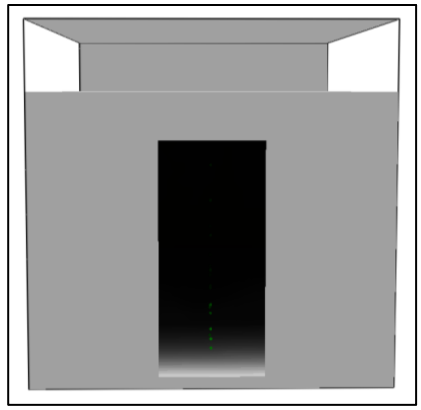

Figure 0.70: Bedroom Simulation 420 Seconds

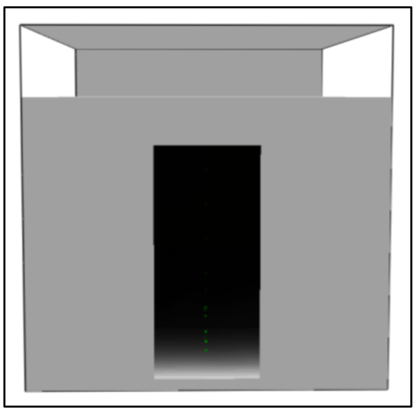

Figure 0.71: Bedroom Simulation 450 Seconds

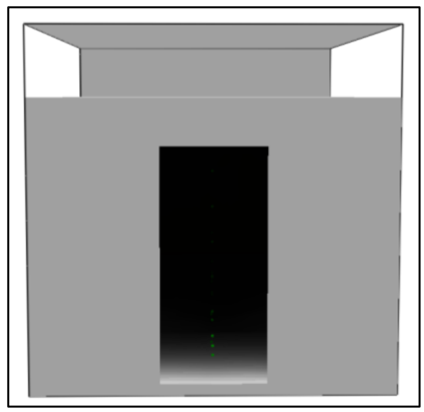

Figure 0.72: Bedroom Simulation 480 Seconds

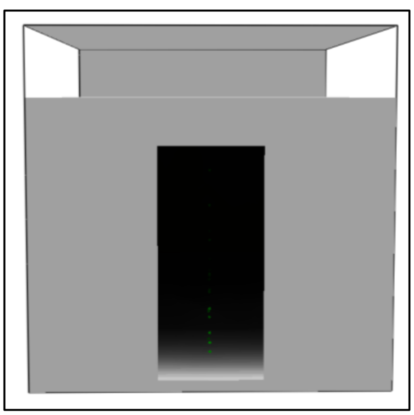

Figure 0.73: Bedroom Simulation 510 Seconds

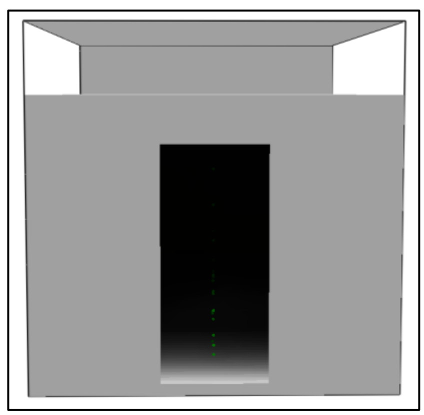

Figure 0.74: Bedroom Simulation 540 Seconds

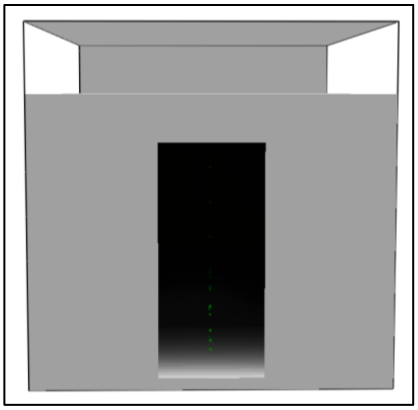

Figure 0.75: Bedroom Simulation 570 Seconds

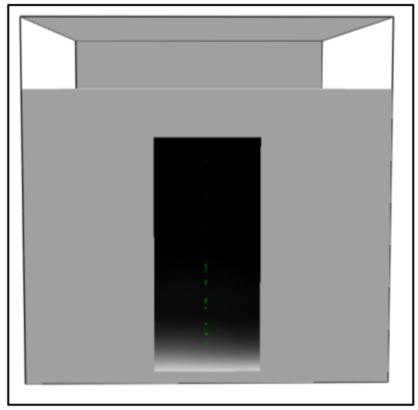

Figure 0.76: Bedroom Simulation 600 Seconds

Again, as conducted earlier the thermocouple tree was placed in the room to determine the temperatures at various points in the room. The thermocouples on this virtual thermocouple tree were also placed 0.30 meters apart. Figure 3.77 below shows a graphical representation of each of these thermocouples in a temperature versus time curve. Again, the T1 thermocouple represents the temperature 0.30 meters from the ground, T2 represents the temperature 0.61 meters from the ground, and so forth.

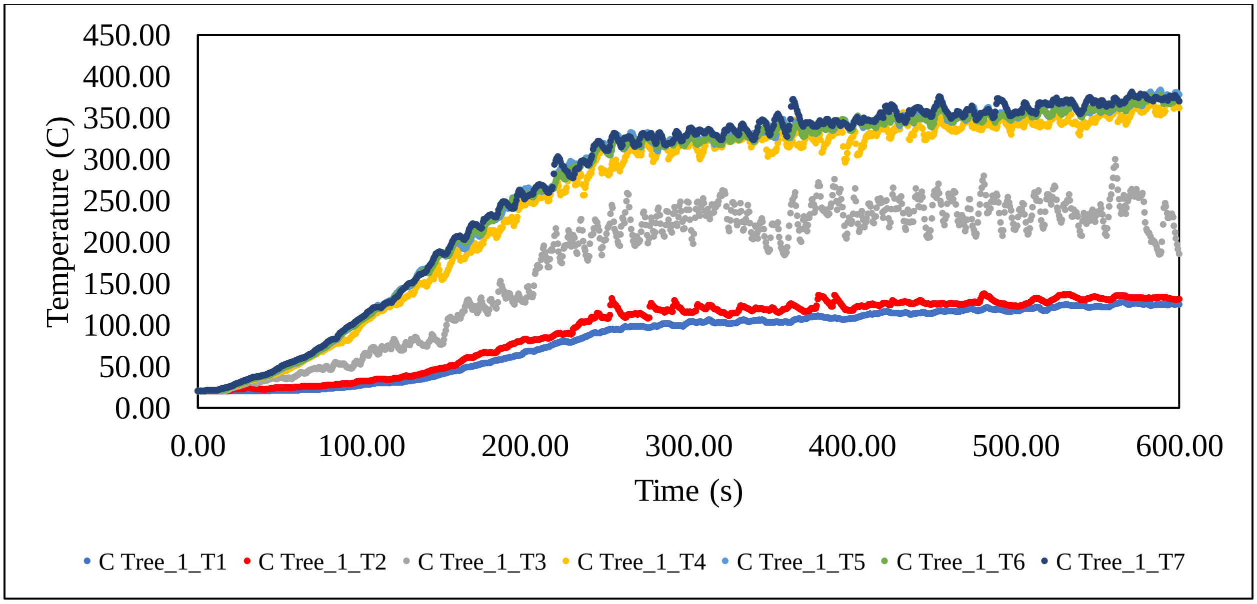

Figure 0.77: Bedroom FDS Simulation Temperature versus Time Curves

Also, the smoke layer heights are presented below in Figures 3.82. Additionally, the same figures that were produced for the living room can be found below as Figures 3.78 through 3.82.

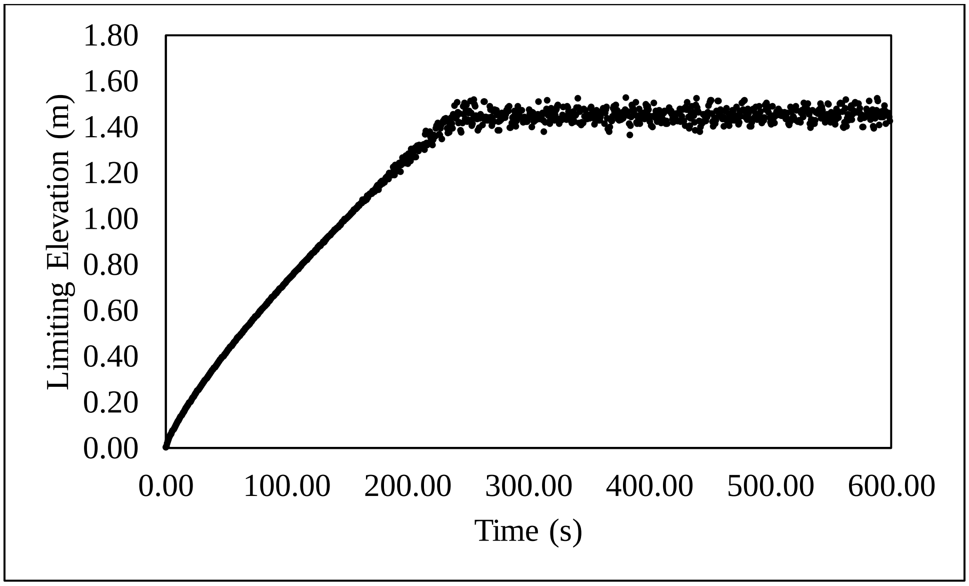

Figure 0.78: Bedroom Simulation Limiting Elevation

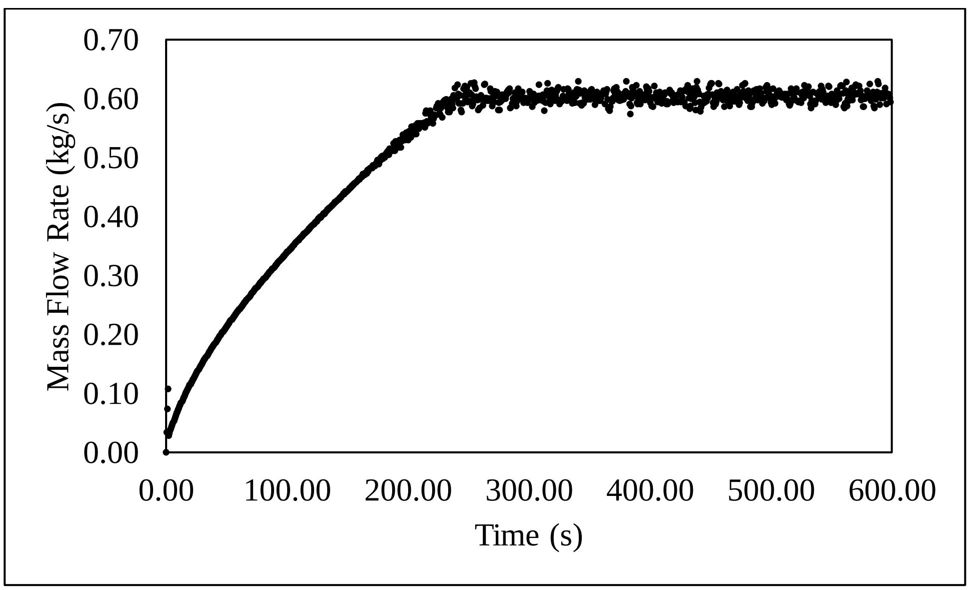

Figure 0.79: Bedroom Simulation Mass Flow Rate

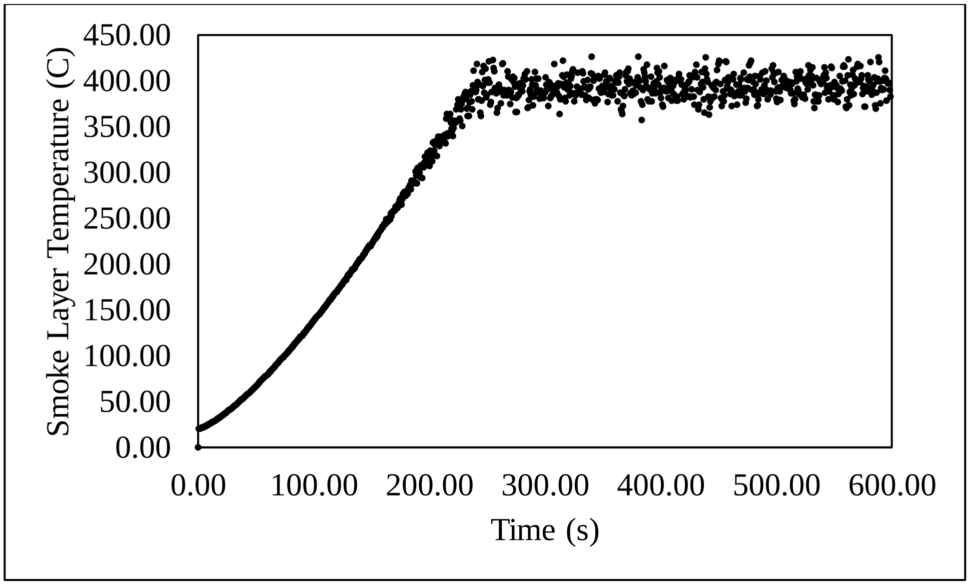

Figure 0.80: Bedroom Smoke Layer Temperature

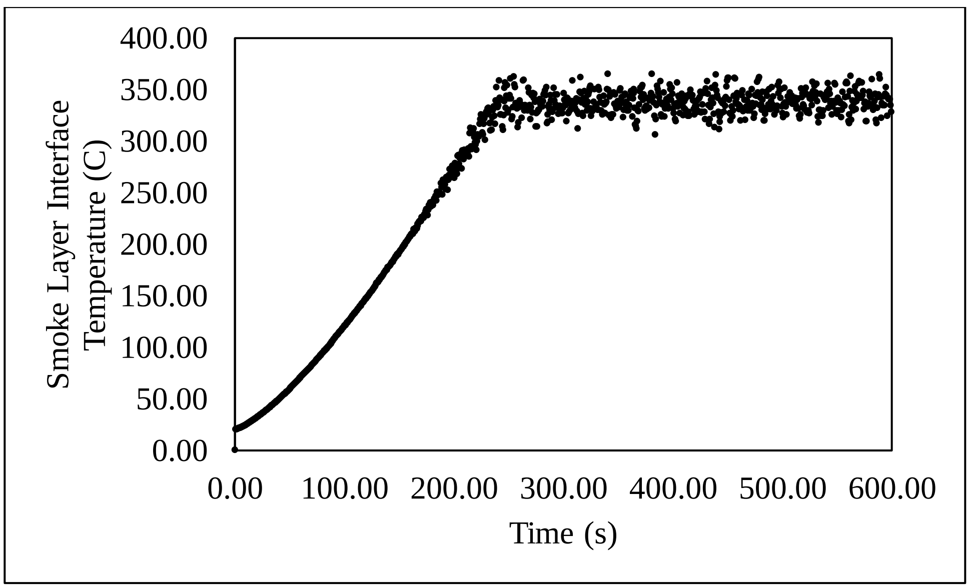

Figure 0.81: Bedroom Smoke Layer Interface Temperature

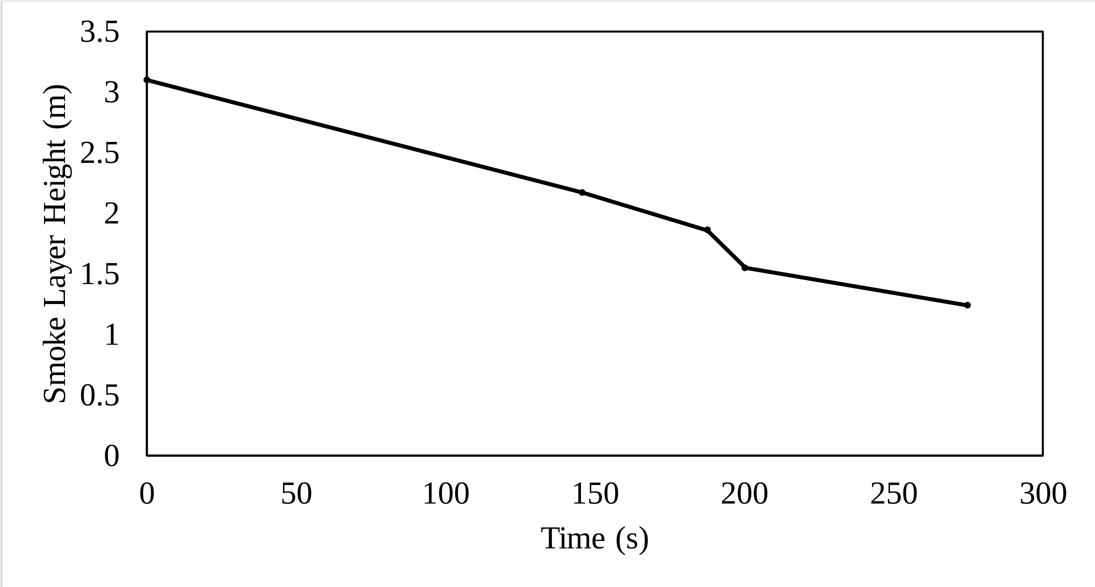

Figure 0.82: Bedroom Simulation Smoke Layer Height from Temperature Data

The heat flux versus time graphs are also found below for each firefighter. Again, Figure 3.83 shows the differences between crawling and standing Firefighter 1, Figure 3.84 shows these differences for Firefighter 2, and so forth.

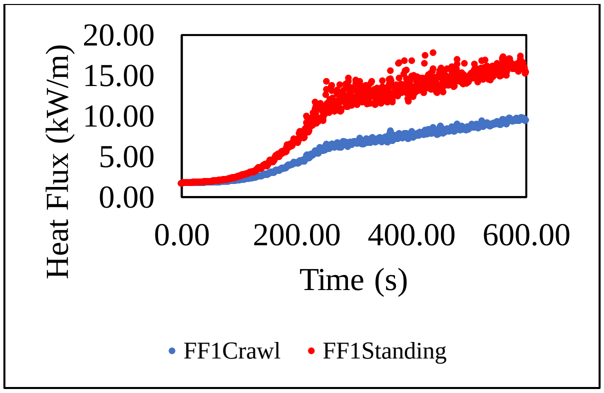

Figure 0.83: Bedroom Heat Flux versus Time for Firefighter 1

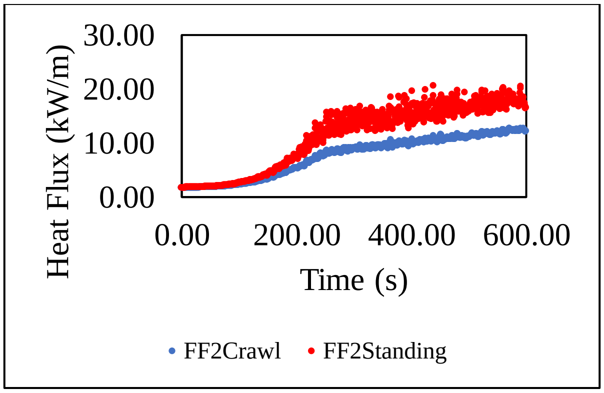

Figure 0.84: Bedroom Heat Flux versus Time for Firefighter 2

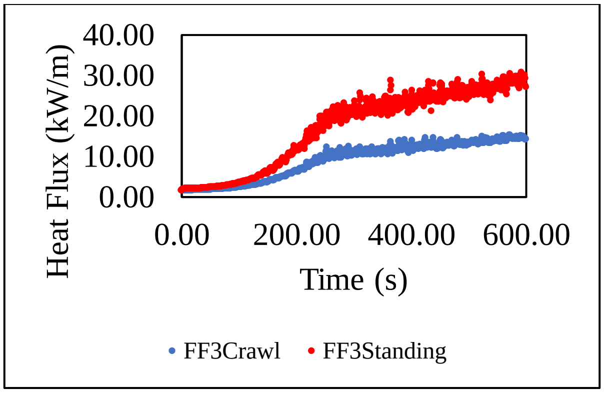

Figure 0.85: Bedroom Heat Flux versus Time for Firefighter 3

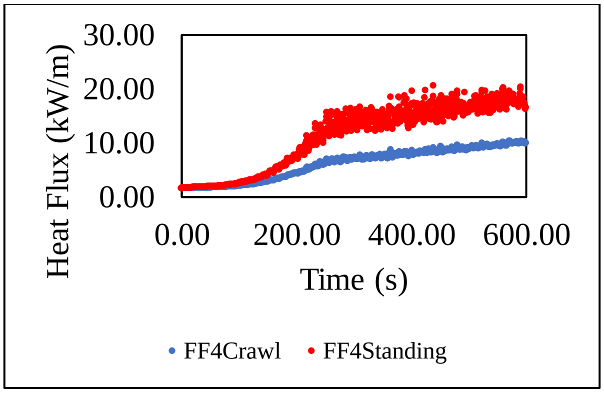

Figure 0.86: Bedroom Heat Flux versus Time for Firefighter 4

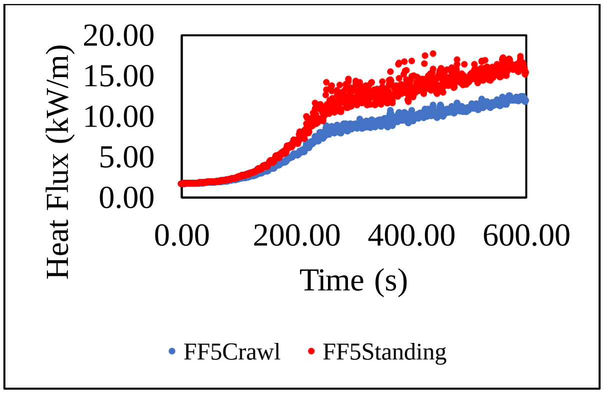

Figure 0.87: Bedroom Heat Flux versus Time for Firefighter 5

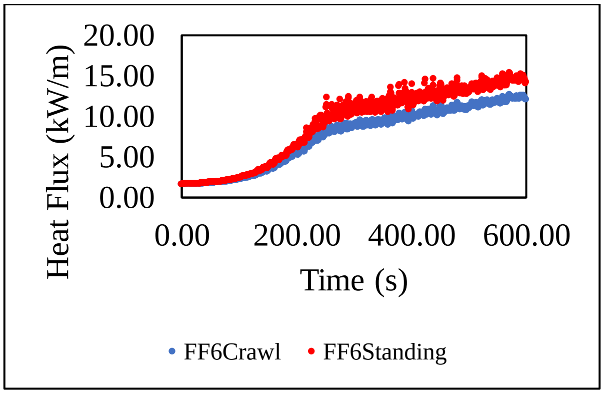

Figure 0.88: Bedroom Heat Flux versus Time for Firefighter 6

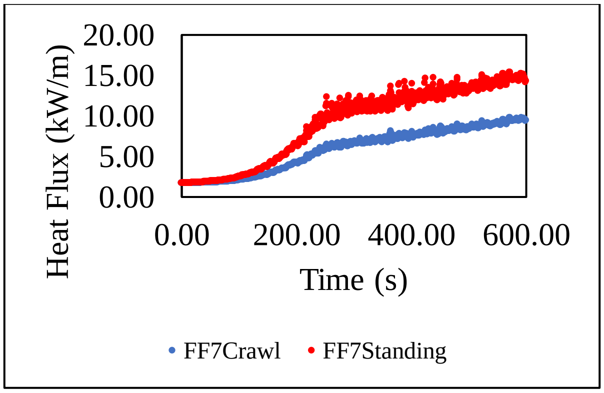

Figure 0.89: Bedroom Heat Flux versus Time for Firefighter 7

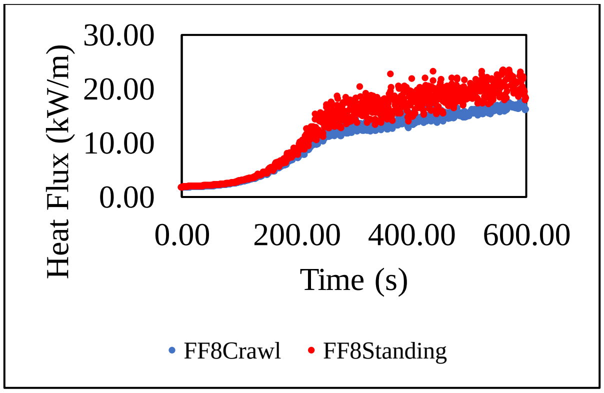

Figure 0.90: Bedroom Heat Flux versus Time for Firefighter 8

Again, hand calculations were conducted to approximate these heat fluxes. The findings for the Equation 6 analysis can be found below in Table 3.6. While the distances to the fire are the same, the main difference is the diameter of the mattress. The narrower portion of the mattress was used as this diameter, equating to 1.932 meters. Therefore, because the diameter is double the couch diameter, the heat flux would understandably be double, and a factor of four when the safety factor of 2.0 is applied.

Table 0.6: Bedroom Simulation Equation 6 Analysis for Radiative Heat Flux

Simulation Firefighter	Distance to Fire (D_t) (m)	Calculated Heat Flux ($^{kW}/_{m^2}$)	Calculated Heat Flux with Safety Factor ($^{kW}/_{m^2}$)
Crawling Firefighter 1	1.6	9.8	19.6
Crawling Firefighter 2	1.1	13.8	27.7
Crawling Firefighter 3	1.4	11.5	23.1
Crawling Firefighter 4	1.6	9.8	19.6
Crawling Firefighter 5	1.4	11.5	23.1
Crawling Firefighter 6	1.6	13.8	27.7
Crawling Firefighter 7	1.4	9.8	19.6
Crawling Firefighter 8	1.1	13.8	27.7
Standing Firefighters	1.6	11.5	23.1

As above, the point source radiation model, shown as Equations 8 and 9 earlier were conducted as a second way to determine the heat flux, especially with the larger heat fluxes shown above. The same pool diameter, taken as the width of the mattress, was used in this analysis. The X_r was found to be 0.203 while the heat release rate was determined to be 1900 kW. This equation is presented above as Equation 3 while calculated values are found below in Table 3.7.

Table 0.7: Bedroom Simulation Equation 8 Analysis for Radiative Heat Flux

Simulation Firefighter	Distance to Fire (D_t) (m)	Calculated Heat Flux ($^{kW}/_{m^2}$)
Crawling Firefighter 1	1.60	7.8
Crawling Firefighter 2	1.10	13.9
Crawling Firefighter 3	1.35	10.2
Crawling Firefighter 4	1.60	7.8
Crawling Firefighter 5	1.35	10.2
Crawling Firefighter 6	1.10	13.9
Crawling Firefighter 7	1.60	7.8
Crawling Firefighter 8	1.10	13.9
Standing Firefighters	1.35	10.2

Again, these values would appear to be more appropriate. Additionally, because this equation uses a heat release rate in its determinations, it should be considered more accurate than the previous equation.

One of the reasons for these much lower modeled heat fluxes is the lower heats of combustion. The heat of combustion, measured in $^{kJ}/_{kg}$, is a measure of how much energy is released per kilogram of fuel combusted. Therefore, even though there is more fuel in the bedroom, the amount of energy released per kilogram is far lower. Additionally, the bedroom is a larger room. With the same ventilation openings, there is still more volume in the bedroom for the dispersion of the combustion byproducts.

The same temperature analysis was also determined as above. First, the temperature values for each firefighter are shown below. Figure 3.91 shows the temperature differences between a crawling and a standing Firefighter 1, Figure 3.92 shows these differences for Firefighter 2, and so forth.

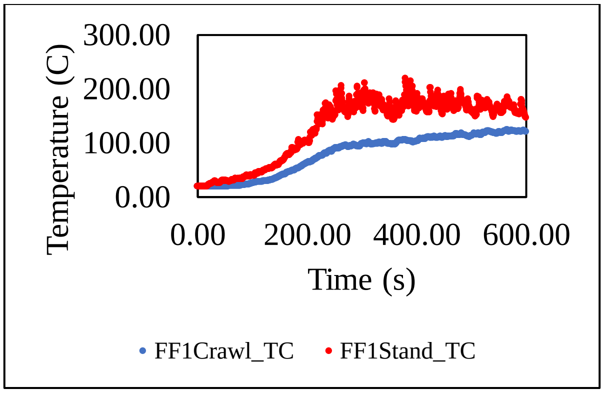

Figure 0.91: Bedroom Temperature versus Time for Firefighter 1

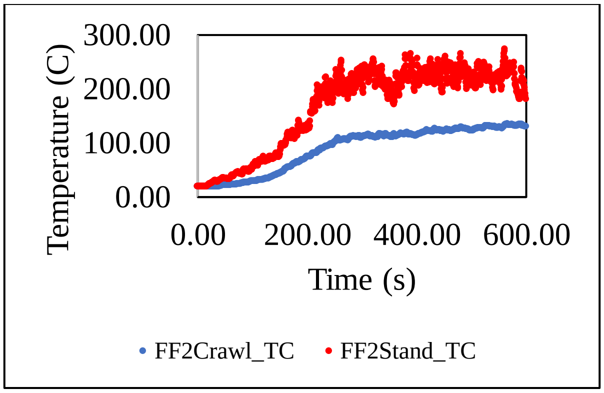

Figure 0.92: Bedroom Temperature versus Time for Firefighter 2

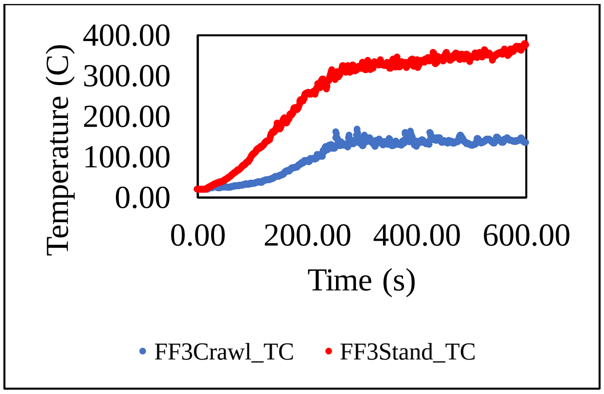

Figure 0.93: Bedroom Temperature versus Time for Firefighter 3

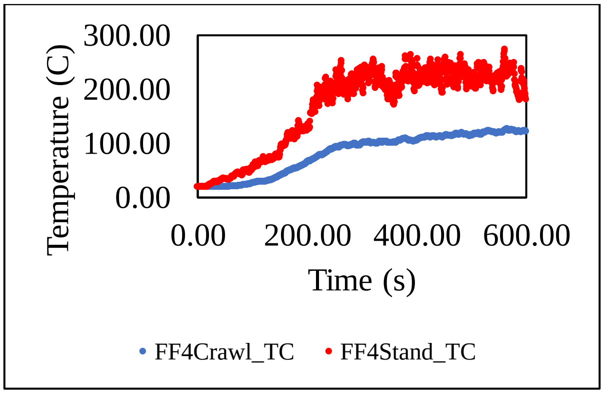

Figure 0.94: Bedroom Temperature versus Time for Firefighter 4

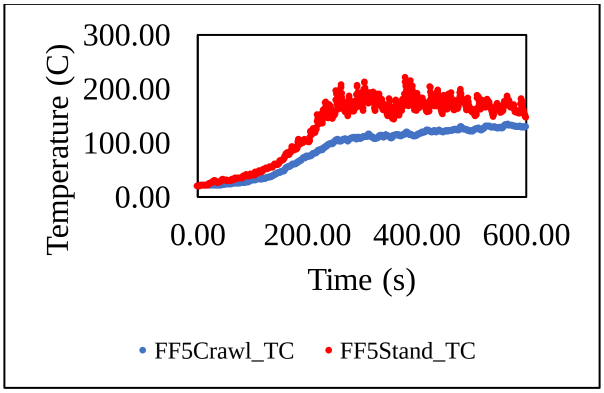

Figure 0.95: Bedroom Temperature versus Time for Firefighter 5

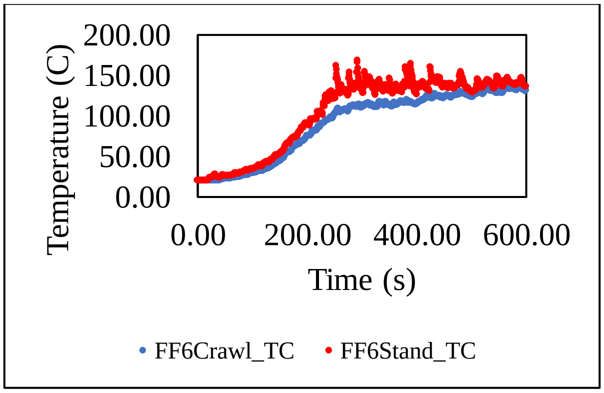

Figure 0.96: Bedroom Temperature versus Time for Firefighter 6

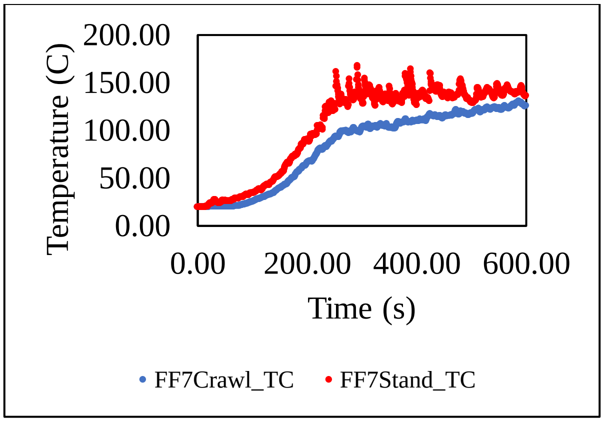

Figure 0.97: Bedroom Temperature versus Time for Firefighter 7

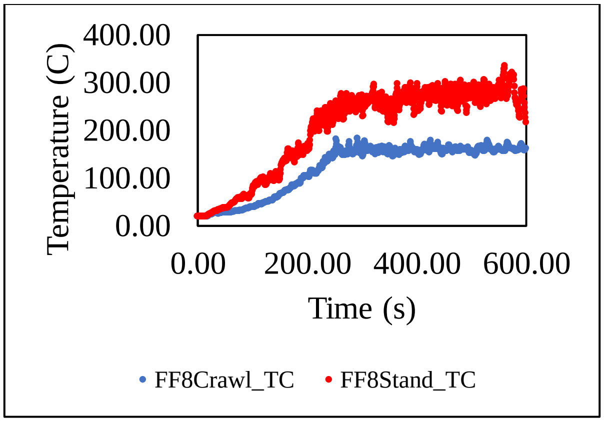

Figure 0.98: Bedroom Temperature versus Time for Firefighter 8

The temperature differences between a crawling radio strap equipped and radio pocket equipped firefighter is shown in Figure 3.99 while a standing radio strap equipped, and radio pocket equipped firefighter is shown in Figure 3.100.

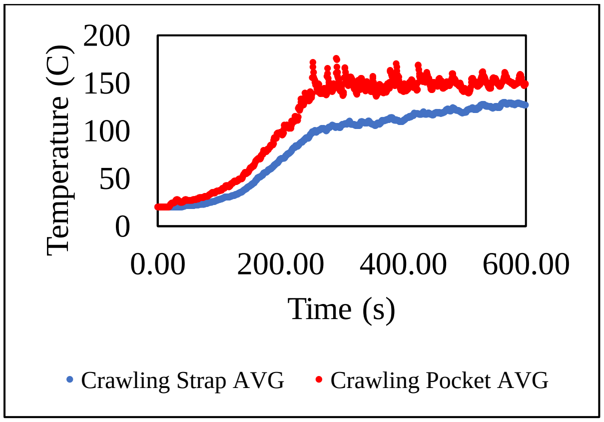

Figure 0.99: Temperatures when Crawling with a Pocket and with a Strap

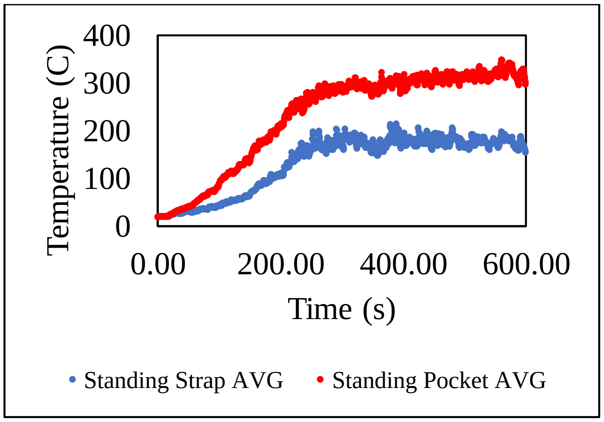

Figure 0.100: Temperatures when Standing with a Pocket and with a Strap

Figures 3.101 through 3.102 also show the temperature differences between each firefighter depending on their positioning.

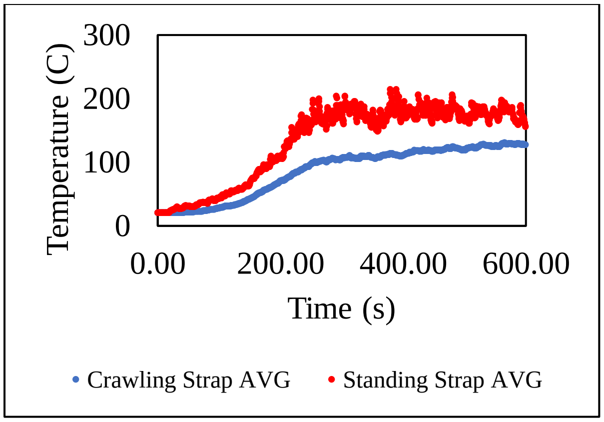

Figure 0.101: Crawling and Standing Temperatures with a Strap

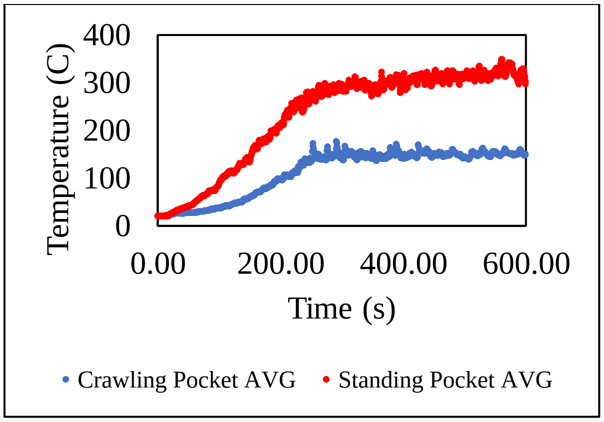

Figure 0.102: Crawling and Standing Temperatures with a Pocket

1.13 Heat Flux Selection

To select the particular heat flux for the empirical testing efforts, times must be chosen. To select these times, emphasis was placed on fire department response times. While fire departments across the United States obviously have different response times, the 2020 edition of NFPA *1710: Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments* provides guidance on fire department response times for career fire departments [34]. The Origin and Development portion of the front matter states that the first fire apparatus is to arrive in four minutes after leaving the station. Therefore, with the turnout time of 80 seconds, bringing the total time to about five and half minutes. However, a longer duration was chosen to provide some reflex time for both the person alerting the fire department as well as time for the fire department to be dispatched and to enter the building. Therefore, seven minutes and fifteen seconds would be a suitable time for firefighters to reach the seat of the fire. This time provides a heat flux of $8.23\ {}^{kW}/_{m^2}$ for the radio strap and $12.3\ {}^{kW}/_{m^2}$ for the radio pocket. Therefore, $8\ {}^{kW}/_{m^2}$ was selected for the radio strap heat flux and 12 $^{kW}/_{m^2}$ was used for the radio pocket analysis for the bedroom analysis. When evaluating these heat fluxes for the bedroom simulation, there would appear to be agreement. However, because of the differences between the two compartments, the living room values were selected as the reference heat fluxes.

Therefore, with this data, the empirical testing was conducted using the aforementioned heat flux data. These findings will be discussed in the following chapter.

Empirical Testing

1.14 Introduction

To assess the behavior of actual radios under simulated real-world conditions, empirical testing was conducted. These tests were completed over multiple days in the Fire Science Laboratory at the University of Maryland, College Park. The following section will outline the specific testing methods utilized in this analysis as well as the findings. Conclusions based on these results will be presented in the following and final chapter.

1.15 Testing Methodology

1.15.1 Test Set Up

First, a frame was constructed to support the turnout coat and radio assembly. A 2x4 was cut to construct a stand before a 0.91-meter-tall vertical portion of the 2x4 was secured to the top of the stand. Two 0.6-meter-long portions of 2x4 lumber were nailed across the stand, to act as hips and shoulders. The entire frame was then wrapped in aluminum foil to reflect the radiant energy so that the single frame would be able to withstand all tests. Additional nails were then added to the frame to support the radio strap.

After the frame had been constructed, the assembly was then placed on the stand. For the radio strap tests, the radio strap was placed on the stand first, with the radio holster portion of the device on the left side of the stand. This positioning represents a radio being worn on a firefighter's right side. The turnout coat was then placed on top of the radio strap. For the radio pocket tests, the radio strap was omitted.

To instrument the assembly, alterations were needed in the turnout coat. For the radio pocket analysis, incisions were made in the outer shell of the turnout coat so that the thermocouple and shoulder microphone wires could be run through the coat. These wires were held between the layers of the turnout coat and then extended through the neck where it was connected to the data acquisition system. The shoulder microphone was also protected from the thermal environment by wrapping the location where the wire connected to the portable radio with a piece of aluminum foil to reflect some of the thermal radiant energy directed at the radio. For the radio strap, no incisions were needed as the wires extended above the top of the radio, following the radio strap, and extending through the coat at the neck. Figures 4.1 through 4.3 show the radio pocket setup for a variety of angles and Figures 4.4 through 4.6 show the various radio strap assembly.

Figure 0.1: Radio Pocket Testing Setup Front View

Figure 0.2: Radio Pocket Setup Top View

Figure 0.3: Radio Pocket Testing Shoulder Microphone Protection

Figure 0.4: Radio Strap Protected by Coat

Figure 0.5: Radio Strap Beneath Coat Positioning

Figure 0.6: Exterior Radio Strap Positioning

Each radio battery was instrumented with a Type K thermocouple with a wire diameter of 0.125 mm. These thermocouples were used to ensure that the batteries did not overheat. However, the batteries powering these radios were not lithium-ion batteries, but it is expected that future developments both in radios and in batteries will result in lithium-ion fire service batteries. Type K thermocouples were also placed at the front of the radio to measure the temperature of the air at the front of radio. Graphs of the data from all these thermocouples will be presented later in this chapter.

A video camera was also used to film potential radio degradation as well as to serve as an audio recording. This camera was placed in very similar locations for each test. The camera was also used to record the removal of each specimen and the comments made on the conditions of each device.

While not recorded for this analysis, a Gardon heat flux gauge was used to ensure that the radio would be exposed to the desired heat flux. This gage was held facing a "warmed up" radiant panel and was moved closer until the desired reading was found.

LabView was the software used to record the data for each of these simulations. Two thermocouples and the heat flux gauge were all recorded every second, with LabView calculating the heat flux from the measured voltage through a user-input equation.

Finally, other instruments included a stopwatch to ensure that the tests were kept on track while also recording the times of interest. Testing criteria and the timeline of each test will be discussed in the following sub-section.

1.15.2 Testing Process

As mentioned above, each day of testing began by determining the positioning of the radiant panel in comparison to the testing specimen. These distances varied depending on the internal conditions of the lab, generally with a 0.1-meter distance to achieve the 12 $^{kW}/_{m^2}$ heat flux and a 0.15-meters distance to achieve the 8 $^{kW}/_{m^2}$ heat flux. After these distances had been determined, the panel was allowed to cool while the radio was prepared.

The test specimen was then tested prior to insertion into the assembly. The radio battery was attached to the radio and powered on. The radio used to communicate with the test specimen was also powered on and the transmission and reception abilities of both radios were tested. The test specimen was then inserted into the testing apparatus. The thermocouple measuring the air temperature at the face of the radio was then tested to ensure that it was operating properly before being inserted into the holder. Once the panel had cooled, it was placed at the predetermined distance from the test specimen. A large piece of Kaowool thermal insulation was then placed in front of the test specimen to initially shield it from the radiant panel. The radios were both tested a final time, with assurance made that the test specimen had its volume turned to its maximum level. This volume level equates to the highest power that the radio was programmed to transmit.

Once the camera began filming, the stopwatch started at the same time as the radiant panel was plugged in, starting the test. The heater was allowed to heat for six minutes before the temperature data collection was started. One minute of the pretest conditions were measured before the insulation was removed, a total of seven minutes after the test began.

The test radio then had its shoulder microphone keyed for a period of fifteen seconds before the other radio was allowed to transmit. The operator of this control radio, who was also serving as the timekeeper, would state the time to keep all operators informed while also serving to check the audio quality of the receiving radio. It should be noted that both radios remained in the same room for the duration of all tests. This was done to improve visual communication between the operators so that a failure could be determined more easily. It also helped to ensure that operators stayed on the correct schedule as when keyed, the testing radio generally overrode the control radio. The control radio could also override the testing radio, meaning whichever radio was keyed first would have transmitting priority.

The radio pocket tests were all allowed to progress until the radio failed. There was no time limit for these tests. The radio strap tests were conducted with the target of a thirty-minute exposure. If the radio was still transmitting and receiving adequately, then the specimen was deemed to have passed the test and the test concluded. To conclude these tests, the insulation was placed in its initial position while the heater was also removed.

The radios were allowed to cool for a minimum of five minutes before they were removed from the apparatus. The condition of each radio case was also evaluated during this period. The test battery was removed from the radio and allowed to cool while the radio was disassembled. In the case of a failure, the individual components were also tested. The antenna and battery were placed on a radio known to function and new antennas and batteries were placed on the tested radio after it had cooled. If the radio could successfully pass this final test, then the radio was used in a subsequent test.

1.15.3 Test Matrix

Below are four test matrices, one for each series of tests. In total, 20 tests were conducted using twelve different radios. The findings from radios that were tested multiple times can be found near the end of the testing results section which follows this subsection. The first matrices describe the radio pocket tests and can be found below as Table 4.1. These tests were also the first ones conducted. Series-specific information can also be found in the Radio Pocket Testing subsection of the following section. Next, the 8 $^{kW}/_{m^2}$ radio strap simulations are shown in Table 4.2 as these were the second series of tests conducted. These tests were repeated at the higher 12 $^{kW}/_{m^2}$

heat flux in the third matrix, shown in Table 4.3. The final two tests are shown in Table 4.4 as the two tests conducted in a radio strap on the exterior of the turnout gear.

Table 0.1: 12 kW/m^2 Radio Pocket Test Matrix

Test Number	Radio Model Used	Radio Exposure Number
Pocket Test #1	Radio A.1	1st Exposure
Pocket Test #2	Radio B	1st Exposure
Pocket Test #3	Radio A	1st Exposure
Pocket Test #4	Radio A.3	1st Exposure
Pocket Test #5	Radio C.1	1st Exposure
Pocket Test #6	Radio A.1	2nd Exposure

Table 0.2: 8 kW/m^2 Radio Strap Test Matrix

Test Number	Radio Model Used	Radio Exposure Number
8 Strap Test #1	Radio A.4	2nd Exposure
8 Strap Test #2	Radio A.3	2nd Exposure
8 Strap Test #3	Radio A.4	3rd Exposure
8 Strap Test #4	Radio C.2	1st Exposure
8 Strap Test #5	Radio C.3	1st Exposure
8 Strap Test #6	Radio A.3	3rd Exposure

Table 0.3: 12 kW/m^2 Radio Strap Test Matrix

Test Number	Radio Model Used	Radio Exposure Number
12 Strap Test #1	Radio A.4	4th Exposure
12 Strap Test #2	Radio C.4	1st Exposure
12 Strap Test #3	Radio C.3	2nd Exposure
12 Strap Test #4	Radio A.3	4th Exposure
12 Strap Test #5	Radio A.4	5th Exposure
12 Strap Test #6	Radio C.4	2nd Exposure

Table 0.4: Exterior Radio Strap Test Matrix

Test Number	Exposure Heat Flux ($^{kW}/_{m^2}$)	Radio Model	Radio Exposure Number
8 Strap Outside #1	8	Radio C.5	1st Exposure
12 Strap Outside #1	12	Radio C.6	1st Exposure

1.16 Testing Results

Six replicates each of the radio pocket and under coat radio strap tests were conducted. A single replicate of each external radio strap test was conducted. Each section below contains both a thermal analysis of each test as well as an overview table. These tables state the pass or fail status of each test and any notes taken during the evaluations. In the case of a failure, the time that the signals degraded and the time that the radio was deemed a failure is also shown. The signal degradation took many forms, with some manifesting as dramatically increased audio feedback, significantly decreased volume, or the inability to transmit.

1.16.1 Radio Pocket Testing

The first set of tests completed were the radio pocket tests. These tests were conducted first to coordinate the findings with those of the previous NIST TN 1477 study. In addition, these tests served as a benchmark to the following tests. It was determined that if a future test could surpass the duration of the longest radio pocket test, then the radio was better protected from using the alternate carrying method. Another reason for this selection was the heat flux used for these tests. As discussed in the previous chapter, the heat flux for these tests was approximately $12\ ^{kW}/_{m^2}$.

Many of these radios had quite similar failure times, excluding the first radio. This radio was tested without a shoulder microphone, using a bungee cord assembly to relieve pressure from the radio's PTT button. Images of the setup of this radio can be seen as Figure 4.7.

Figure 0.7: Radio Pocket R1 Setup Image

It was noted during this test that this assembly would not be feasible, as the radio moved toward the heater, increasing the heat flux. However, this test remained part of the test series as it did partially account for some heat flux variations. As mentioned previously in this report, firefighters would likely be moving while working inside of the structure, producing a varying heat flux. These variations would also be caused by the fire itself not emitting a perfect, constant heat flux. Because the heat flux gage was not placed next to the radio during the testing, the heat flux variation was not measured in the testing. However, an analysis was conducted to determine this variation.

Assuming the radio moved 0.01 meters closer to the radiant panel, the previous hand calculations were used. Using Equation 5, an analysis was first conducted to determine the D_p value. This analysis was conducted using the fixed $12\ {}^{kW}/_{m^2}$ heat flux and the 0.1 m distance.

This D_p value was calculated as 0.15 m, and when inserted into Equation 5, the altered heat flux was determined to be 13.50 $^{kW}/_{m^2}$.

This test is included in the temperature analysis below as well as in the failure analysis. However, it was removed from the calculations of the average temperature and time to failure calculation presented at the end of this subsection. The temperature graph for Radio Pocket Test 1 is shown as Figure 4.8.

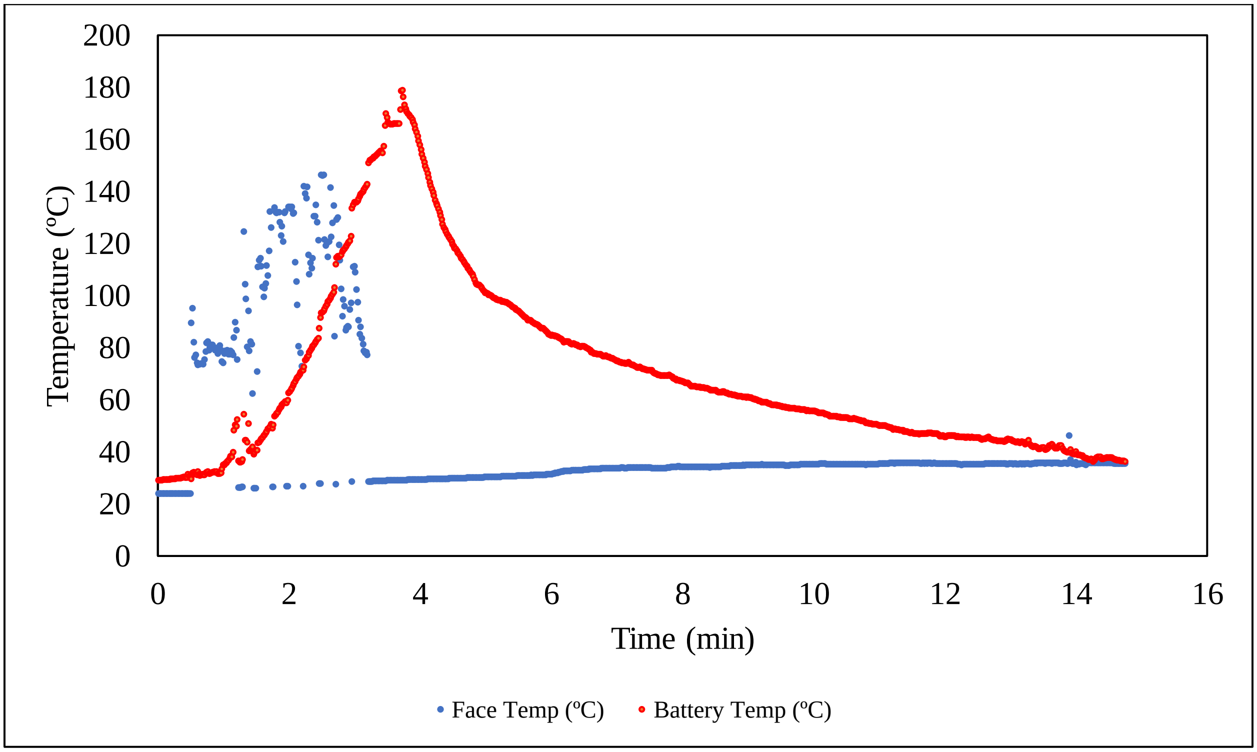

Figure 0.8: Radio Pocket Test #1 Temperature Data

The radio used during this first test did not sustain any discernable visual damage. Before and after pictures of this radio are shown as Figure 4.9 and 4.10. However, there was some slight discoloration to the radio's antenna. Pictures can be seen as Figures 4.11 and 4.12. However, it should be noted that the radio, battery, and antenna were able to transmit separately after this test. The antenna was not used for any future tests, but the radio and battery were used for subsequent tests.

Figure 0.9: Radio A.1 Pre-Test

Figure 0.10: Radio A.1 Post Pocket Test R1

Figure 0.11: Radio A.1 Antenna Post Pocket Test R1

Figure 0.12: Radio A.1 Antenna Post Pocket Test R1 Close Up

The first radio also did not provide any significant degradation, possibly in response to the short duration of the test. However, this should serve as a concern for firefighters as a user would not have advanced warning that his or her radio was on the verge of failure. Also, in the absence of a set schedule of messages, it could possibly be impossible for a firefighter to know that his or her radio had already failed. Therefore, as in the Riverdale Heights incident discussed earlier, the trapped firefighter would likely have no idea that a MAYDAY message was not being received.

The second test also served as a bit of an outlier as it was the longest test of any carrying arrangement that resulted in a failure. This radio was a more modernized radio than the others and used its own battery. The same style antenna was used for all radios. This radio experienced significant signal degradation about halfway through the test, but it was able to continue the test. The radio was unable to transmit after the test was completed. The radio and antenna both showed extensive damage. The radio had to be removed from the radio pocket with a knife as the rubber sheathing on the antenna melted during the test and coated much of the speaker of the battery. The rubberized channel selector and power knobs also showed significant damage, with the channel selector knob being left inoperable. A pair of pliers was used to power up the radio, but the radio remained unable to transmit after the test. Furthermore, the radio produced a chirp when powered up before the test, but this was absent after the test. Coupled with the extreme screen damage, it was not possible to determine if the radio could be powered on. Figures 4.13 through 4.17 show this damage.

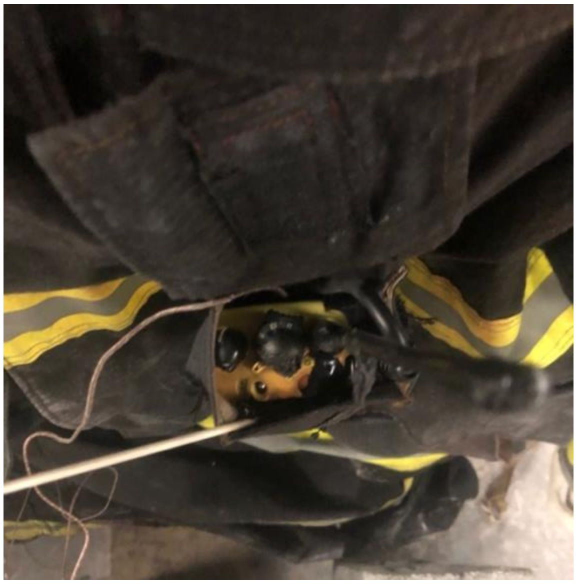

Figure 0.13: Radio B Damage Before Removal

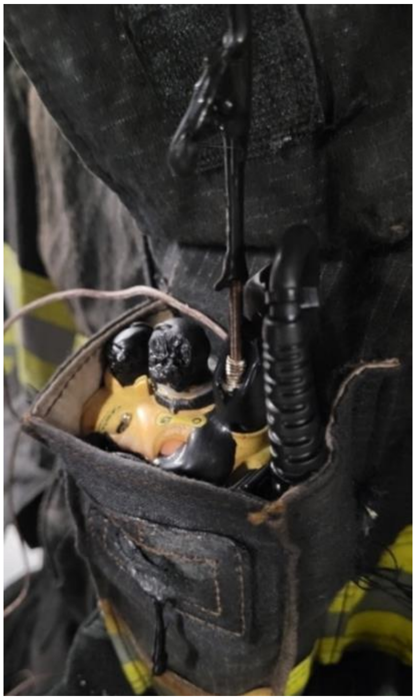

Figure 0.14: Radio B Antenna and Knob Melting

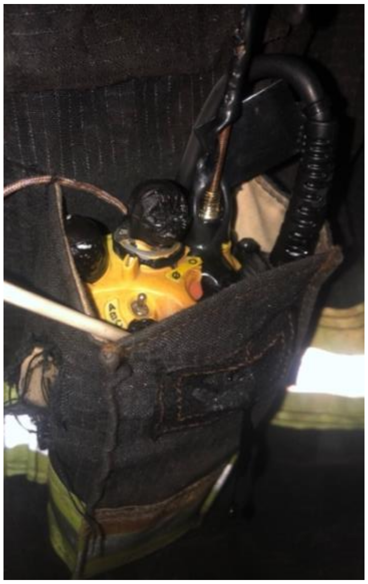

Figure 0.15: Radio B Close Up Damage Prior to Removal

Figure 0.16: Radio B Damage After Removal

Figure 0.17: Radio B Damage Close Up After Removal

The temperature data for this second radio is very similar to the other radios tested, only this radio survived for a longer duration. The comparison can be seen at the end of this subsection, but the radio did not increase in temperature at the same rate as the other radios. This could be the reason that the radio lasted for a longer duration. A graph of this radio's face temperature and the temperature at the battery can be seen below as Figure 4.18.

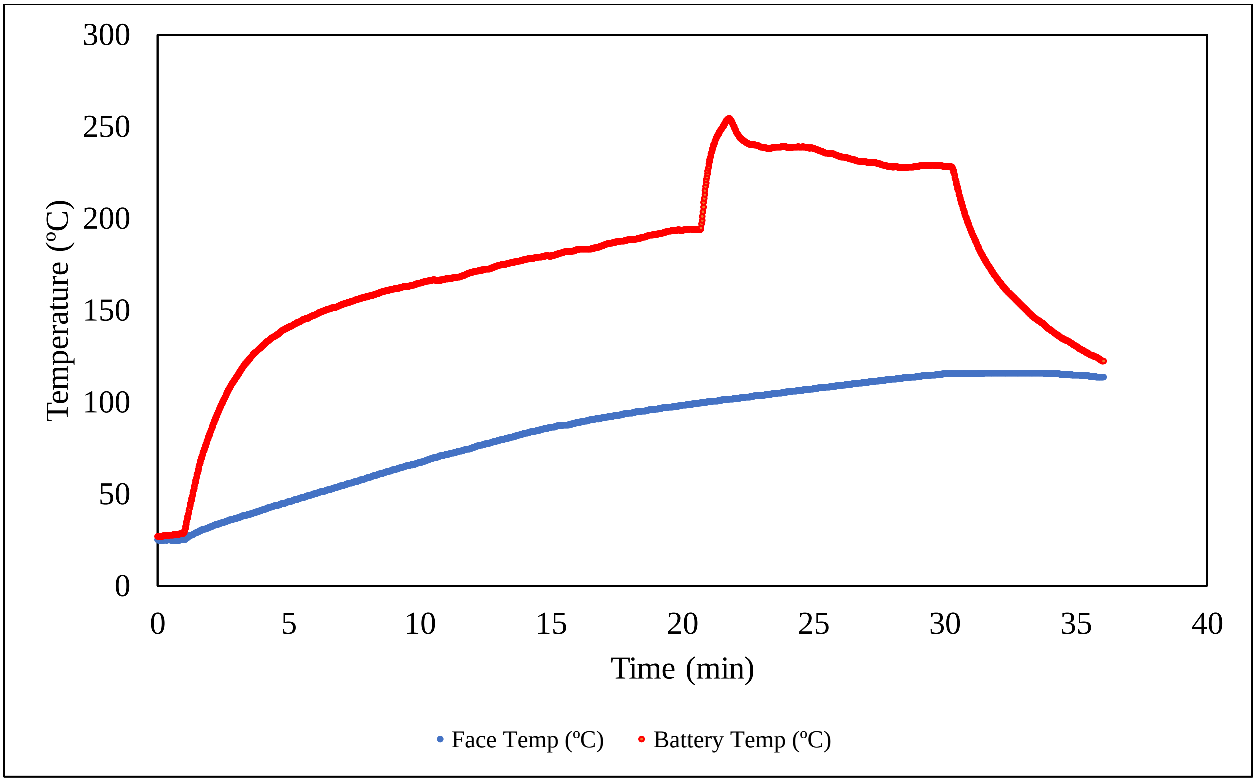

Figure 0.18: Radio Pocket Test #2 Temperature Data

The third radio to be tested provided results which were consistent with the rest of the pocket radio tests. Note, this radio also did show some significant static about ten minutes into its exposure, but it was still able to transmit and receive. However, it did suffer the significant signal loss just over twenty minutes into the test, as depicted in Table 4.5. The radio also suffered significant visual damage. The screen was significantly crazed and unreadable. The top of the case also suffered melting and shape deformation, allowing some of the radio's internal components to be visible. Figures 4.19 through 4.21 show this damage. However, the radio and its battery continued to function with a new antenna. Both devices were used in subsequent testing.

Figure 0.19: Radio C Damage After Pocket Test R3

Figure 0.20: Radio C Melting After Pocket Test R3

Figure 0.21: Radio C Screen Crazing After Pocket Test R3

This radio also behaved like the other radios thermally. The temperature recorded at the battery followed the same slope as many of the other tests. The face temperature on this radio also largely followed those of the other radios tested in the pocket. Figure 4.22 shows the battery and face temperatures of this third radio.

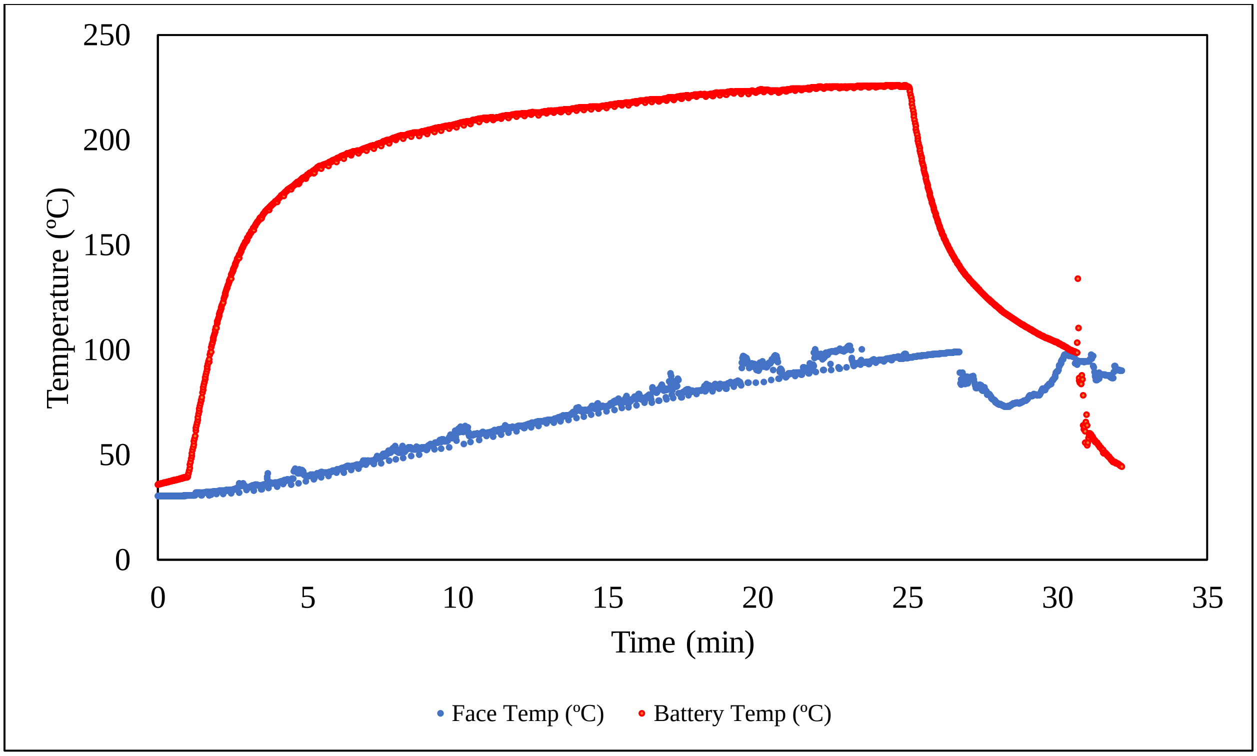

Figure 0.22: Radio Pocket Test #3 Temperature Data

The fourth radio again behaved like the other radios tested in the radio pocket. However, this radio was the first radio that demonstrated a "bonk." The cause of this failure was unknown, but the radio was able to transmit for the remainder of the test, resulting in the radio's failure. The radio also experienced a dramatic increase in feedback at seven minutes and forty-five seconds of exposure to the radiant panel. However, the radio remained able to transmit. This radio also did not experience a significant amount of visual damage.

The fourth radio did follow the same trend as the other radios in terms of temperature at the battery, but its face temperature was very erratic during the early stages of the test. The general trend of the temperature increase was visible, but there were instantaneous temperatures that proved to be quite high. A potential explanation for these spikes could be that the thermocouple moved and contacted the outer surface of the turnout gear, rather than measuring the air temperature between the radio and the pocket's outer edge. This theory is supported by the damage shown to the radio pocket after the tests. Images and discussion of the turnout gear's performance can be found at the end of this chapter and a graph of this radio's temperature can be found in Figure 4.23.

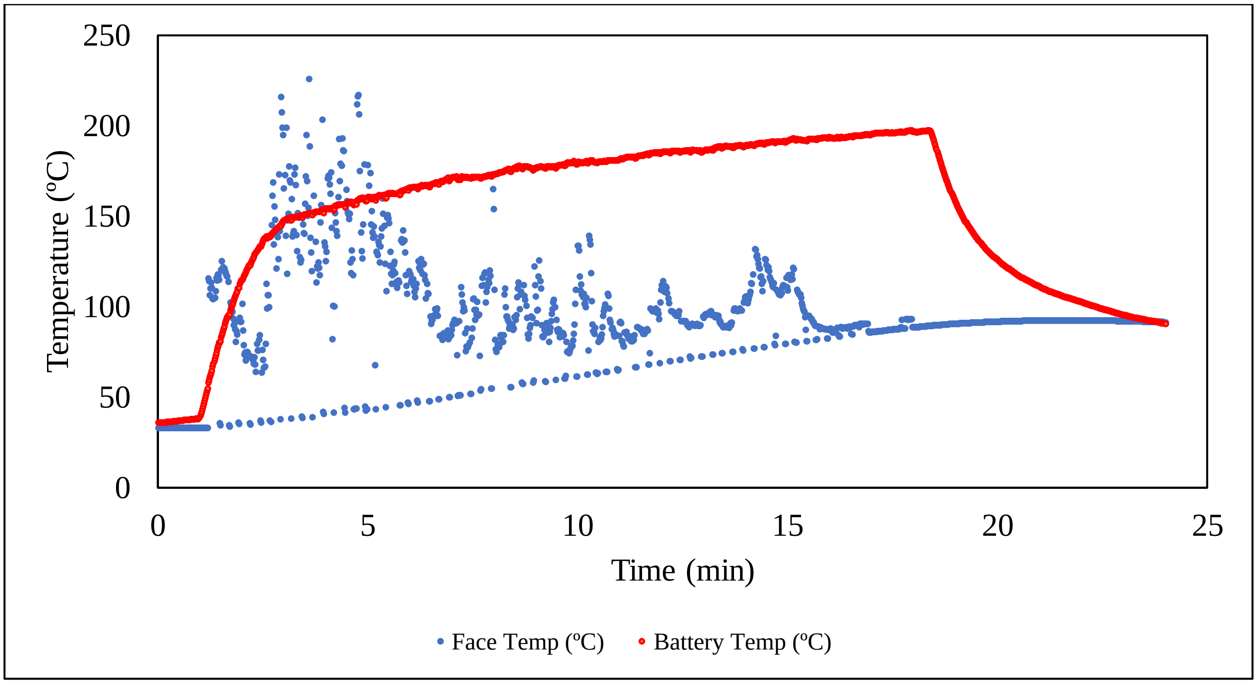

Figure 0.23: Radio Pocket Test #4 Temperature Data

The fifth radio to be tested in the turnout coat pocket showed the fastest time to failure other than the first test. This radio experienced severe visual damage with the face thermocouple melted to the face of the radio. The antenna was visually bent and internal components of the radio were visible. The screen could not be read, and the radio again had to be cut from the turnout coat as the coat was fused to the radio due to the melted rubber sheathing. This radio and its antenna were unable to be used for any further testing. The radio's battery was usable for future testing after it had cooled. Figures 4.24 through 4.28 show the extensive thermal damage experienced by radio C.1.

Figure 0.24: Radio C.1 Damage After

Pocket Test #5 Prior to Removal

Figure 0.25: Radio C.1 Top View after

Pocket Test #5 Prior to Removal

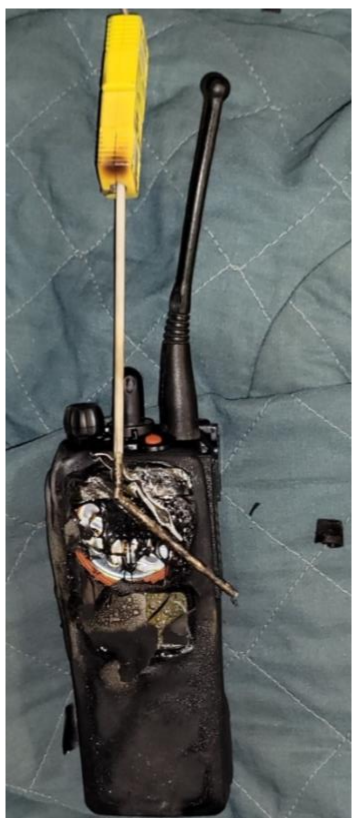

Figure 0.26: Radio C.1 and Thermocouple Damage After Removal After Pocket Test #5

Figure 0.27: Radio C.1 and Antenna Damage After Removal After Pocket Test #5

Figure 0.28: Radio C.1 Damage Close Up After Pocket Test #5

While the fifth radio lasted significantly longer than the first radio, it fared similarly regarding the lack of advanced warning. The radio did not experience a dramatic increase in feedback or reduction in volume. Also, no “bonk” was heard from this radio.

Regarding temperature, the fifth radio did experience a higher temperature at the battery than the other radios that were tested. The face temperature also followed an erratic shape, likely due to the fusion of the thermocouple insulation with the face of the radio. This thermocouple likely contacted the face of the radio rather than measuring the air temperature that the radio was exposed to inside of the pocket. However, the general trend of an increase in temperature was observed. Figure 4.29 shows the temperature data for this fifth test.

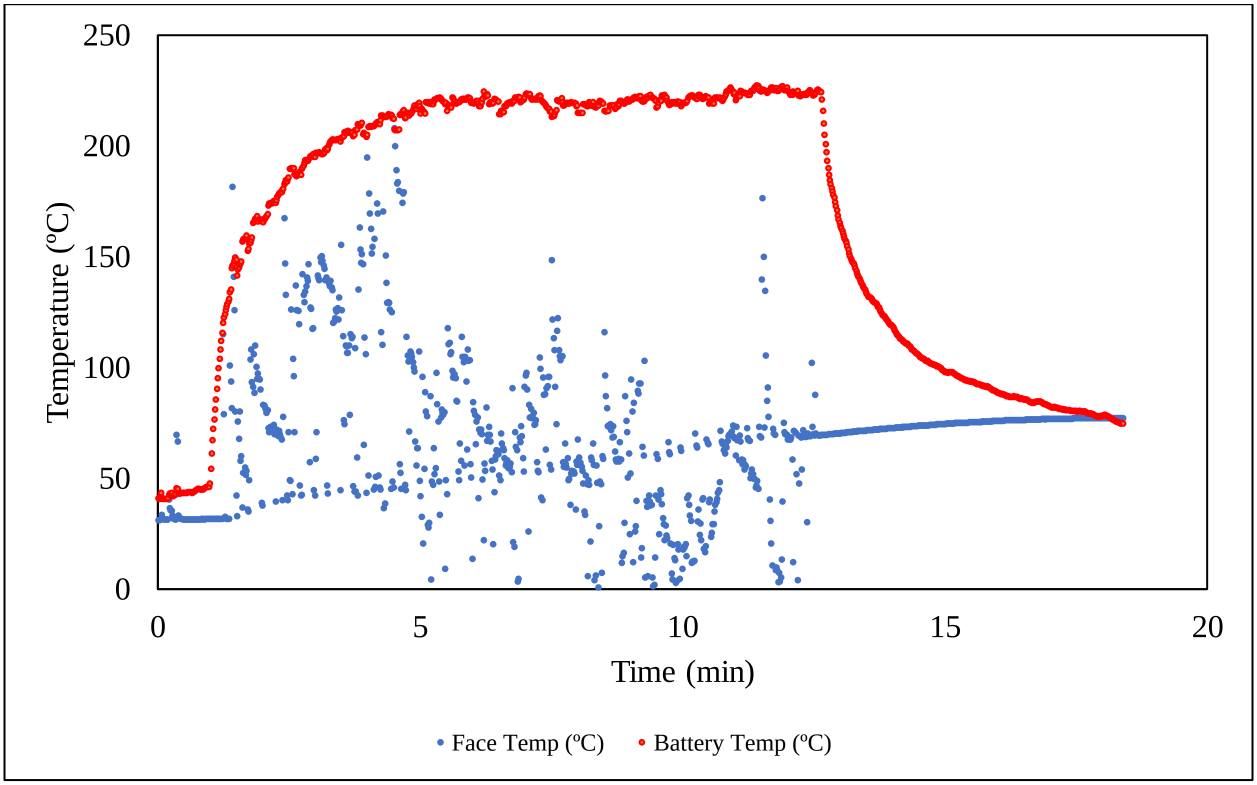

Figure 0.29: Radio Pocket Test #5 Temperature Data

The final pocket test conducted was the sixth test. The radio used for this analysis was the first radio used in the pocket testing. However, this radio lasted significantly longer during this final pocket test yet experienced significant thermal damage. The antenna's rubber sheathing melted significantly onto the face of the radio, again requiring the radio to be cut from the turnout coat pocket. The face temperature thermocouple also melted to the face of the radio, possibly explaining the erratic face temperature behavior. The radio casing itself also melted near the top of the radio, leaving plastic melted to the screen. Internal components of the radio were also visible at the conclusion of this test. At a cursory glance, this radio experienced more visual thermal damage than any other radio tested. Figures 4.30 through 4.35 attest to this extreme damage.

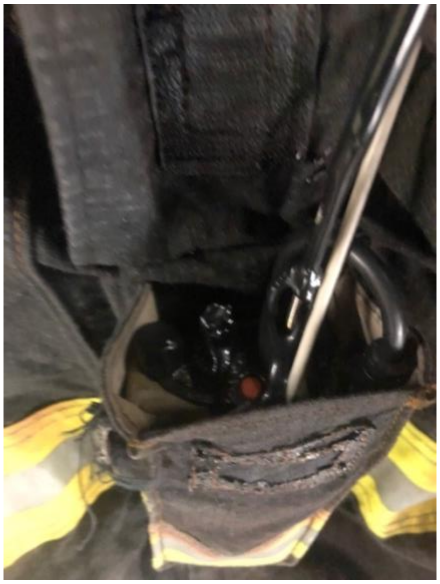

Figure 0.30: Radio A.1 Damage Prior to Removal After Pocket Test #6

Figure 0.31: Radio A.1 Damage Post Removal After Pocket Test #6

Figure 0.32: Radio A.1 Damage Post Removal After Pocket Test #6

Figure 0.33: Radio A.1 Damage Close Up After Pocket Test #6

Figure 0.34: Radio A.1 Top Damage After Pocket Test #6

Figure 0.35: Radio A.1 Knob and Antenna Melting After Pocket Test #6

Thermally, the sixth test largely followed the same trends outlined by the prior tests. This radio experienced the highest temperature measured at the battery, with a few points over 300ºC. The face temperature did experience some variation as discussed in the prior paragraph, but this was far less than some of the other radios. The temperature at the battery also experienced some variation, with the figure below suggesting that there were two sets of battery measurements. These measurements would likely be due to the air movement through the radio. With the radio suffering the extreme thermal damage shown in the figures above and the failed radio pocket closure integrity, heated air was able to travel through the case and into the radio itself. Figure 4.36 below shows the graph of the temperature data of this sixth and final pocket test.

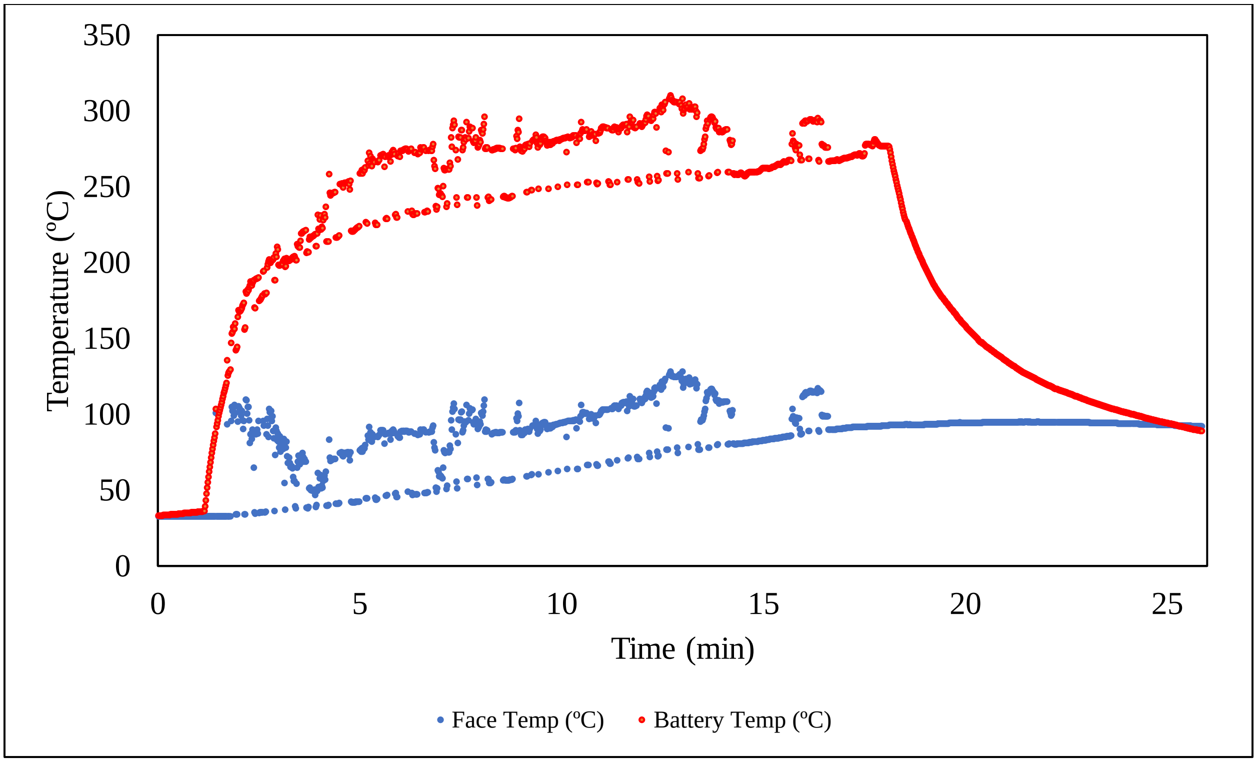

Figure 0.36: Radio Pocket Test #6 Temperature Data

With all the pocket tests completed, an analysis of all the radios tested in the pocket was conducted. As previously mentioned, the main measured metric of these tests was the duration of the testing with the failure criteria for all tests were two consecutive unsuccessful transmissions. Again, these periods were fifteen seconds each. First, Table 4.5 is presented to show both the failure time and the failure temperature measured at the battery of each of these radios. From this table, Figure 4.37 is generated to serve as a graphical depiction of the time to failure as well as the temperature at the battery when these radios failed. This figure is presented to show the proximity of both the times and temperatures at which the radio failed. It should be noted that all radios testing during this analysis, except for the second radio tested during the pocket tests, were from the same manufacturer and were the same style radio.

Table 0.5: Radio Pocket Failure Time and Temperatures

Test	Radio	Failure Time (s)	Failure Temperature at Battery (ºC)	Time to Signal Degradation (s)	Total Test Duration (s)	Failure Mode
Pocket Test R1	A.1	224	178.7	N/A	570	Transmission Failure
Pocket Test R2	B	1815	228.0	525	2168	Transmission Failure
Pocket Test R3	A.2	1503	225.4	600	1854	Transmission Failure
Pocket Test R4	A.3	1101	197.2	465	1422	Transmission Failure
Pocket Test R5	C.1	755	225.2	N/A	1117	Transmission Failure
Pocket Test R6	A.1	1082	276.8	N/A	1425	Transmission Failure

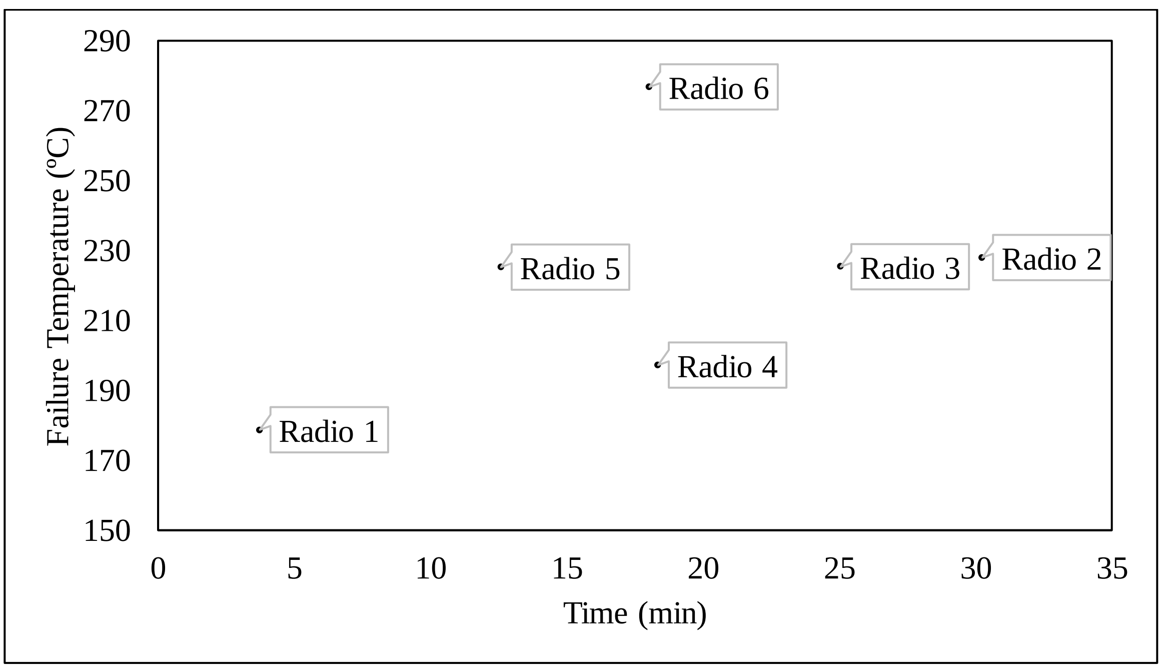

Figure 0.37: Radio Pocket Failure Time and Temperature

Next, the cumulative temperatures at the battery and at the face of each radio are presented below as Figures 4.38 and 4.39 respectively.

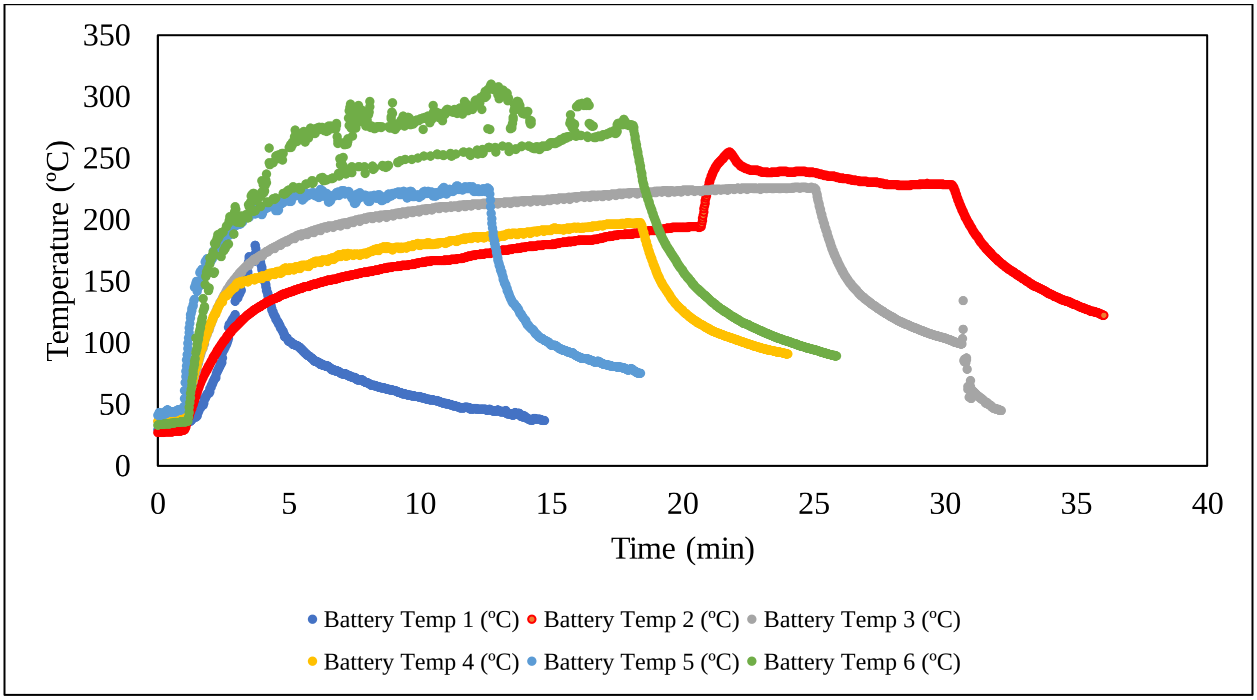

Figure 0.38: Radio Pocket Test Temperature at Battery

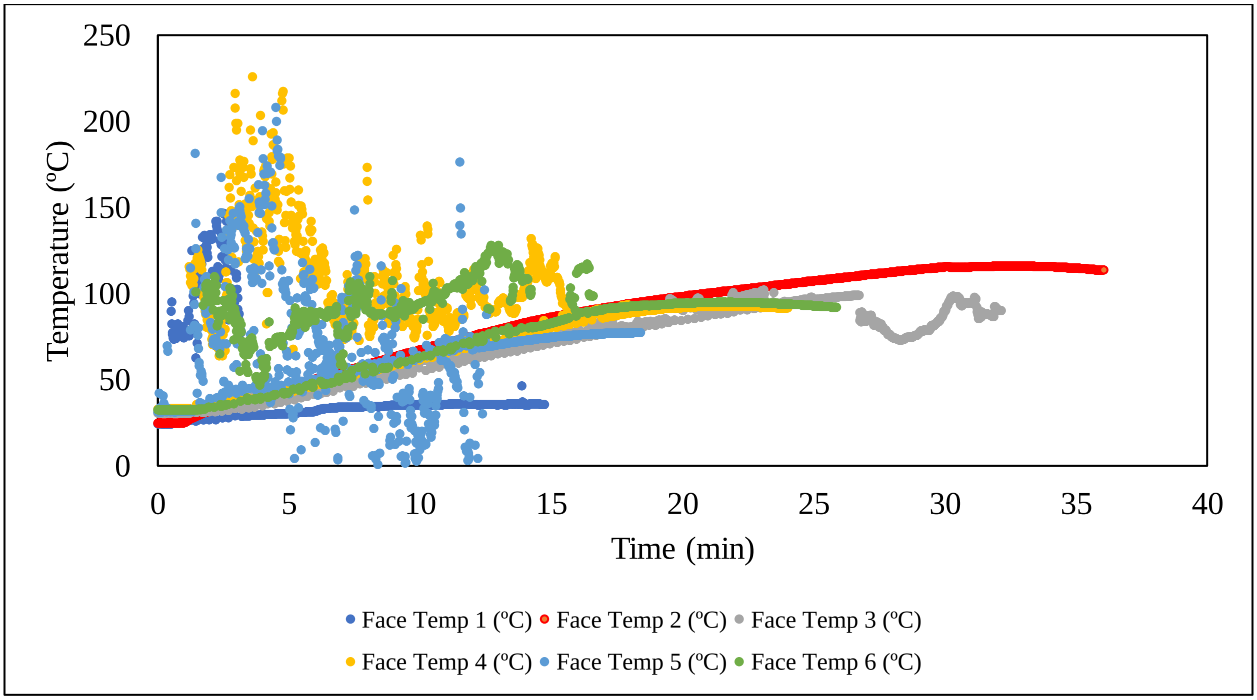

Figure 0.39: Radio Pocket Test Face Temperatures

Additionally, it was desired to note specifically what components in the radio failed. Of the twenty total tests, thirteen of radios failed throughout all four test series. However, some of these radios returned to their normal functions at the conclusions of the tests and the cool down period. Therefore, because only four radios did not return to their normal function after the conclusion of the tests, it was deemed impossible to determine the specific compoents that led to each radio's failure. Additional comments will be made about the "bonk" failures that occurred in the following series. Finally, it is believed that the time to failure of each radio and the radio temperature are in relation to each other. In an effort to determine this relationship, the area under the time temperature curve was determined. The results of this analysis are shown below in Table 4.6.

Table 0.6: Total Average Pocket Time vs. Tempearture Data

Radio	Duration of Exposure (s)	Area Under the Battery Failure Time-Temperature Curve ($℃ * s$)
Radio 1	224	61,950
Radio 2	1815	377,600
Radio 3	1503	342,600
Radio 4	1101	219,800
Radio 5	755	183,800
Radio 6	1082	323,700

These areas provide a relatively small margin of error, with the average of these values equalling $251{,}592 \pm 48{,}627\ ℃ * s$. However, an effort was made to reduce this standard error by removing the first radio from this analysis. For Radios 2 through 6, the average value increases to $289{,}522 \pm 37{,}270\ ℃ * s$. While this analysis removes the first radio, this average provides a smaller standard error. Coupled with the substiantial time difference, this smaller error would apear to better account for the radio failures. Additionally, the precision of these values would seem to confirm the suspicion that radio failures are driven based on tempearture at the radio battery. This observation will be discussed in the Conclusions chapter of this report.

While many of these trends were discussed above, Figures 4.38 and 4.39 show all of the temperature data for the radios worn in the turnout coat pocket. While the failure times may be quite different, there are a few possible explanations that can be made. The first is the radios themselves. All Radios with an A prefix had a keypad, meaning that numerical entries could be made on the radio. While firefighters rarely use these functions, many radios remain equiped with these buttons. However, while the functionality is increased in these radios, the apertures allow for more heated air to enter the radio and to increase the internal temperature. Because the radios have the same size vents located at the rear of the radio facing the battery, this heat is dispated at the same rate in both A and C model radios. Therefore, Radio A models were more succeptable to thermal soak damage. Figures of these two different models can be seen below in Figure 4.40.

Figure 0.40: Radio Model A (L) and C (R).

Another potential explanation for the failure time discrepancies are the dates of manufacture. Radio A models were the oldest radios tested. During the period where model A radios were most common, the radio industry was on the precipice of digital technology [36]. Therefore, as many fire departments and public safety agencies updgraded to digital 800 MHz frequencies, the portable radios were upgraded. Because of the increased cost of these newer radios, upgrading the older radios was much more cost effective. Therefore, some of the Radio A models that were obtained from agencies that had previously conducted these upgrades may have been able to transmit both in a digital and analog modes. This consideration would also explain why Radio A models did not endure the "bonk" failures that Radio C models did. Again, more information will be provided on these failures in the following subsections of this report.

While all of these radios, other than the first, would exceed the classifications outlined in the NIST TN 1477 study, many of the radios experienced significant degradation during this period. It is important to note that both the receiving radio and the transmitting radio were located in the same laboratry space, with the radios never being more than thirty feet away from each other. While this distance may seem large enough to communicate through a typical home in the United States, it would almost certainly be exceeded by a commercial or a multi-family structure. The same radios might even experience significant challenges transmitting to firefighters even in other rooms as typical buildings would have partitians such as walls. While these radios might still be able to transmit through a typical gypsum and plywood wall, they might not be able to communicate through walls constructed of concrete and steel. More information about transmitting through walls can be found in the NIOSH/Tri-Data report discussed in the first chapter of this report [36].

These tests show agreement with the NIST TN 1477 study and would seem to indiciate that the radio pocket is a viable way to carry a portable radio, in terms of thermal performance.

1.16.2 8 $^{kW}/_{m^2}$ Radio Strap Testing

The second test battery conducted were the radio strap tests at a 8 $^{kW}/_{m^2}$ heat flux. These tests were conducted at this heat flux in alignment with the fire modeling described in the previous chapter. Unlike the tests described in the previous section, a time limit was placed for these tests. Each test was given the same seven-minute warm-up time, a maximum of thirty minutes of exposure, and a minimum of a five-minute cool down period. This period was also chosen as it exceeded the radio pocket test with the longest duration of 2,168 seconds. If the radio survived this entire period, then it was deemed to have successfully survived the test.

The temperature data from the first test is presented below as Figure 4.41. This curve shows a similar shape as the pocket tests, with much lower temperatures. The radio used for this test had already been exposed during the pocket tests, but no visual damage was seen in this test for the radio. However, the radio strap itself did suffer from some melting with the label and some of the loop portion of the hook and loop closure melted. The hook portion of the closure also became more brittle as its nylon backing was repeatedly exposed to the thermal insult. It should be noted that these two portions of the assembly were the only two portions exposed during the test. The upper portions of the radio, including the knobs, screen, and antenna were all protected by the turnout coat. One case was tested after the conclusion of these tests with the entire radio strap assembly exposed.

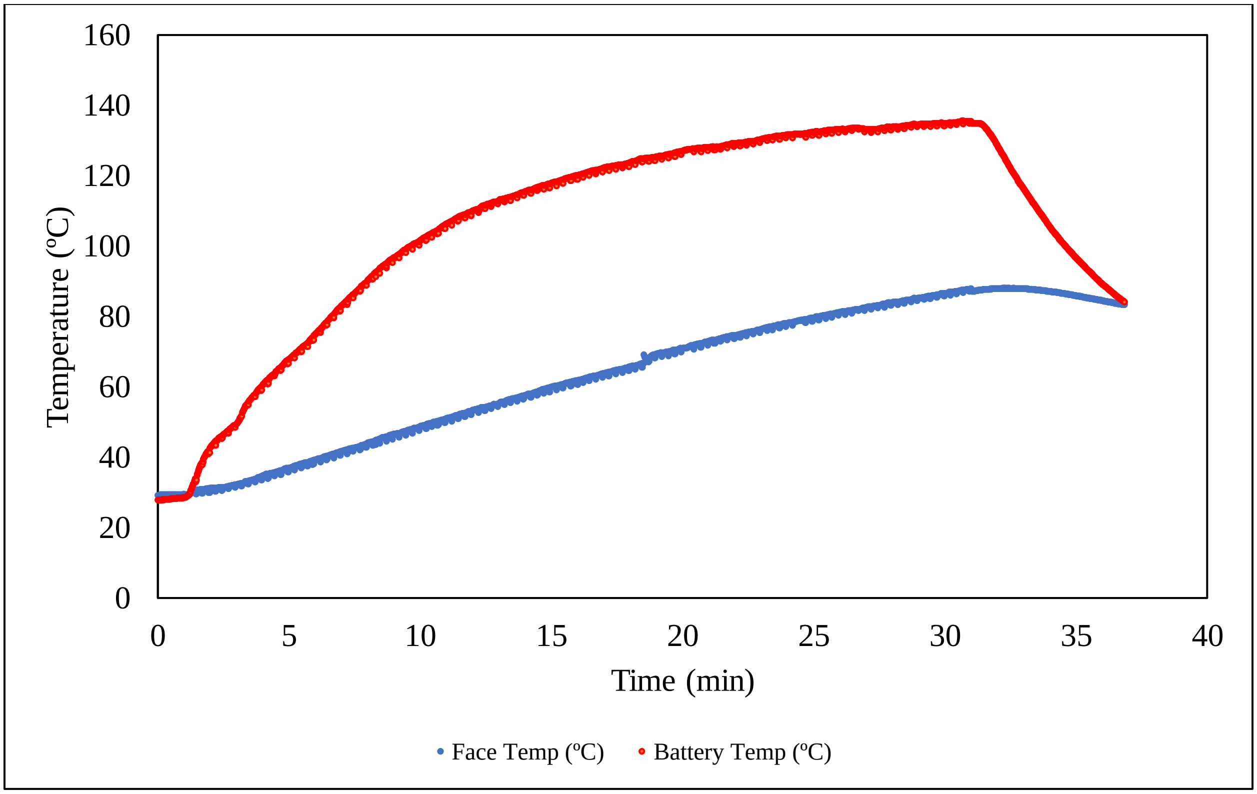

Figure 0.41: 8 $^{kW}/_{m^2}$ Radio Strap Test #1 Temperature Data

Like the first test, the second test did not experience a failure or any discernable signal degradation. There also was not any visually discernable damage to this radio. The temperature data from this test are shown below in Figure 4.42.

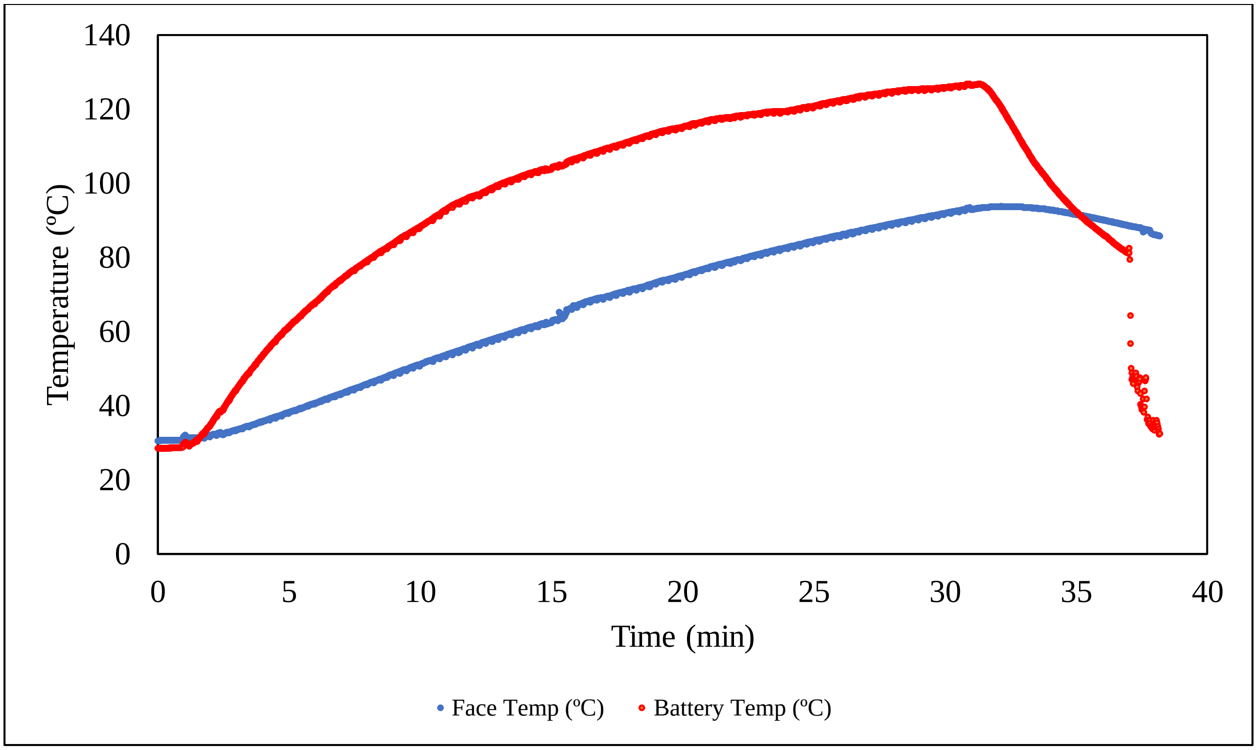

Figure 0.42: 8 $kW/_{m^2}$ Radio Strap Test #2 Temperature Data

As mentioned previously, the third radio did experience a failure. This radio was deemed a failure after it suffered a "bonk" or a busy signal. Attempts were made to key the radio several times, but they all proved to be unsuccessful. The control radio was always able to transmit, despite this busy signal. The control radio was also powered off so that the test radio could be activated without any other radio on the same frequency, but this did not remedy the problem. However, the radio was keyed after about twenty seconds of the "bonk." The same message schedule was then used, and the control radio was keyed on schedule. After this control radio message, the test radio was able to transmit for another fifteen seconds. However, after that message from the control radio, the test radio encountered another "bonk." This cycle continued four times until the radio was deemed a failure when the "bonk" could not be overcome. The temperature data for this radio is found below as Figure 4.43.

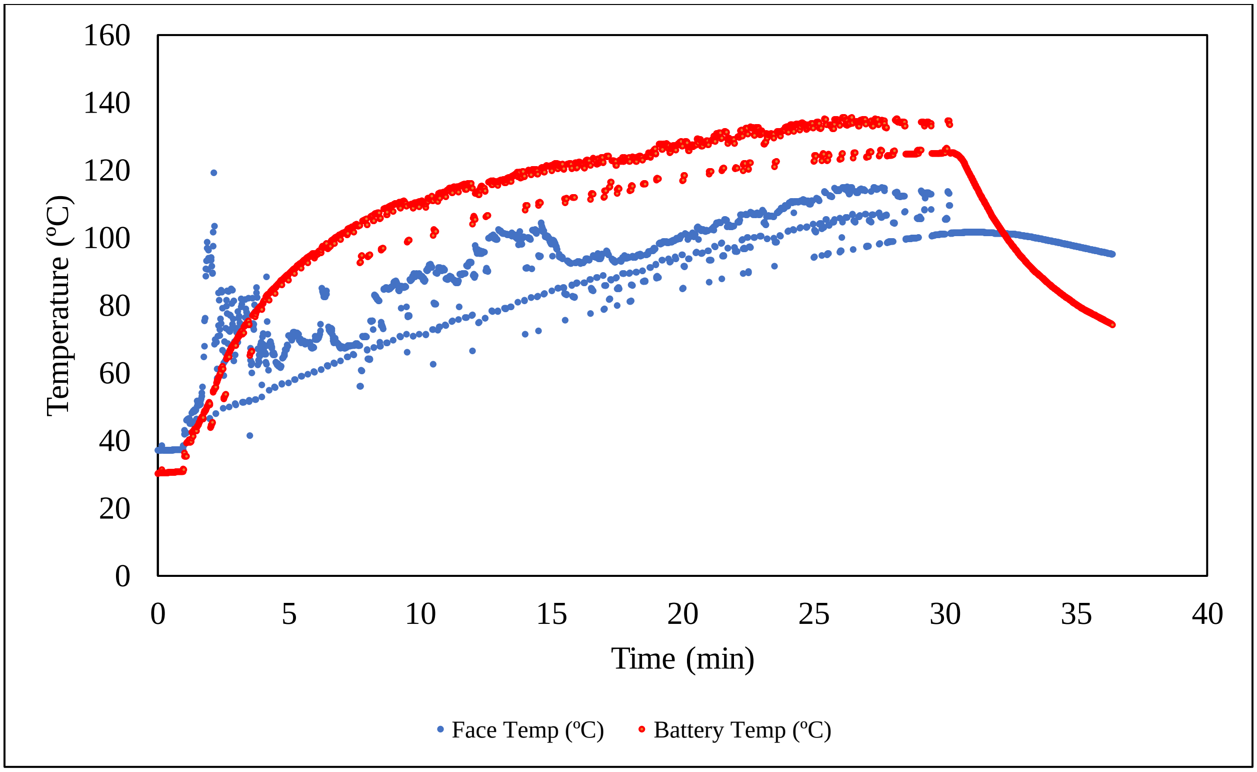

Figure 0.43: 8 $^{kW}/_{m^2}$ Radio Strap Test #3 Temperature Data

The fourth test proceeded in the same manner as the first two tests in that this test did not fail. As with the first two tests, a radio from the pocket tests was used rather than an untested radio like in the third test. The temperature data followed a relatively smooth curve and can be seen below in Figure 4.44.

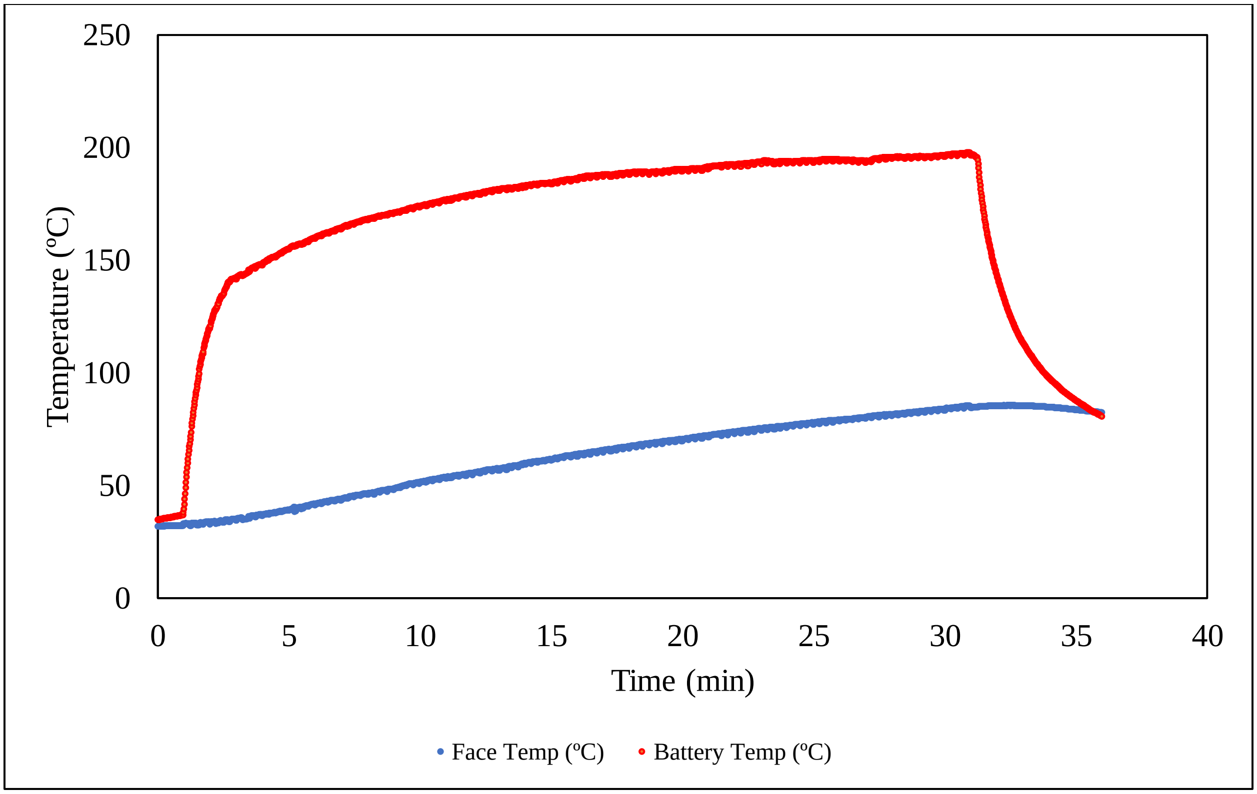

Figure 0.44: 8 $^{kW}/_{m^2}$ Radio Strap Test #4 Temperature Data

The fifth test suffered the same fate as the third test, albeit at a lower exposure time. This test also was conducted on a radio of the same model and sourced from the same vendor as the third test. However, as with the third test, there was no discernable visual damage to the radio. This radio produced its first "bonk" in just under eighteen minutes of exposure time. This signal was overcome four times before the "bonk" could not be overcome in a thirty second period, identical to the third test. The same efforts were taken by turning off the control radio so that the only radio that was transmitting was the tested radio, but this effort was unable to overcome the transmission failure. The temperatures for this radio also followed a similar curve as the other tests and is shown below as Figure 4.45.

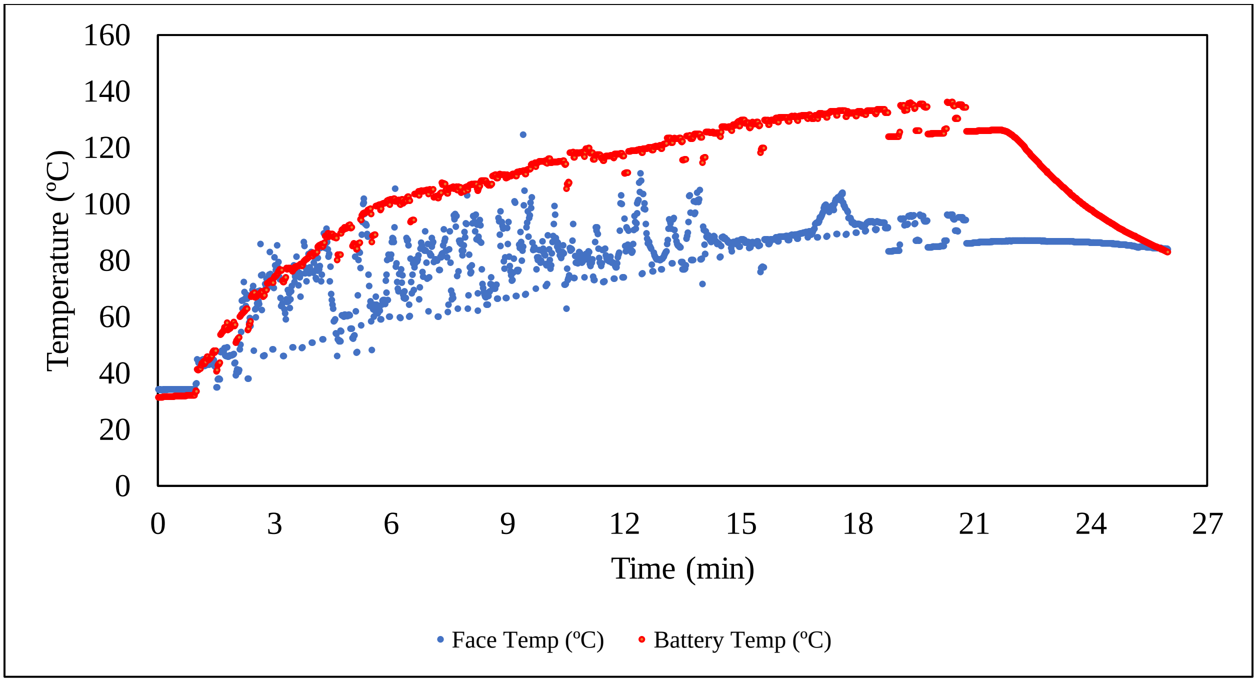

Figure 0.45: 8 $^{kW}/_{m^2}$ Radio Strap Test #5 Temperature Data

The sixth and final test conducted did not result in a failure. This test was conducted using Radio A.3 which was used for a previous test in this series as well as one of the radio pocket tests. No additional visual damage was noted at the conclusion of this test. The radio, battery, and antenna were also used for testing in the next test series. The temperature data recorded during this test can be seen in Figure 4.46 below.

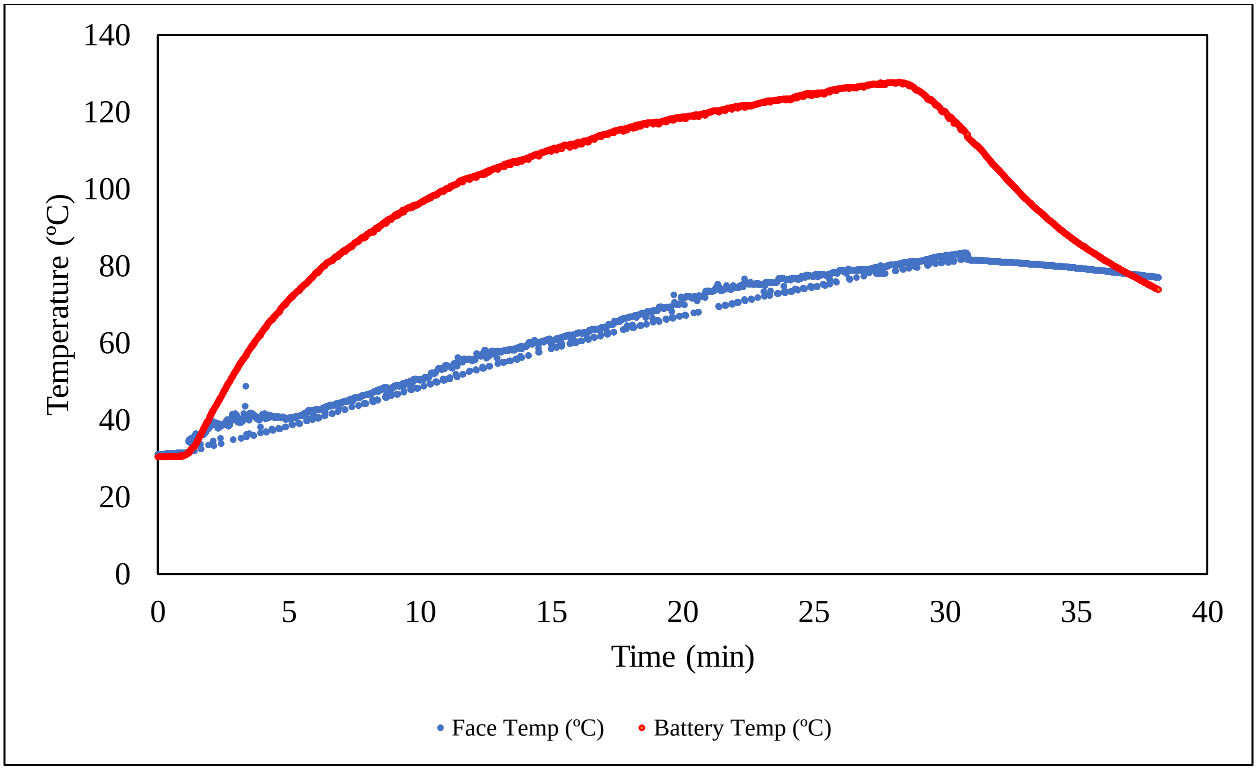

Figure 0.46: 8 $kW/_{m^2}$ Radio Strap Test #6 Temperature Data

While all these radio strap tests were discussed in detail in this subsection, an important note is that only two radios failed. These two radios were of the same model and were sourced from the same vendor. These two radios both failed due to their "bonks." It is unknown why these radios gave "bonks" as there was no other audible traffic on the radio frequency. However, these two radios were not moved to a different frequency during their tests. In the interest of safety and to maintain continuality, the radios were left untouched and undisturbed. However, attempts were made constantly during the period, both with immediate activations of the PTT while also allowing a period to pass before keying the mic. The radios did not return to normal until they had reached ambient conditions. The antennas, batteries, and radios themselves all worked after they had concluded this cool down phase, and all were used for subsequent testing. Table 4.7 shows the failure time and temperature of both the radios that failed, and Figure 4.47 is generated from this table.

Table 0.7: 8 $^{kW}/_{m^2}$ Radio Strap Exposure Failure Time and Temperatures

Test	Radio	Exposure Time to Failure (s)	Failure Temperature at Battery (ºC)	Time to Signal Degradation (s)	Total Test Duration (s)	Failure Mode
8 $^{kW}/_{m^2}$ Strap R1	A.4	N/A	N/A	N/A	2220	N/A
8 $^{kW}/_{m^2}$ Strap R2	A.3	N/A	N/A	N/A	2220	N/A
8 $^{kW}/_{m^2}$ Strap R3	A.4	1740	125.145	1595	2160	"Bonk"
8 $^{kW}/_{m^2}$ Strap R4	C.2	N/A	N/A	N/A	2220	N/A
8 $^{kW}/_{m^2}$ Strap R5	C.3	1239	126.172	1073	1659	"Bonk"
8 $^{kW}/_{m^2}$ Strap R6	A.3	N/A	N/A	N/A	2220	N/A

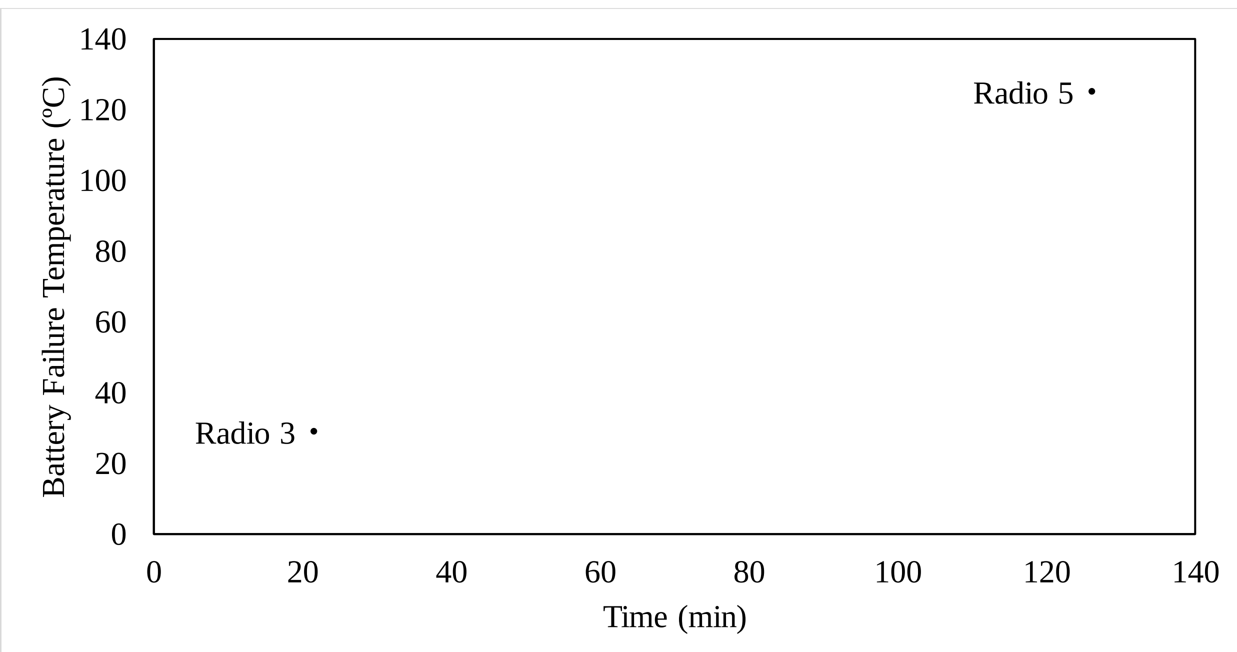

Figure 0.47: 8 $^{kW}/_{m^2}$ Radio Strap Failure Temperature vs. Time

This figure is presented to show the proximity of both the times and temperatures at which the radio failed.

Also, as mentioned above, the “bonks” were digital failures. Named for the sound emitted by the radios, these are “busy” signals, signifying to a user who is attempting to key the radio microphone that someone else is transmitting on the radio channel. However, during these simulations, when a “bonk” was heard, the control radio was powered down to see if the radio that was being tested would produce this “busy” signal. Each time, the radio did immediately reproduce this sound, meaning that the radio was not transmitting. Efforts were also made to attempt to transmit a message despite this signal, but these proved to be unsuccessful. However, after the radios cooled, a “bonk” signal did not manifest itself when the radio was keyed.

Therefore, while impossible to ascertain the specific component that failed, it would appear to be a portion of the computerized internals responsible for the radio to select a channel.

Next, the battery and temperatures are presented below as Figures 4.48 and 4.49 respectively.

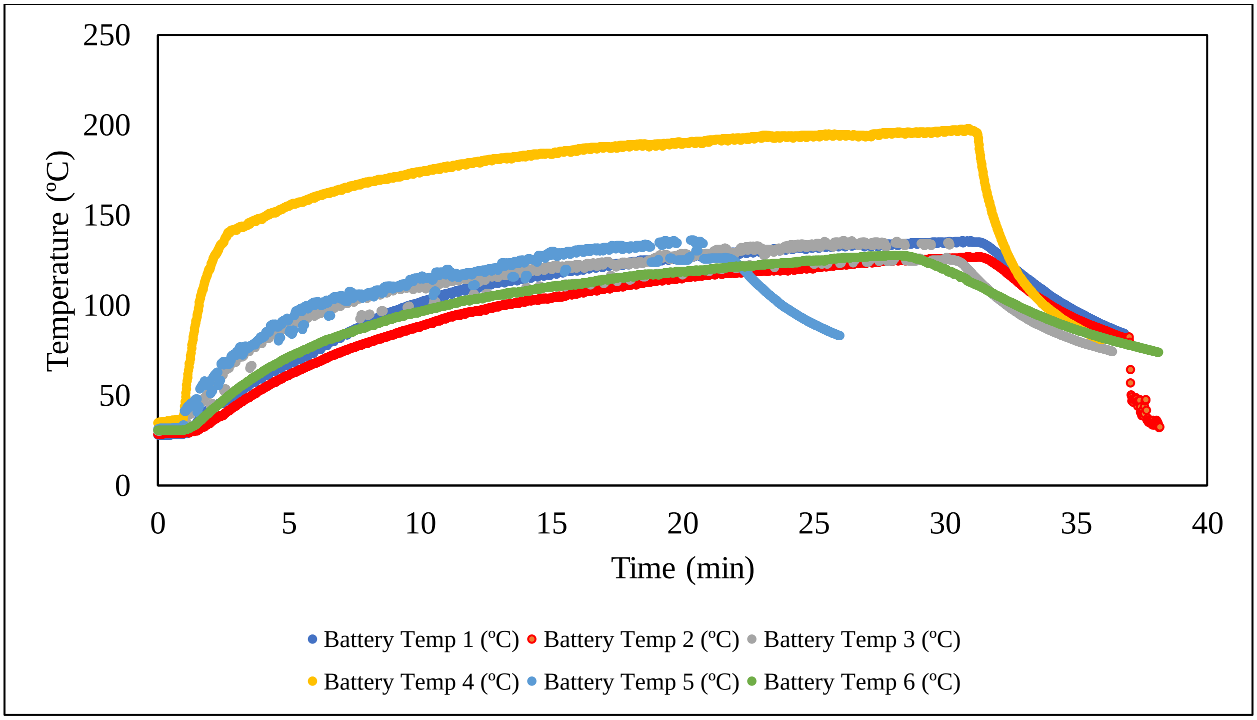

Figure 0.48: 8 $^{kW}/_{m^2}$ Radio Strap Temperature at Battery

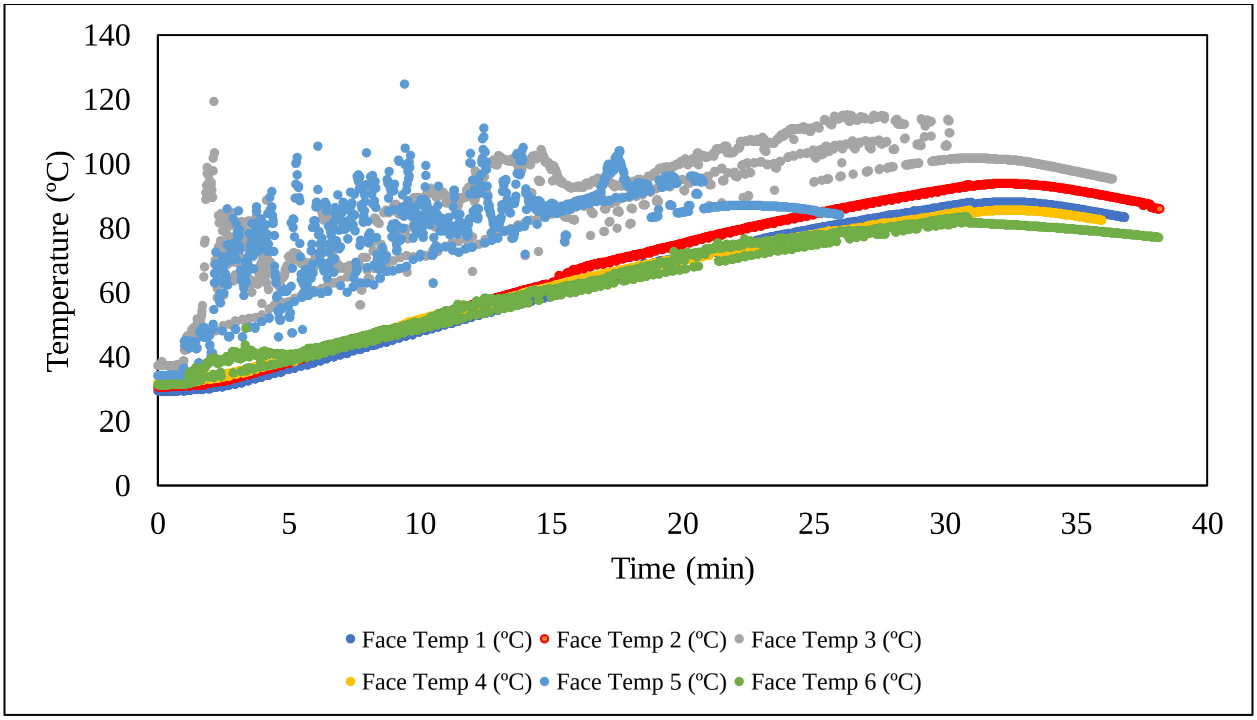

Figure 0.49: 8 $^{kW}/_{m^2}$ Radio Strap Face Temperature

Again, as done with the radio pocket tests, an effort was made to correlate the failure temperatures with the times. Table 4.8 is included below to summarize the third and fifth radios that failed during these radio strap tests.

Table 0.8: Total Average 8 $^{kW}/_{m^2}$ Radio Strap Time vs. Tempearture Data

Test	Duration of Exposure (s)	Area Under the Battery Failure Time-Temperature Curve ($℃ * s$)
Radio 3	1740	233,600
Radio 5	1239	356,100

While there were only two measurements for this test battery, the average value equated to $294{,}87 \pm 61{,}227\ ℃ * s$. As a refresher, the average failure tempearture, when omitting the outlying first radio pocket test, of the radio pocket tests was $289{,}500 \pm 37{,}270\ ℃ * s$. When these radio strap tests are added to this average, the area beneath the curve averages to $291{,}100 \pm 29{,}000\ ℃ * s$. These values will be discussed at the conclusion of the subsection, however it would again seem to confirm that the radio temperature at the battery and exposure time are signifcant factors to determine when the radio will fail.

Furthermore, these tests again exceed the NIST TN 1477 thermal classifications, signifying that the radio strap would be a suitable way to carry a portable radio. Furthermore, due to the significantly increased exposure duration for these tests, radio straps would apear to be the superior way to carry a radio in terms of thermal protection. However, the radios would also be exposed to a $12\ ^{kW}/_{m^2}$ heat flux, the same heat flux exerted on the radios when held in the radio pocket, to verify these findings.

1.16.3 12 $kW/_{m^2}$ Radio Strap Testing

While the 8 $kW/_{m^2}$ heat flux was found for the radio strap positioning, but a 12 $kW/_{m^2}$ heat flux was also used to represent the same heat flux used for the radio pocket. This test series produced similar findings from the previous radio strap and the radio pocket tests. As with the previous radio straps, each of these radios was subjected to a maximum of thirty minutes of exposure, and if the radio was able to transmit and receive messages for the duration of this exposure, then the radio was deemed to have passed the test.

The first test that was conducted used one of the radios that had been tested during the pocket test as well as during the first set of radio strap tests. This radio was used to determine the lowest time that a radio could be expected to survive. However, this radio did not fail. No additional visual damage was observed with this radio and the temperature data followed a very similar curve, as shown below in Figure 4.50.

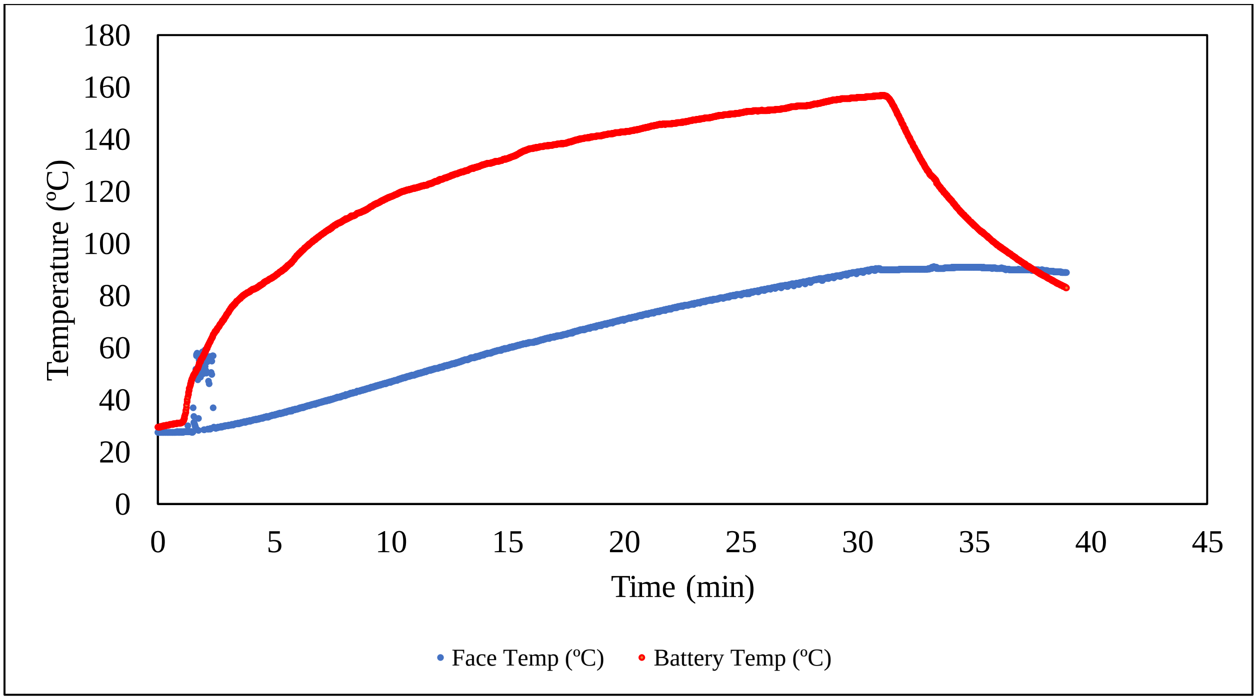

Figure 0.50: 12 $kW/_{m^2}$ Radio Strap Test #1 Temperature

The second tested radio did fail. As with all the failure tests in this series, the "bonk" signals could not be overcome. This radio first gave a "bonk" just over twenty-two minutes of exposure. The process of attempting to overcome these "bonks" continued until the test was deemed a failure about three minutes later. The test was allowed to cool for a total of eight minutes to allow for the face temperature to return to the levels below that of the battery. The radio used during this test was one of the newer radios that did endure some thermal damage. The radio casing was partially misshapen, but more dramatically, some of the nylon coating inside of the radio holster had adhered to the radio. Images of this radio before and after can be seen in Figures 4.51 and 4.52 and the temperature data for this radio can be seen below in Figure 4.53.

Figure 0.51: Radio E.4 Thermal Damage After 12 Strap Test #2

Figure 0.52: Radio E.4 Thermal Damage After 12 Strap Test #2 Close Up

The curve followed roughly the same shape as the other tests as well, although the temperatures remained far lower than the other tests that failed. This radio, battery, and antenna were all able to be used in following tests.

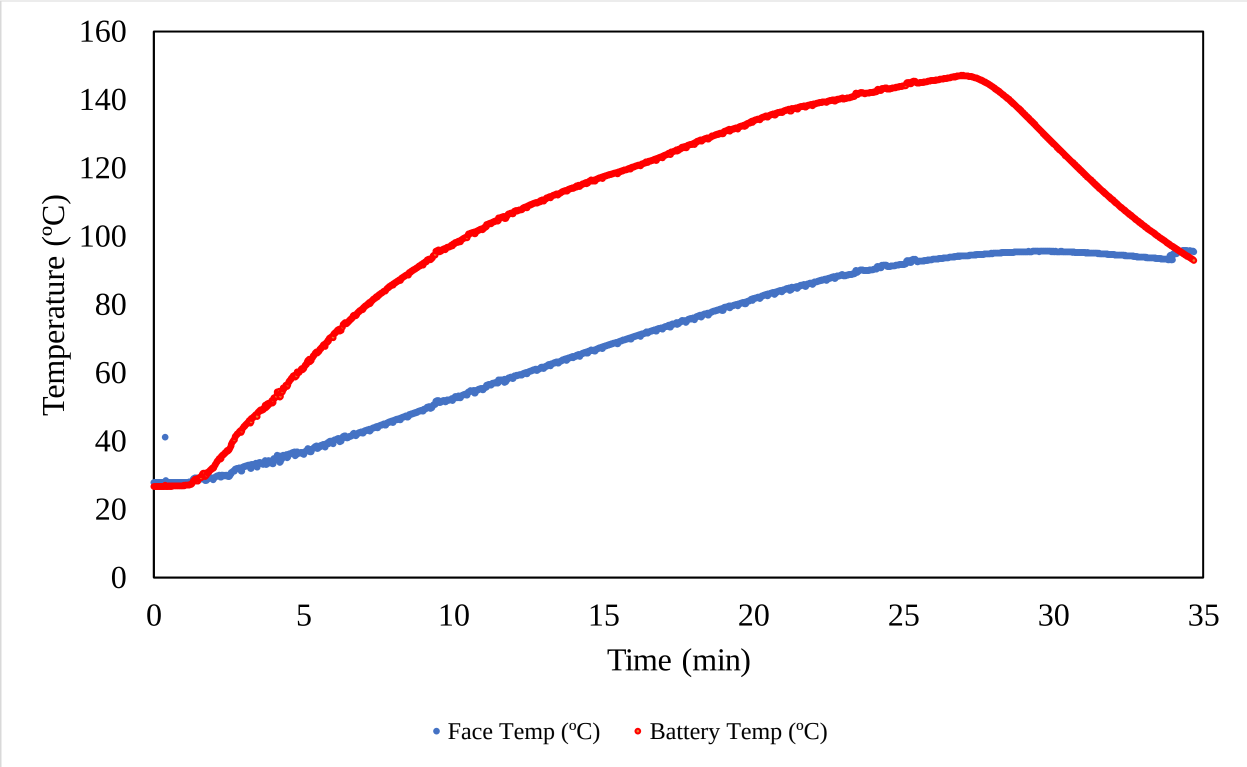

Figure 0.53: 12 $^{kW}/_{m^2}$ Radio Strap Test #2 Temperature Data

The third test also was deemed a failure as the radio also emitted a "bonk" that could not be overcome. This radio had its signal degraded earlier than the any of the other test in this series and it also had the earliest failure. However, no thermal damage was observed after the conclusion of this test. It should also be noted that temperature data followed a somewhat similar shape, but the face temperatures were far more erratic, but they do appear to follow the same general trends. This temperature data for this report is shown below in Figure 4.54.

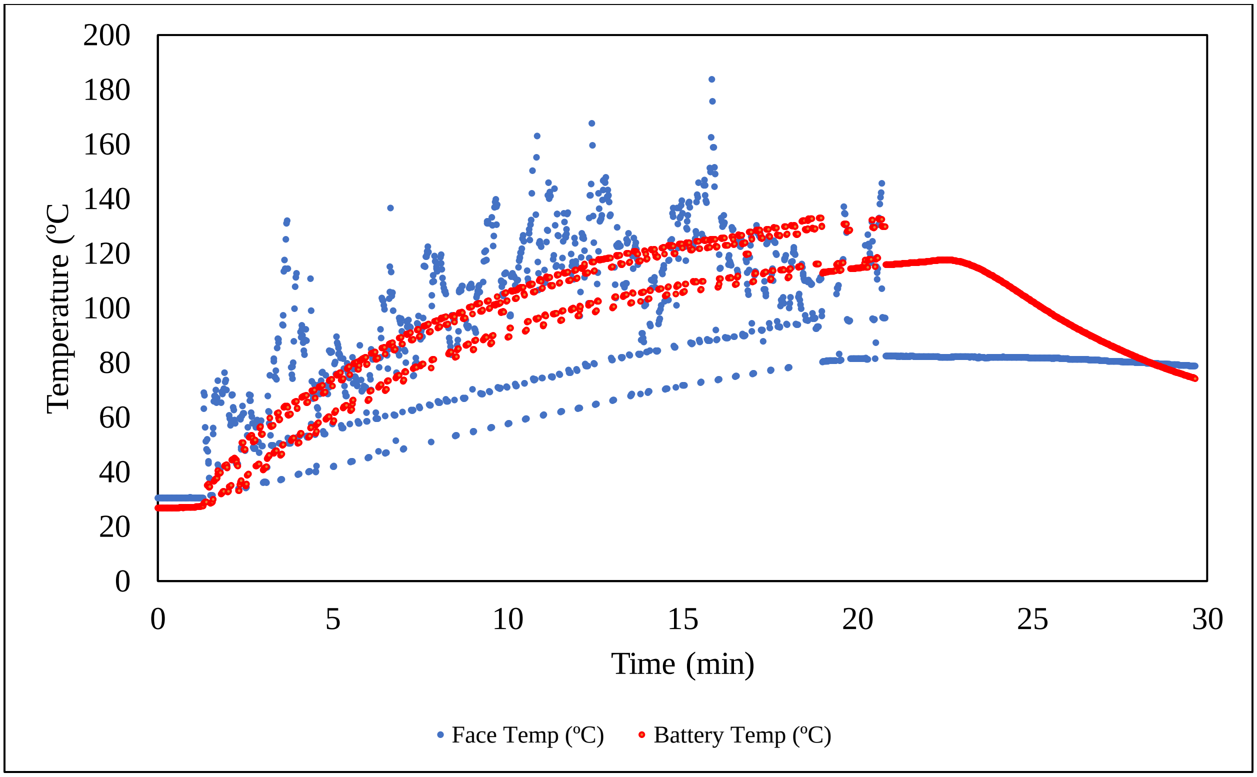

Figure 0.54: 12 $^{kW}/_{m^2}$ Radio Strap Test #3 Temperature Data

The fourth test was conducted with one of the same radios that had been used for multiple tests across all the test series, and as with the other tests, this radio did not fail. Again, no thermal damage was seen from this radio. The temperature data followed roughly the same curves that were shown in the previous tests, but the temperature at the battery did reach a higher temperature than many of the other tests. A graph of these values can be seen below in Figure 4.55.

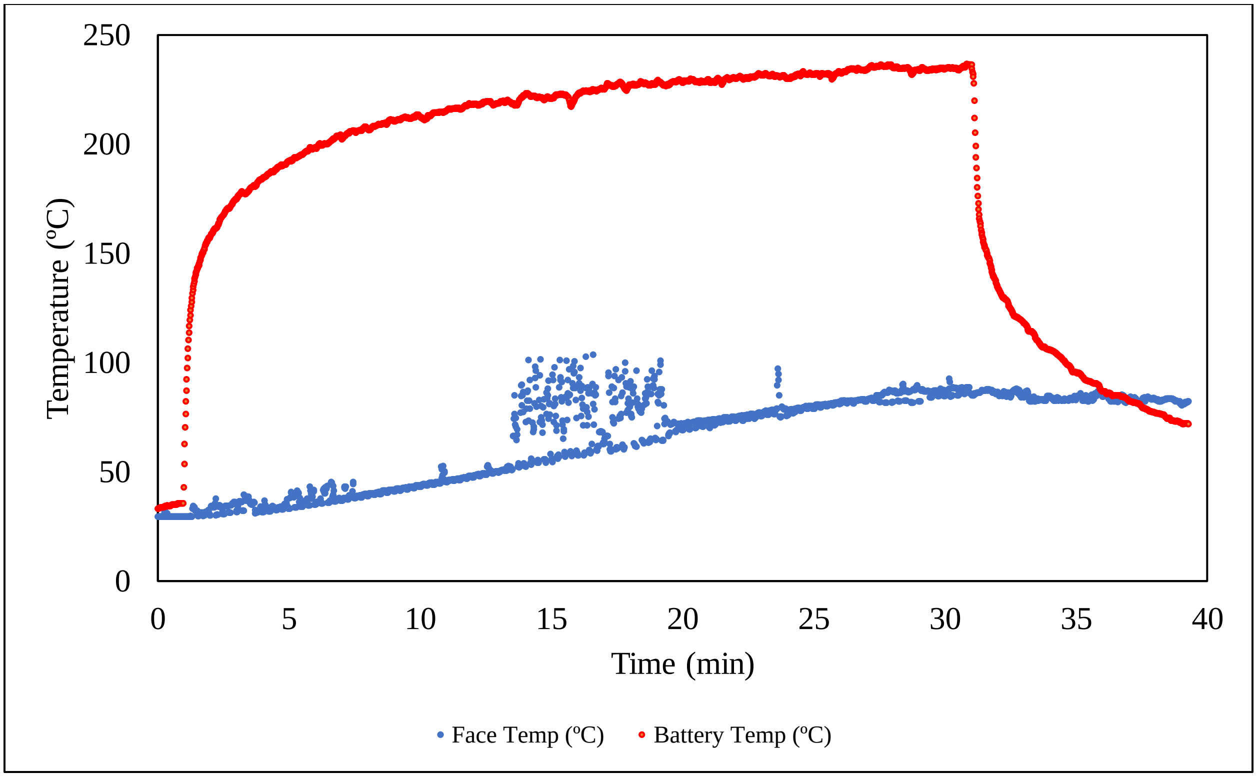

Figure 0.55: 12 $^{kW}/_{m^2}$ Radio Strap Test #4 Temperature Data

The fifth test was also conducted using one of the same radios from the previous tests, and like the fourth test in this series, the radio did not fail. As with before, the radio did not show any thermal damage and the temperature data followed the same trends as many of the other radio strap tests. The thermal data can be seen below in Figure 4.56.

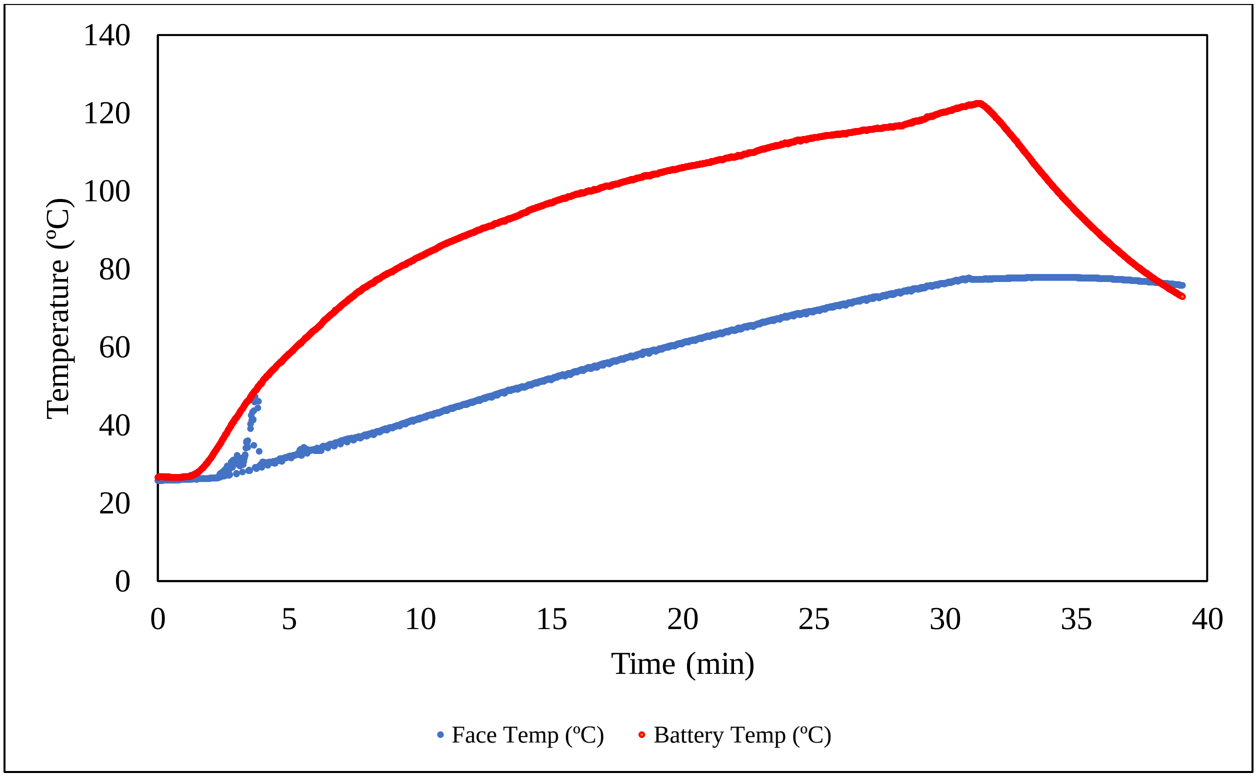

Figure 0.56: 12 $^{kW}/_{m^2}$ Radio Strap Test #5 Temperature Data

The final test conducted in this series did result in a failure. This test was conducted with one of the radios that were sourced from the same vendor as the others that created the "bonks." These bonks also resulted in the failure of this radio as well. The first "bonk" was observed as the radio was keyed at twenty minutes and fifteen seconds of exposure. However, this signal could be overcome more readily than all the other tests. Seven "bonk" cycles were produced during this test with the radio deemed to fail the test six minutes later. The temperatures were a bit more erratic than some of the other tests, but the curves of these temperatures were well in line with the other tests. A graph of the temperature data from this sixth and final 12 $^{kW}/_{m^2}$ radio strap test is seen below as Figure 4.57.

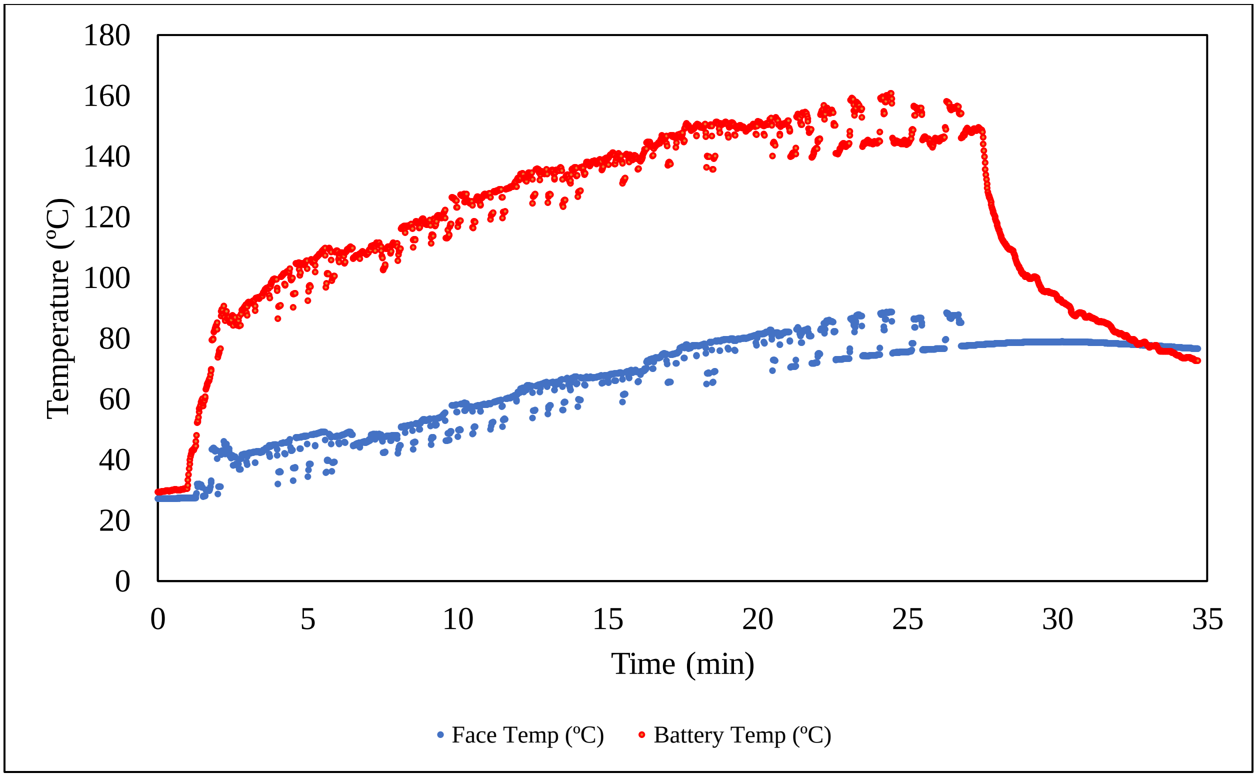

Figure 0.57: 12 $^{kW}/_{m^2}$ Radio Strap Test #6 Temperature Data

Finally, as conducted with the previous test series, a summary of the testing can be found below. Table 4.9 below provides the failure time and temperatures while Figure 4.58 shows a graphic representation of the table. Figures 4.59 and 4.60 that follow show the face and the temperature at the battery.

Table 0.9: 12 kW/m^2 Radio Strap Failure Time and Temperatures

Test	Radio	Failure Time (s)	Failure Temperature at Battery (ºC)	Time to Signal Degradation (s)	Total Test Duration (s)	Failure Mode
12 kW/m^2 Strap R1	A.4	N/A	N/A	N/A	2220	N/A
12 kW/m^2 Strap R2	C.4	1536	147	1327	1956	"Bonk"
12 kW/m^2 Strap R3	C.3	1230	117	1095	1650	"Bonk"
12 kW/m^2 Strap R4	A.3	N/A	N/A	N/A	2220	N/A
12 kW/m^2 Strap R5	A.4	N/A	N/A	N/A	2220	N/A
12 kW/m^2 Strap R6	C.4	1560	149	1215	1980	"Bonk"

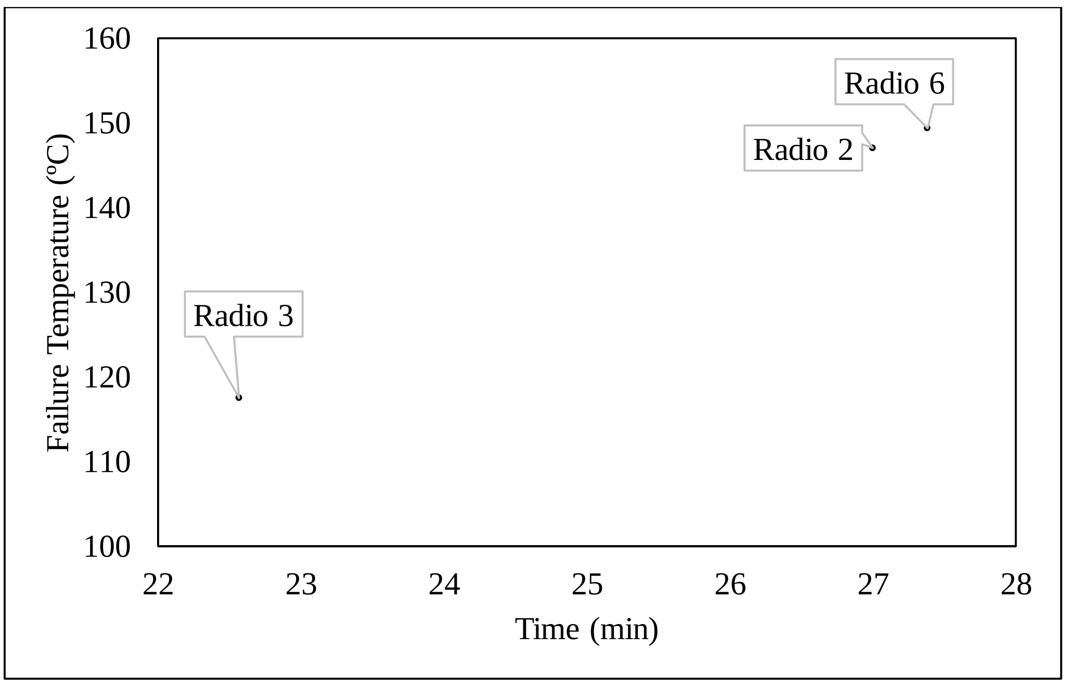

Figure 0.58: 12 kW/m^2 Radio Strap Failure Temperature vs. Time

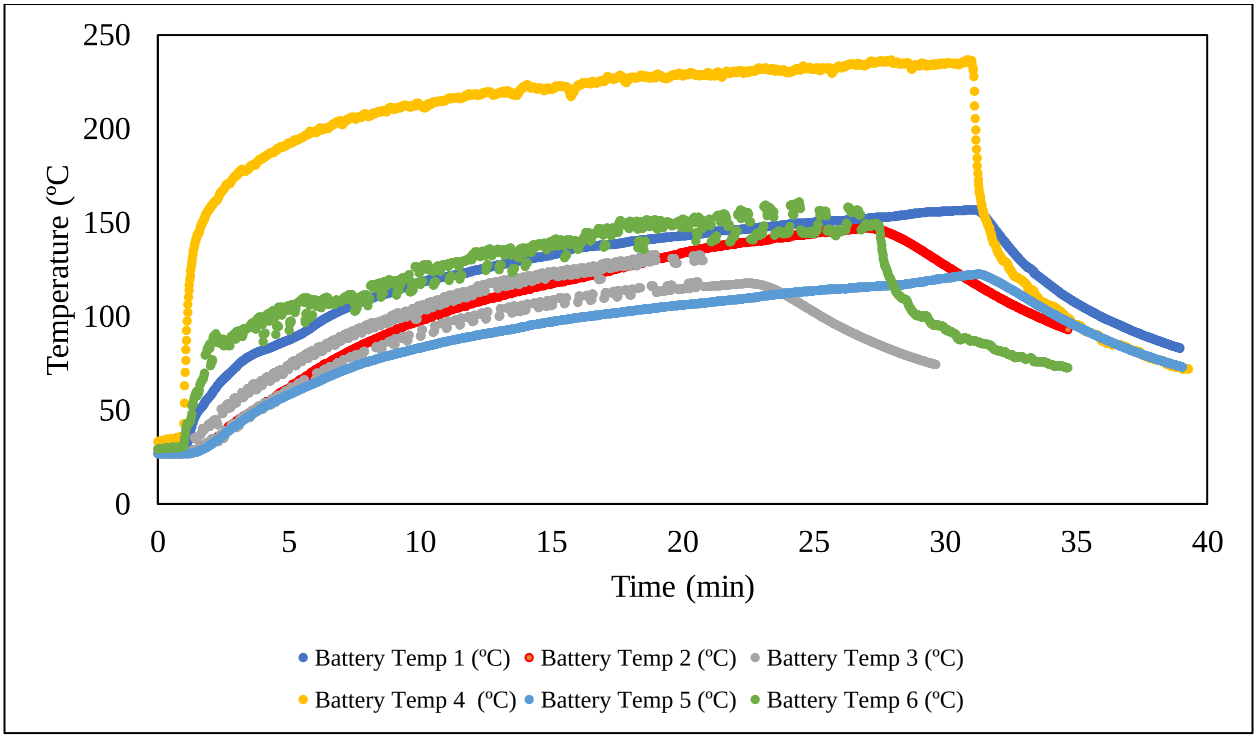

Figure 0.59: 12 $^{kW}/_{m^2}$ Radio Strap Temperature at the Battery

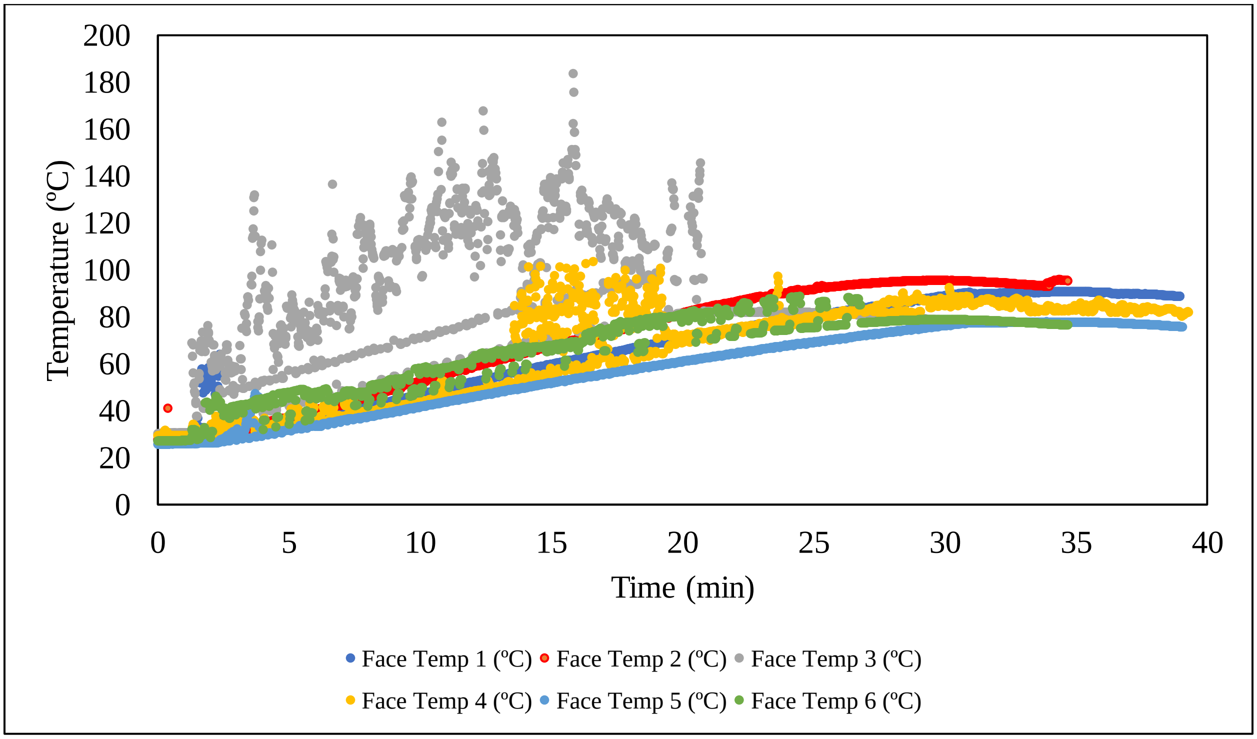

Figure 0.60: 12 $^{kW}/_{m^2}$ Radio Strap Face Temperature

The final portion of this analysis was to determine the average temperature during the three failing simulations. These averages can be found below in Table 4.10.

Table 0.10: Total Average 12 $^{kW}/_{m^2}$ Radio Strap Time vs. Tempearture Data

Test	Duration of Exposure (s)	Area Under the Battery Failure Time-Temperature Curve ($℃ * s$)
Radio 2	1536	221,400
Radio 3	1230	166,800
Radio 6	1560	441,200

Equipped with these averages for each test, the average of the failure 12 $^{kW}/_{m^2}$ Radio Strap tests is $276{,}500 \pm 83{,}900(℃ * s)$. Additionally, with these three failures, the failure criteria can be calculated for the radio strap tests. This value averages to $245{,}500 \pm 508{,}900\ (℃ * s)$. And finally, these additional radios drive the cumulative average of all the failure tests to $267{,}500 \pm 30{,}630(℃ * s)$. Again, the proximity of these average failure temperatures would seem to suggest that the temperature at the battery for a sustained duration is what causes the radio to fail, or to emit the "bonk" signal. More information on this revelation will be discussed in the following chapter.

1.16.4 Exterior Radio Strap Testing

The final tests done in this analysis involved two radios outside of the turnout coat in a radio strap. While this arrangement generally goes against guidance issued to firefighters, this arrangement was tested as it remains a somewhat popular method to carry a portable radio. These tests also examined the conditions when the radio was not protected under the turnout coat, but rather left exposed.

These two tests were conducted at different incident heat fluxes with the intention of examining both the 8 $^{kW}/_{m^2}$ heat flux, and the 12 $^{kW}/_{m^2}$ heat flux that were both tested during the original analyses. Only a single replicate of each test was done as there were not enough additional radios or shoulder microphones to conduct a full test battery of six replicates due to prohibitive radio costs. Therefore, an average graph will not be presented in this analysis, but the failure findings will be considered in conjunction with the previous tests.

Both radios used in this analysis were the radios that provided the “bonks”. The radio used in the 8 $^{kW}/_{m^2}$ heat flux analysis had its signal degrade at approximately fifteen minutes of exposure. The radio, antenna, and battery all did function as normal after a cool down period.

The thermal data produced from this test followed a slightly different profile than the previous tests, with a much more erratic face temperature. These variations are likely due to the decreased insulation around the thermocouple. The thermocouple again melted to this radio, likely causing some variations. The temperatures at battery shown in this test did not reach the “steady” portions of the curve that was seen in the previous trials as the temperatures continued to increase throughout the test. This temperature data is presented below as Figure 4.61.

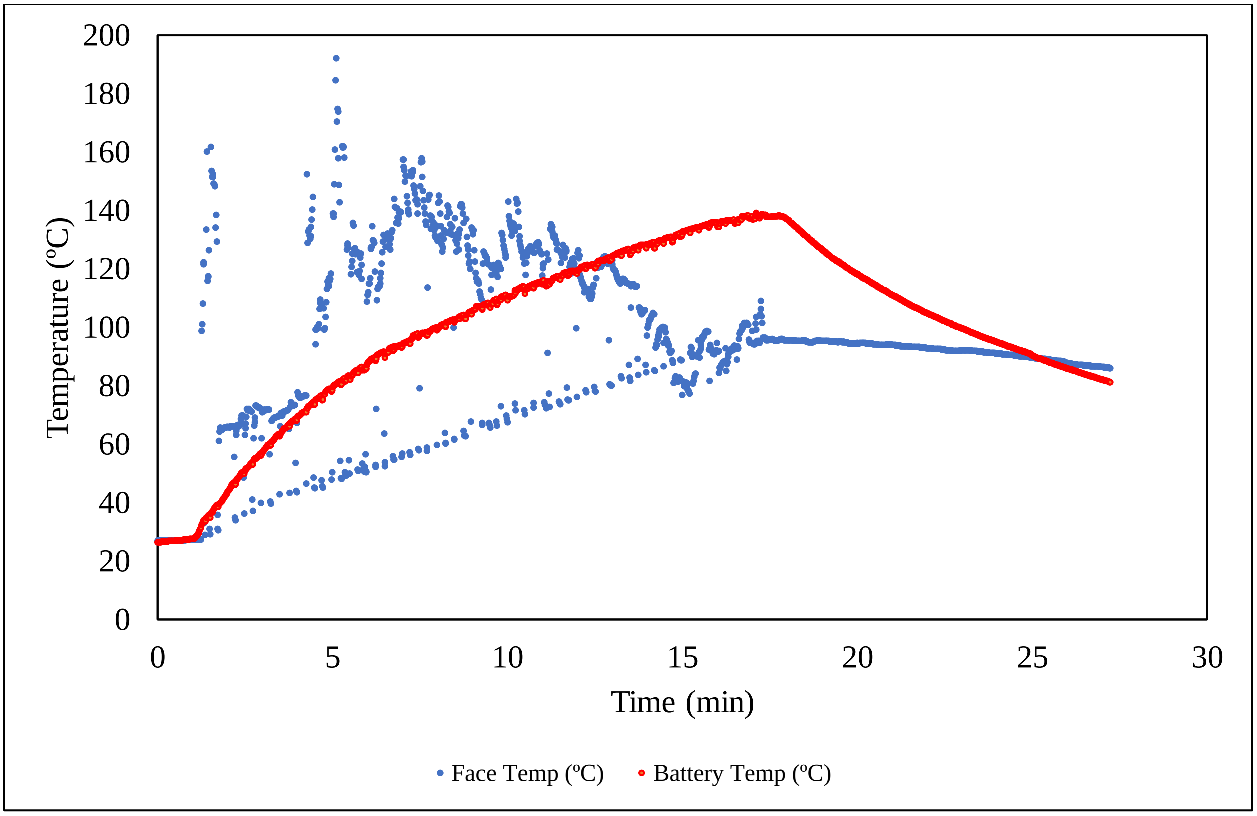

Figure 0.61: 8 $^{kW}/_{m^2}$ Exterior Radio Strap Test Temperature

The findings were similar for the analysis conducted of the radio strap assembly directly exposed to the 12 $^{kW}/_{m^2}$ heat flux. This radio also suffered severe thermal damage. Interior components of the radio were visible at the conclusion of the test and the rubber channel selector knob suffered severe deformation. The antenna was also bent at the conclusion of this test. However, the battery and the antenna were able to transmit and receive at the conclusion of the test, although the radio was not. Figures 4.62 through 4.64 below show this damage.

Figure 0.62: Radio E.6 Damage After Removal After 12 Strap Outside Test #1

Figure 0.63: Radio E.6 Melting After 12 Strap Outside Test #1

Figure 0.64: Radio E.6 Melting Close Up After 12 Strap Outside Test #1

The temperature data obtained for this test show results in line with both the previous outside radio test as well as the other tests. However, the temperatures at the battery rapidly exceeded the face temperature as it followed the increasing trend until the radio failed about twelve minutes after the exposure. The radio did not give any advanced warning of an impending failure as once the significant signal degradation was observed at just under twelve minutes, it could not be overcome. The temperature data from this test is seen below as Figure 4.65.

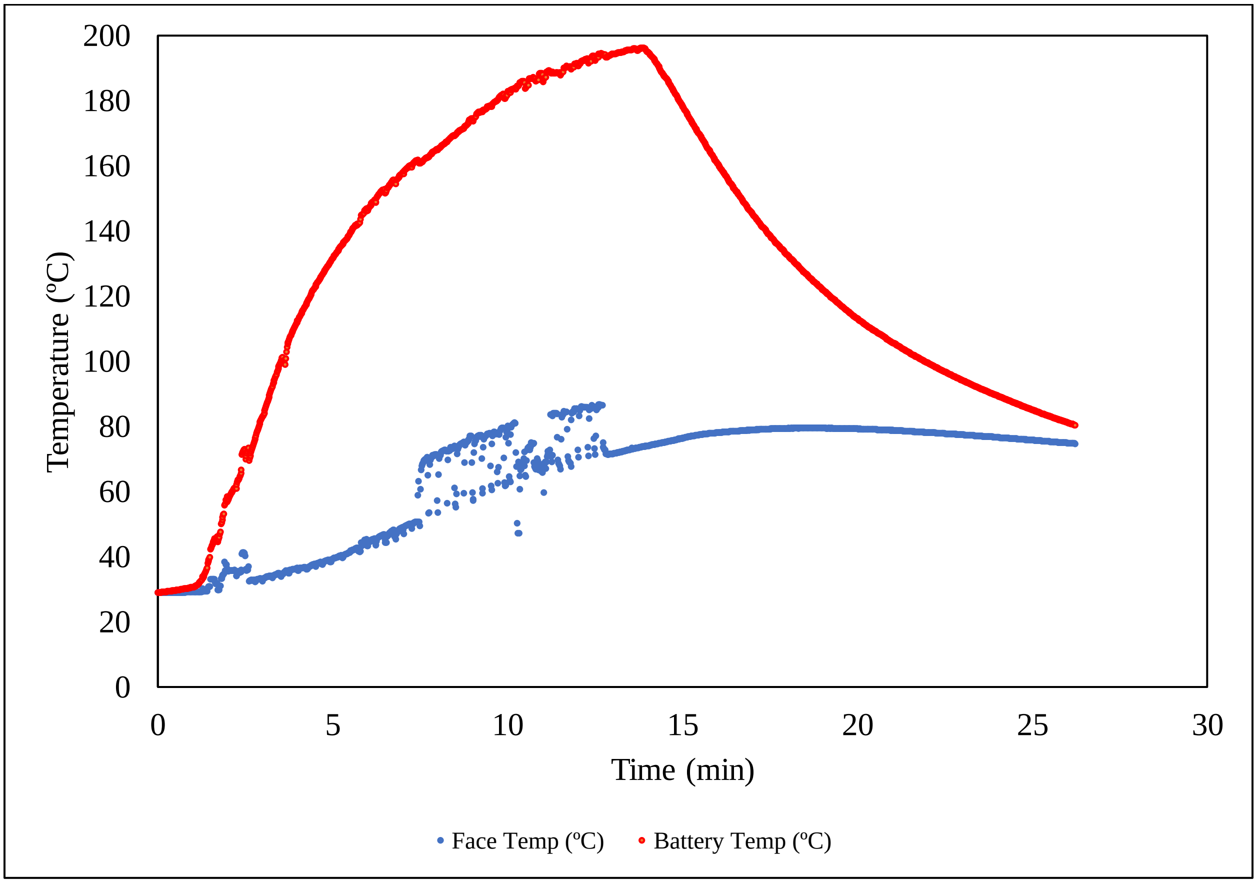

Figure 0.65: 12 ${}^{kW}/_{m^2}$ Exterior Radio Strap Test Temperature

As previously mentioned, the two temperature graphs will not be compared to each other, but Table 4.11 shows the same basic information such as test duration, exposure time to failure, and time to signal degradation.

Table 0.11: Exterior Radio Strap Failure Time and Temperatures

Test	Radio	Failure Time (s)	Failure Temperature at Battery (ºC)	Time to Signal Degradation (s)	Total Test Duration (s)	Failure Mode
8 $^{kW}/_{m^2}$ Exterior Strap	C.5	975	138	900	1395	"Bonk"
12 $^{kW}/_{m^2}$ Exterior Strap	C.6	735	196	705	1155	"Bonk"

The same analysis of the time vs. temperature curves conducted in the previous test series are shown below in Table 4.12.

Table 0.12: Average Failure Temperatures for Exterior Radio Strap Tests

Test	Duration of Exposure (s)	Area Under the Battery Failure Time-Temperature Curve (ºC*s)
8 $^{kW}/_{m^2}$ Exterior Strap	975	162,600
12 $^{kW}/_{m^2}$Exterior Strap	735	204,500

While these temperatures are quite different from each other, this can likely be explained both by the time differences, but mainly by the different heat fluxes to which the radios were exposed. The average of these temperatures is $183{,}500 \pm 20{,}940$ ℃ $*$ s. This brings the average failure temperature for all radios, excluding the first radio pocket test, to $237{,}100 \pm 21{,}080$ ℃ $*$ s. While these numbers appear quite large, this is both a function of the heat fluxes as well as the exposure times. Therefore, a standard error that is less than 10% of the mean would seem to imply that this correlation is valid. As discussed previously, the proximity of these measurements would seem to indicate that the temperatures at the battery and the exposure duration are the driving factor for the radio to fail.

1.16.5 Analysis of Repeated Use Radios

During this test, five radios were used multiple times. Images of the radios are presented above, along with a description of how each test fared for each radio, but this section is included with the intention of listing the results of radios that were exposed multiple times. Radios A, E.3, and E.4 were all used twice while Radio C survived four tests and Radio D surviving five. All these radios failed at least one test.

Radio A is of special interest as the radio was used for the first test that only survived an exposure of 150 seconds. As mentioned above, the antenna suffered some damage, but the radio remained in usable condition. However, after the sixth pocket test, this radio failed and exhibited severe thermal damage.

Radios E.3 and E.4 both were first used during the radio strap tests, with E.3 being used during the $8\,{}^{kW}/_{m^2}$ series and E.4 first used in the $12\,{}^{kW}/_{m^2}$ series, where they both failed. These two radios failed due to the “bonk” signal that they produced, a common point of failure for all radios of the E series. A table showing the results of Radio A and these two E series radios is presented below as Table 4.13.

Table 0.13: Results of Radios Used in Two Tests

	Radio A	Radio E.3	Radio E.4
First Test	Pocket Test #1	8 Strap Test #5	12 Strap #2
Fist Test Failure Time (seconds)	150	1295	1602
Second Test	Pocket Test #6	12 Strap Test #3	12 Strap Test #6
Second Test Failure Time (seconds)	1082	1354	1643

Table 0.14: Results of Radios Used in Four or More Tests

	Radio C	Radio D
First Test	Pocket Test #3	Pocket Test #4
Fist Test Failure Time (seconds)	1503	1101
Second Test	8 Strap Test #2	8 Strap Test #1
Second Test Failure Time (seconds)	N/A	N/A
Third Test	8 Strap Test #5	8 Strap Test #3
Third Test Failure Time (seconds)	N/A	N/A
Fourth Test	12 Strap Test #4	12 Strap Test #1
Fourth Test Failure Time (seconds)	N/A	N/A
Fifth Test	N/A	12 Strap Test #5
Fifth Test Failure Time (seconds)	N/A	N/A

1.16.6 Notes on Turnout Coats

While not one of the main focuses of this analysis, the turnout coat performance was also measured visually. For this research, two different turnout coats were used. Both coats had incisions made for the radio pocket tests, but these did not appear to have any influence over the condition of the coat. The reason that two different coats were used was due to the rubber sheathing of several antennas melting to the coat. Figures are presented below of both turnout coats, but much of the damage was seen on the reflective trim. This finding would appear to be consistent with the Loudon County report discussed in the earlier chapters [43]. In Appendix 7 which discussing the firefighters' protective equipment, many of the firefighters had the trim either charred or completely deteriorated. As a side note, one of the firefighters also had their, "Radio microphone melted to right side of coat," while another had, "a microphone cord that is melted to FF's right front lower cargo pocket." The main body of the report provides the recommendation, “Encourage a national effort to minimize reflective striping on structural firefighting PPE from areas of possible compression.” [43]

The same nylon radio strap was used for all the tests, which experienced a significant amount of melting. Figures 4.66 through 4.68 show these results. The hook and loop closure on the radio pockets of both turnout coats also experienced similar results. During the first tests in which these pockets were used, the closures opened and were exposed to the heat flux. The materials then began to melt. After the first test, the pockets could still be closed, but much more effort was required than originally. After the second test for each coat, the pockets could not be closed as the closure materials began to drip. Images of the pocket can be seen in Figures 4.69 through 4.71. Finally, figures of the reflective striping discussed earlier are also shown as Figures 4.72 through 4.74.

Figure 0.66: Radio Strap Degradation Between Tests

Figure 0.67: Nylon Radio Strap Label Melted After Testing

Figure 0.69: Radio Strap and Reflective Trim Damage

Figure 0.68: Turnout Coat Radio Pocket Closure Degradation after Pocket Test #1

Figure 0.70: Radio Pocket Closure Dripping After Pocket Test #2

Figure 0.71: Radio Pocket Closure Completely Degraded

Figure 0.72: Radio Pocket Trim Degradation

Figure 0.73: Trim Degradation and Turnout Gear Discoloration

Figure 0.74: Trim Damage After Strap Tests

1.16.7 Summary of Failure Times and Temperature

Finally, a summary can be included for the failures of each radio. Tables were presented above with each testing set of testing, but to coordinate these failure times and temperatures, a table is presented below to show this information. From Table 4.15 below, Figure 4.75 shows a graphical representation of the failure temperatures at the battery and the failure time.

Table 0.15: Total Radio Failure Time and Temperatures

Test	Radio	Failure Time (s)	Failure Temperature at Battery (ºC)	Time to Signal Degradation (s)	Total Test Duration (s)	Failure Mode
Pocket R1	A.1	224	178	N/A	570	Transmission Failure
Pocket R2	B	1815	228	525	2168	Transmission Failure
Pocket R3	A.2	1503	225	600	1854	Transmission Failure
Pocket R4	A.3	1101	197	465	1422	Transmission Failure
Pocket R5	C.1	755	225	N/A	1117	Transmission Failure
Pocket R6	A.1	1082	276	N/A	1425	Transmission Failure
8 kW/m^2 Strap R3	A.4	1740	125	1595	2160	"Bonk"
8 kW/m^2 Strap R5	C.3	1239	126	1073	1659	"Bonk"
12 kW/m^2 Strap R2	C.4	1536	147	1327	1956	"Bonk"
12 kW/m^2 Strap R3	C.3	1230	117	1095	1650	"Bonk"
12 kW/m^2 Strap R6	C.4	1560	149	1215	1980	"Bonk"
8 kW/m^2 Exterior Strap	C.5	975	138	900	1395	"Bonk"
12 kW/m^2 Exterior Strap	C.6	735	196	705	1155	"Bonk"

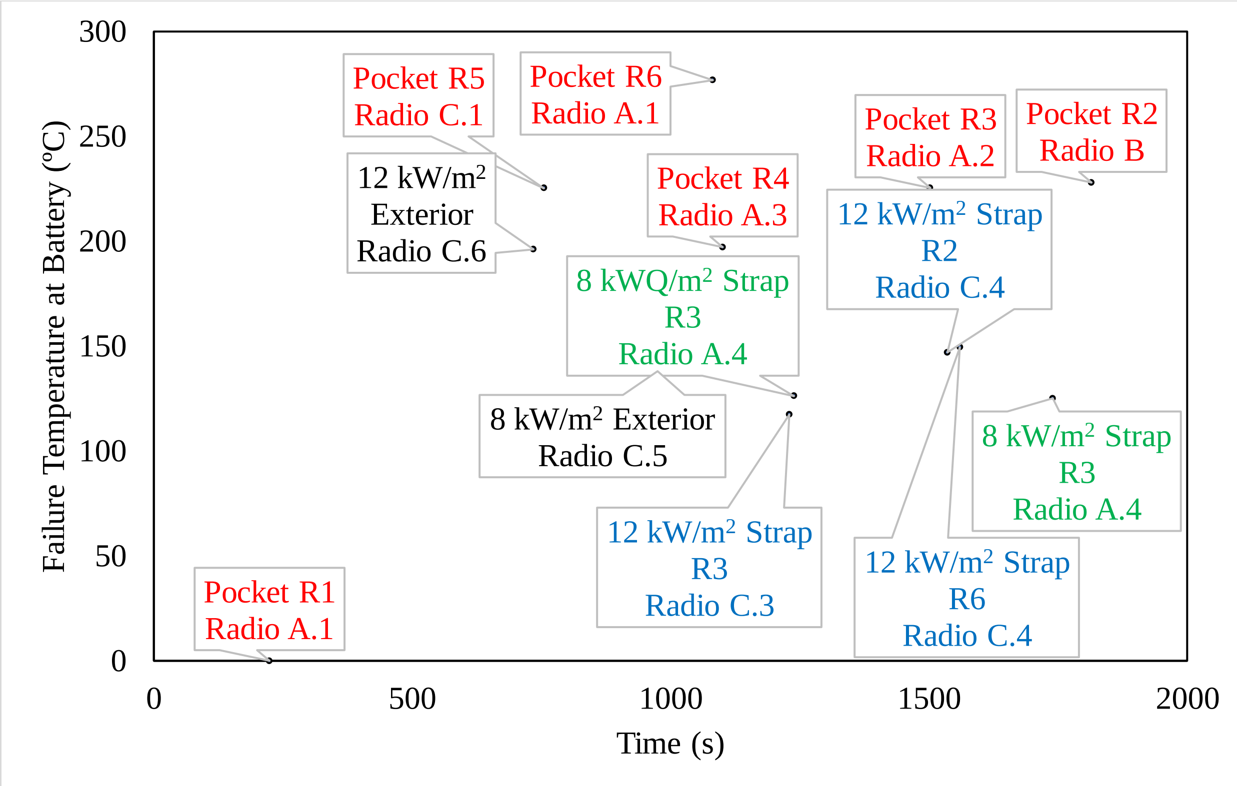

Figure 0.75: Failure Temperature at Battery and Failure Time Comparison

While the graph above shows large disparities between different radios, it does show a few trends, especially when coupled with the signal degradation times discussed earlier. As a trend, the highest battery failure temperatures were seen in the radio pocket tests. While Radio B, tested as a part of the radio pocket analysis, had the longest failure time, it should again be noted that this radio was the only radio of a different model. Also, the radios that endured the longest were those carried in a radio strap. These also had the lowest temperatures when they failed, which would confirm the hypothesis that wearing the radio beneath the turnout coat would provide superior thermal protection. Finally, wearing the radio in a radio strap above the turnout coat does not provide the same protection as wearing the strap beneath the coat. It also led to more dramatic failures as the signal degradation times were far less for these radios than for the other carrying methods.

Conclusions

1.17 Final Thoughts

With the conclusion of the empirical testing portion of this report, some best practices can be gleaned, and some recommendations made to policy makers in the fire service. Also, it is hoped that those involved in the firefighting equipment manufacturing industry and in the standards making process would take some recommendations of their own from this research. The recommendations toward the firefighters and to policy makers are listed below.

1.18 Experimental Program Comments

As shown above, these radios do show a large disparity in failure time, even in the same carrying configuration. However, the 8 $^{kW}/_{m^2}$ is not an extreme heat flux, so it is quite alarming for these radios to have failed at this lower heat flux. Therefore, the placement of a radio certainly increases the radio's durability in a fire situation. While wearing a radio beneath a turnout coat will certainly extend the time to failure, it also provides many other benefits outlined in the Fairfax County Study [38]. Additionally, wearing a radio in a position where it will remain in its holder is preferable as shown in the NIST study. Wearing a radio in a turnout pocket greatly increases the possibility that the radio will become completely exposed and unprotected. This may prove detrimental to the firefighter and implies that wearing a radio in a radio strap is the superior way to carry a radio strap.

Also, while the first radio strap test had a significantly reduced failure time, the heat flux varied much like a normal fire situation. Furthermore, as the radio moves closer to the radiant panel, the heat flux was increased. While this increased heat flux was not determined, it is unlikely that the heat flux increased above a 20 $^{kW}/_{m^2}$ threshold. Therefore, when a firefighter is exposed to more severe thermal conditions, it is likely that his or her radio will fail. When a radio fails at such a critical juncture, a firefighter may become severely injured or potentially even killed. While thankfully it did not result in a fatality, this situation occurred in the Riverdale Heights incident referenced earlier [44].

1.19 Recommendations to Firefighters

Firefighters first need to be able to operate their radio whenever they are engaged in dangerous activities, even if only to call for assistance when endangered. However, firefighters often use their radios to communicate when involved in emergency activities. Therefore, firefighters first must be able to always operate their radios. Firefighters should know the features of their radios and be comfortable operating it in uncomfortable conditions. Firefighters may become trapped and have their range of motion compromised, meaning that they might not be able to reach a radio. To achieve this goal of radio proficiency, firefighters must ensure that they train with the radios in real world scenarios often.

While firefighters may be allowed to choose the side or location where they prefer to wear their radio, it is imperative to protect the radio's battery. However, this consideration may seem to be unnatural, as many would view the screen to be the front of the radio and the battery to be the rear, with the desire to protect the screen. This effort can be especially challenging for the radio pocket, as firefighters often place the screen toward themselves while the battery faces the outside environment. Firefighters orient their radios in this way both to provide increased visibility to the screen as well as to place the radio in a more comfortable position. The flat portion of the radio is where the screen is generally located, meaning that that end of the radio is the one often left to face the firefighter. Therefore, the battery is left facing the outside environment.

In addition to training, firefighters must be comfortable with how they wear their radios. If a fire department requires a firefighter to wear his or her radio in a certain location, then the firefighter should be comfortable with that model of radio worn in that location. However, where firefighters have a choice, it would certainly appear that wearing a radio under the turnout coat in a radio strap provides the best protection. As alluded to earlier, firefighters should also be comfortable and confident in their ability to change volume or channels when operating in dangerous environments. This proficiency will assist firefighters with overcoming the main drawback of this carrying method: having to move the turnout coat to access the channel selector and volume knobs on the radio. If a firefighter is unable to use the knobs with the extremely limited dexterity afforded by firefighting gloves, then it may take them longer to make these critical changes. The longer that the firefighter must lift his or her turnout coat, then the longer that the station uniform below the turnout gear will be exposed to the environment. This uniform, mainly composed of cotton and polyester work and t-shirts, provides far less thermal protection than turnout gear. Another way to eliminate this potential hazard is found in the section below.

1.20 Recommendations to Fire Department Policy Makers

Fire departments generally use one channel to dispatch their emergency calls, and one channel for each large incident. Some fire departments require their firefighters to transition their radios from the dispatch channel to the incident channel when the units first begin to respond while others switch channels when firefighters arrive at the incident. Finally, some departments may not switch to an incident channel unless requested to do so. This may mean that several firefighters may already be operating in a dangerous environment before suddenly being required to switch to a different channel.

Firefighters also often switch their radios during a MAYDAY incident. When a firefighter becomes trapped, the firefighter, incident commander, and rapid intervention team all work on the same channel while the other crews on the scene work on a different channel. To achieve this, some fire departments have the endangered firefighter, rapid intervention team, and officer switch channels while the rest of the crews operate on the same channel. Other agencies do the reverse, with the rest of the crews operating on the incident changing channels. While this allows for two complex operations to be conducted simultaneously, it is very important to ensure that all firefighters are on the correct channel, and if possible, they should wait to change their channels until they are in a safer environment with improved visibility.

Fire departments also need to ensure that they are providing their firefighters with adequate turnout gear. While turnout gear is sized a standard firefighter, it is also important to make sure that the length is properly measured. Firefighters will often work with their hands extended above their heads, meaning that a turnout coat must be sized larger than a standard coat so that the coat will not rise and expose station uniform. These serves in addition to the comments made earlier regarding reflective striping possibly being eliminated.

Fire departments should also investigate providing their firefighters with radio straps and safer equipment such as SCBA mounted microphones. This equipment can be vital for firefighters operating in dangerous environments, as illustrated earlier in this report.

Finally, fire departments need to evaluate their radios. While the NFPA 1802 standard is evaluating the temperature conditions that a radio will experience in a firefighting environment, it will certainly take a long time to be implemented in the fire service. Many agencies have undergone an upgrade to the "best" radios that were on the market at the time of their upgrade. However, these were largely before the NFPA 1802 standard was published. Now that the standard has been published, and technology continues to advance, radios that are tested in accordance with this standard are far more expensive than other radios on the market. Therefore, it may take many more years for radios tested in accordance with this standard to become "mainstream" in the fire service. Until this development, firefighters and fire departments must be vigilant to ensure that portable radios are provided with the greatest protection to ensure that firefighters operate safely and efficiently at the fires of today and of tomorrow.

1.21 Suggestions for Future Research

While this study focuses on different carrying methods, it is far from comprehensive. First, as noted above in the methodology discussion, no objects were placed under the turnout coat. While placing a person inside of the turnout coat would serve to better represent the realistic situation, it was not deemed a safe for test tests. However, in the absence of a firefighter, no thermal mass was located behind the turnout coat. This mass would likely consume some of the thermal energy that remained in the radio pocket or strap assembly. This may increase the time to failure for each of these radios. Additionally, care should be taken to quantify the thermal conductivity, thickness, and air gap width of the turnout gear and the radio holder assembly. This will allow for a specific heat transfer analysis to be conducted for each case. In this test series, two turnout coats were used with different air gap thicknesses and thermal conductivity, eliminating the possibility for an accurate analysis.

In terms of quantities to identify, the orientation of the battery will factor into the radio's failure time. Therefore, further research should be conducted to determine the impact of this positioning. Furthermore, research into specific holders should be conducted. Different leather radio strap manufacturers produce various types of holsters. Some other manufacturers may also use thicker leather on certain radio holsters, which would provide more thermal protection than others. This research could also be updated with more modern radios. Additionally, using only one type of radio may also prove beneficial. This may eliminate the thermal soak differences. An analysis of a similar nature should also be done to the shoulder microphone assembly. This portion of the radio apparatus has been deemed to be the "weakest link" in the assembly, so this would likely provide shorter failure times than identified in this research. Finally, determining the transmission capability through walls and other structural components can be researched. The testing conducted above replicates a scenario seldom seen in the fire service. Positioning the target radio behind a simulated wall could dramatically alter the results as the signal at the control radio would likely be far weaker.

Appendices

Appendix A: Living Room FDS Simulation Input File

```
&HEAD CHID='Couch', TITLE='Couch'  /

&MESH IJK=31,31,31, XB=0.75,3.85,3.45,6.55,0.0,3.1 /

&TIME T_END=600. /

&REAC SOOT_YIELD=0.01,FUEL='PROPANE'/
&MATL ID                    = 'FABRIC'
      FYI                   = 'Properties completely fabricated'
      SPECIFIC_HEAT         = 1.0
      CONDUCTIVITY          = 0.1
      DENSITY               = 100.0
      N_REACTIONS           = 1
      NU_SPEC               = 1.
      SPEC_ID               = 'PROPANE'
      REFERENCE_TEMPERATURE = 320.
      HEAT_OF_REACTION      = 3000.
      HEAT_OF_COMBUSTION    = 20000. /

&MATL ID                    = 'FOAM'
      FYI                   = 'Properties completely fabricated'
      SPECIFIC_HEAT         = 1.0
      CONDUCTIVITY          = 0.05
      DENSITY               = 40.0
      N_REACTIONS           = 1
      NU_SPEC               = 1.
      SPEC_ID               = 'PROPANE'
      REFERENCE_TEMPERATURE = 320.
      HEAT_OF_REACTION      = 1500.
      HEAT_OF_COMBUSTION    = 30000. /

&MATL ID            = 'GYPSUM PLASTER'
      FYI           = 'Quintiere, Fire Behavior'
      CONDUCTIVITY  = 0.48
      SPECIFIC_HEAT = 0.84
      DENSITY       = 1440. /

&SURF ID            = 'UPHOLSTERY'
      FYI           = 'Properties completely fabricated'
      COLOR         = 'PURPLE'
```

```
      BURN_AWAY      = .TRUE.
      MATL_ID(1:2,1) = 'FABRIC','FOAM'
      THICKNESS(1:2) = 0.002,0.1  /

&SURF ID            = 'WALL'
      DEFAULT       = .TRUE.
      RGB           = 200,200,200
      MATL_ID       = 'GYPSUM PLASTER'
      THICKNESS     = 0.012 /


&OBST XB= 1.50, 3.10, 5.80, 6.60, 0.00, 0.40 /
&OBST XB= 1.50, 3.10, 5.80, 6.60, 0.40, 0.60, SURF_ID='UPHOLSTERY',
BULK_DENSITY=41.176 /
&OBST XB= 1.30, 1.50, 5.80, 6.60, 0.00, 0.90, SURF_ID='UPHOLSTERY',
BULK_DENSITY=41.176 /
&OBST XB= 3.10, 3.30, 5.80, 6.60, 0.00, 0.90, SURF_ID='UPHOLSTERY',
BULK_DENSITY=41.176 /
&OBST XB= 1.50, 3.10, 6.35, 6.60, 0.60, 1.20, SURF_ID='UPHOLSTERY',
BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 3.49, 3.5, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 6.54, 6.55, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.77, 0.78, 3.5, 6.55, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 3.81, 3.82, 3.5, 6.55, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 3.5, 3.55, 0.0, 0.1, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 3.5, 6.55, 2.4, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /

&PART ID='ignitor particle', SURF_ID='ignitor', STATIC=.TRUE. /
&SURF  ID='ignitor',  TMP_FRONT=1000.,  GEOMETRY='CYLINDRICAL',  LENGTH=0.15,
RADIUS=0.01 /
&INIT XYZ=2.45,6.30,0.65, DX=0.1, PART_ID='ignitor particle', N_PARTICLES=3 /

&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /

&HOLE XB=1.84,2.76,3.44,3.56,0.0,2.13/
&HOLE XB=0.74,0.8,4.73,5.33,1.0,2.0/

&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /
&BNDF QUANTITY='NET HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /

&SLCF         PBX=2.50,         QUANTITY='TEMPERATURE',VECTOR=.TRUE.,
CELL_CENTERED=.TRUE. /
```

&SLCF PBX=2.50, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBX=2.50, QUANTITY='RADIATION LOSS', CELL_CENTERED=.TRUE. /
&SLCF PBX=2.50, QUANTITY='VISCOSITY', CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='TEMPERATURE',VECTOR=.TRUE., CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='RADIATION LOSS', CELL_CENTERED=.TRUE. /

&DEVC ID='Tree_1_T1', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,0.31/
&DEVC ID='Tree_1_T2', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,0.62/
&DEVC ID='Tree_1_T3', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,0.93/
&DEVC ID='Tree_1_T4', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,1.24/
&DEVC ID='Tree_1_T5', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,1.55/
&DEVC ID='Tree_1_T6', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,1.86/
&DEVC ID='Tree_1_T7', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,2.17/
&DEVC ID='Tree_1_T8', QUANTITY='THERMOCOUPLE', XYZ=2.63,5.13,2.48/

&DEVC XYZ=2.63,4.2,0.25, QUANTITY='INTEGRATED INTENSITY', ID='FF1Crawl' /
&DEVC XYZ=2.63,4.45,0.89, QUANTITY='INTEGRATED INTENSITY', ID='FF1Standing' /
&DEVC XYZ=2.63,4.7,0.51, QUANTITY='INTEGRATED INTENSITY', ID='FF2Crawl' /
&DEVC XYZ=2.63,4.45,0.91, QUANTITY='INTEGRATED INTENSITY', ID='FF2Standing' /
&DEVC XYZ=2.63,4.45,0.74, QUANTITY='INTEGRATED INTENSITY', ID='FF3Crawl' /
&DEVC XYZ=2.63,4.45,1.3, QUANTITY='INTEGRATED INTENSITY', ID='FF3Standing' /
&DEVC XYZ=2.63,4.2,0.33, QUANTITY='INTEGRATED INTENSITY', ID='FF4Crawl' /
&DEVC XYZ=2.63,4.45,0.94, QUANTITY='INTEGRATED INTENSITY', ID='FF4Standing' /
&DEVC XYZ=2.63,4.45,0.51, QUANTITY='INTEGRATED INTENSITY', ID='FF5Crawl' /
&DEVC XYZ=2.63,4.45,0.86, QUANTITY='INTEGRATED INTENSITY', ID='FF5Standing' /
&DEVC XYZ=2.63,4.7,0.53, QUANTITY='INTEGRATED INTENSITY', ID='FF6Crawl' /
&DEVC XYZ=2.63,4.45,0.76, QUANTITY='INTEGRATED INTENSITY', ID='FF6Standing' /
&DEVC XYZ=2.63,4.2,0.25, QUANTITY='INTEGRATED INTENSITY', ID='FF7Crawl' /
&DEVC XYZ=2.63,4.45,0.76, QUANTITY='INTEGRATED INTENSITY', ID='FF7Standing' /
&DEVC XYZ=2.63,4.7,0.81, QUANTITY='INTEGRATED INTENSITY', ID='FF9Crawling' /
&DEVC XYZ=2.63,4.45,1.04, QUANTITY='INTEGRATED INTENSITY', ID='FF8Standing' /
&DEVC XYZ=2.63,4.5,0.4, QUANTITY='HRRPUV', ID='HRRPUV' /
&DEVC ID='FF1Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.2,0.25/
&DEVC ID='FF2Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.7,0.51/
&DEVC ID='FF3Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.74/
&DEVC ID='FF4Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.2,0.33/
&DEVC ID='FF5Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.51/
&DEVC ID='FF6Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.7,0.53/
&DEVC ID='FF7Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.2,0.25/
&DEVC ID='FF8Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.7,0.81/
&DEVC ID='FF1Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.89/
&DEVC ID='FF2Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.91/
&DEVC ID='FF3Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,1.3/
&DEVC ID='FF4Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.94/

```
&DEVC ID='FF5Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.86/
&DEVC ID='FF6Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.76/
&DEVC ID='FF7Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,0.76/
&DEVC ID='FF8Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.63,4.45,1.04/

&TAIL /
```

Appendix B: Bedroom FDS Simulation Input File

```
&HEAD CHID='Bed', TITLE='Bed'  /

&MESH IJK=31,46,31, XB=0.75,3.85,2.0,6.6,0.0,3.1 /

&TIME T_END=600. /

&REAC ID='POLYURETHANE',
     FYI='FM SNL FDS5 Validation',
     FUEL='REAC_FUEL',
     FORMULA='C17H16N2O4',
     SOOT_YIELD=0.02/

&MATL ID            = 'GYPSUM PLASTER'
     FYI           = 'Quintiere, Fire Behavior'
     CONDUCTIVITY  = 0.48
     SPECIFIC_HEAT = 0.84
     DENSITY       = 1440. /

&SURF ID            = 'Fire'
     FYI            = 'Properties completely fabricated'
     COLOR          = 'RED'
     HRRPUA         = 184,
     TAU_Q          =-240.0,
     TMP_FRONT            = 300.0/

&SURF ID            = 'WALL'
     DEFAULT        = .TRUE.
     RGB            = 200,200,200
     MATL_ID        = 'GYPSUM PLASTER'
     THICKNESS      = 0.012 /

&OBST XB= 1.3335, 3.265, 4.01, 6.60, 0.00, 0.90 /
&OBST XB= 0.78, 3.82, 1.99, 2.01, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 6.59, 6.6, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.77, 0.78, 2.0, 6.6, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 3.81, 3.82, 2.0, 6.6, 0.0, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 2.0, 6.6, 0.0, 0.1, SURF_ID='WALL', BULK_DENSITY=41.176 /
&OBST XB= 0.78, 3.82, 2.0, 6.6, 2.4, 2.5, SURF_ID='WALL', BULK_DENSITY=41.176 /

&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
&VENT ID='burner vent', SURF_ID='Fire', XB=1.3335,3.265,4.01,6.60,0.9,0.9, COLOR='RED'/

&HOLE XB=1.84,2.76,1.98,2.02,0.0,2.13/
```

```
&HOLE XB=0.74,0.8,4.73,5.33,1.0,2.0/
&HOLE XB=3.80,3.86,4.73,5.33,1.0,2.0/

&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /
&BNDF QUANTITY='NET HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /

&SLCF PBX=2.50, QUANTITY='TEMPERATURE',VECTOR=.TRUE.,
CELL_CENTERED=.TRUE. /
&SLCF PBX=2.50, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBX=2.50, QUANTITY='RADIATION LOSS', CELL_CENTERED=.TRUE. /
&SLCF PBX=2.50, QUANTITY='VISCOSITY', CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='TEMPERATURE',VECTOR=.TRUE.,
CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='HRRPUV', CELL_CENTERED=.TRUE. /
&SLCF PBY=4.40, QUANTITY='RADIATION LOSS', CELL_CENTERED=.TRUE. /

&DEVC ID='Tree_1_T1', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,0.31/
&DEVC ID='Tree_1_T2', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,0.62/
&DEVC ID='Tree_1_T3', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,0.93/
&DEVC ID='Tree_1_T4', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,1.24/
&DEVC ID='Tree_1_T5', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,1.55/
&DEVC ID='Tree_1_T6', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,1.86/
&DEVC ID='Tree_1_T7', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,2.17/
&DEVC ID='Tree_1_T8', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.5,2.48/

&DEVC XYZ=2.3,2.41,0.25, QUANTITY='INTEGRATED INTENSITY', ID='FF1Crawl' /
&DEVC XYZ=2.3,2.66,0.89, QUANTITY='INTEGRATED INTENSITY', ID='FF1Standing' /
&DEVC XYZ=2.3,2.91,0.51, QUANTITY='INTEGRATED INTENSITY', ID='FF2Crawl' /
&DEVC XYZ=2.3,2.66,0.91, QUANTITY='INTEGRATED INTENSITY', ID='FF2Standing' /
&DEVC XYZ=2.3,2.66,0.74, QUANTITY='INTEGRATED INTENSITY', ID='FF3Crawl' /
&DEVC XYZ=2.3,2.66,1.3, QUANTITY='INTEGRATED INTENSITY', ID='FF3Standing' /
&DEVC XYZ=2.3,2.41,0.33, QUANTITY='INTEGRATED INTENSITY', ID='FF4Crawl' /
&DEVC XYZ=2.3,2.66,0.94, QUANTITY='INTEGRATED INTENSITY', ID='FF4Standing' /
&DEVC XYZ=2.3,2.66,0.51, QUANTITY='INTEGRATED INTENSITY', ID='FF5Crawl' /
&DEVC XYZ=2.3,2.66,0.86, QUANTITY='INTEGRATED INTENSITY', ID='FF5Standing' /
&DEVC XYZ=2.3,2.91,0.53, QUANTITY='INTEGRATED INTENSITY', ID='FF6Crawl' /
&DEVC XYZ=2.3,2.66,0.76, QUANTITY='INTEGRATED INTENSITY', ID='FF6Standing' /
&DEVC XYZ=2.3,2.41,0.25, QUANTITY='INTEGRATED INTENSITY', ID='FF7Crawl' /
&DEVC XYZ=2.3,2.66,0.76, QUANTITY='INTEGRATED INTENSITY', ID='FF7Standing' /
&DEVC XYZ=2.3,2.91,0.81, QUANTITY='INTEGRATED INTENSITY', ID='FF8Crawl' /
&DEVC XYZ=2.3,2.66,1.04, QUANTITY='INTEGRATED INTENSITY', ID='FF8Standing' /
&DEVC XYZ=2.3,2.5,0.4, QUANTITY='HRRPUV', ID='HRRPUV' /
&DEVC ID='FF1Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.41,0.25/
```

```
&DEVC ID='FF2Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.91,0.51/
&DEVC ID='FF3Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.74/
&DEVC ID='FF4Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.41,0.33/
&DEVC ID='FF5Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.51/
&DEVC ID='FF6Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.91,0.53/
&DEVC ID='FF7Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.91,0.25/
&DEVC ID='FF8Crawl_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.91,0.81/
&DEVC ID='FF1Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.89/
&DEVC ID='FF2Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.91/
&DEVC ID='FF3Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,1.3/
&DEVC ID='FF4Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.94/
&DEVC ID='FF5Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.86/
&DEVC ID='FF6Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.76/
&DEVC ID='FF7Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,0.76/
&DEVC ID='FF9Stand_TC', QUANTITY='THERMOCOUPLE', XYZ=2.3,2.66,1.04/

&TAIL /
```

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