# Characterization of a Live Fire Training Simulator for use in the Canadian Fire Service

by

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# Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# Abstract

This thesis reports on the design, instrumentation, testing, and characterization of a live fire training simulator for use in the Canadian Fire Service. The importance of fire training, including live fire training evolutions is researched along with the different types of training structures, their advantages, and their drawbacks. A fire simulator constructed from a steel shipping container was designed and instrumented and a series of tests were conducted to characterize the interior fire environment. Tests were conducted using a variety of fuel loads under varied ambient conditions at the National Research Council's testing facility in Mississippi Mills, Ontario as well as the at Ottawa Fire Service's live fire training site. The interior fire environment was characterized using an array of thermocouples and heat flux gauges, and the measurements were compared to available guidelines about safe operating environments for firefighters. This characterization is based primarily on upper layer temperatures, lower layer temperatures, and heat flux. The environment was found to be safe for most configurations within the ambient condition range of the testing. Recommendations on the design of live fire simulators are presented including: novel design elements, fuel types, and fuel configurations. A simplified instrumentation schematic is proposed that would allow for a reasonable characterization of the thermal environment during live fire training, and this instrumentation is recommended to increase participant safety, enhance learning outcomes, and improve instructor competency.

# Acknowledgements

Loewen, John McDonough, James Mendoza, Shan Raffel, and Etienne Semence. In addition to their expertise, they taught us not only how to control the fire environment, but a love for teaching.

Our brother Shawn Mathieson's journey with the FKTP Project was cut short when he was killed in an accident March 3rd, 2016. Shawn was there for the first test burns included in this research, when we were first learning how to control the fire, but were inspired and mesmerized by it none the less. I hope that this work will inform the Canadian and International Fire Service and will contribute to safe, effective, and valuable live fire training. If this work helps you on your journey, please take a moment to remember all those we've lost along the way.



**Figure 1: Shawn during training in Frankfurt, Germany**

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# List of Symbols

$\alpha$            Absorption [dimensionless]

$\varepsilon$            Emissivity [dimensionless]

$\sigma$            Stefan-Boltzmann constant [$5.67 \cdot 10^{-8}$ W/m$^2$K$^4$]

$Fi\text{-}j$            Radiation view factor from element j to element i

$h$            Convective heat transfer coefficient [W/m$^2 \cdot$K]

$\kappa_m$            Effective absorption of soot [m$^{-1}$]

$\dot{q}''$            Heat flux [kW/m$^2$]

$T$            Temperature [°C or K]

$\Delta T$            Temperature difference [°C or K]

# List of Abbreviations

CFBT            Compartment Fire Behaviour Training

DNVFRS          District of North Vancouver Fire Rescue Services

CFAST           Consolidated Model of Fire and Smoke Transport

CSSP            Canadian Safety and Security Program

EFDS            Enclosure Fire Dynamics Simulator

FB              Fibreboard

FKTP            From Knowledge to Practice

LODD            Line of Duty Death

NFPA            National Fire Protection Association

HFG             Heat Flux Gauge

HRR             Heat Release Rate [kW or MW]

NIOSH           National Institute of Occupational Safety and Health

NIST            National Institute of Standards and Technology

NRC             National Research Council

OFC             Ontario Fire College

OFS             Ottawa Fire Services

OSB             Oriented Strand Board

PASS            Personal Alert Safety Systems

PB              Particleboard

PPE             Personal Protective Equipment

RFD             Rapid Fire Development

SCBA        Self Contained Breathing Apparatus

SME         Subject Matter Expert

TFT         Task Force Tips

TPP         Thermal Protective Performance

UL          Underwriter Laboratory

UL FSRI     Underwriter Laboratory Fire Safety Research Institute

VOC         Volatile Organic Compound

PAH         Poly-aromatic Hydrocarbon

# Chapter 1: Introduction

This research project was undertaken as part of a federally funded project headed by Ottawa Fire Services (OFS). This project, titled From Knowledge to Practice (FKTP) was initially funded through a grant provided through Defence Research and Development Canada's Canadian Safety and Security Program (CSSP) [1]. This program provides federal grants to successful applicants in the goal of strengthening Canadian preparedness for, among other things, natural disasters and serious accidents. OFS received a $1.2 million grant in 2013 with the goal of addressing gaps between the science of fire dynamics and current firefighting strategies and tactics [2]. Work on the FKTP project began in 2014 with the goal of developing an evidence-based fire dynamics curriculum, along with safe and realistic live fire training. The FKTP Project Team worked with partner services from Calgary and Montreal, along with subject matter experts (SMEs) from around the globe, supported by cash and in-kind sponsorship from numerous industry and government collaborators. The development of a live fire training simulator along with its characterization was undertaken as part of a Master's Program with the University of Waterloo.

Work on the FKTP project officially concluded at the end of 2018 and the curriculum, along with lesson plans and safety documents are available free of charge at www.firedynamicstraining.ca [3]

The objective of the current research was to characterize the environment developed in a live fire simulator called the Enclosure Fire Dynamics Simulator (EFDS) which formed a key part of the FKTP project. The characterization was designed specifically to understand conditions within the EFDS as it relates to the fire environment experienced by fire training participants, both instructors and students, in support of the ongoing goal of improving training for fire services across Canada. Results provided new understanding and characterization that directly guided proper implementation of the simulators, critical to effective live fire training [4]. The final goal is to ensure this simulator, and similar designs that might be deployed in other jurisdictions, can be run safely.

# Chapter 2: Literature Review

In support of the objectives and motivation outlined in the Introduction, this Chapter presents an overview of the importance of both in-class and live fire training, along with a background of similar live fire training in other jurisdictions and their associated risks. Given the importance of teaching firefighters basic fire science concepts, an overview of the key concepts that are then supported by live fire evolutions, such as the stages of fire development, heat transfer, ventilation and the two-zone model are reviewed. Finally, this Chapter concludes with a review of current training structure types, along with fuel type and fuel load considerations that will be used in the EFDS. Critical elements of the safety and exposure of firefighters during training evolutions are discussed throughout this Chapter.

## 2.1 Importance of Training in the Fire Service

Firefighting is a high-risk profession despite the low frequency of responding to fire incidents, particularly as the total number of fires has declined in the past decades (as shown in Figure 2). In addition, the fire environment faced by firefighters in North America has changed in recent decades due to changes in building construction and increased fuel loads. As such, both conceptual and live-fire training are required to ensure that firefighters are prepared to react effectively during incidents.
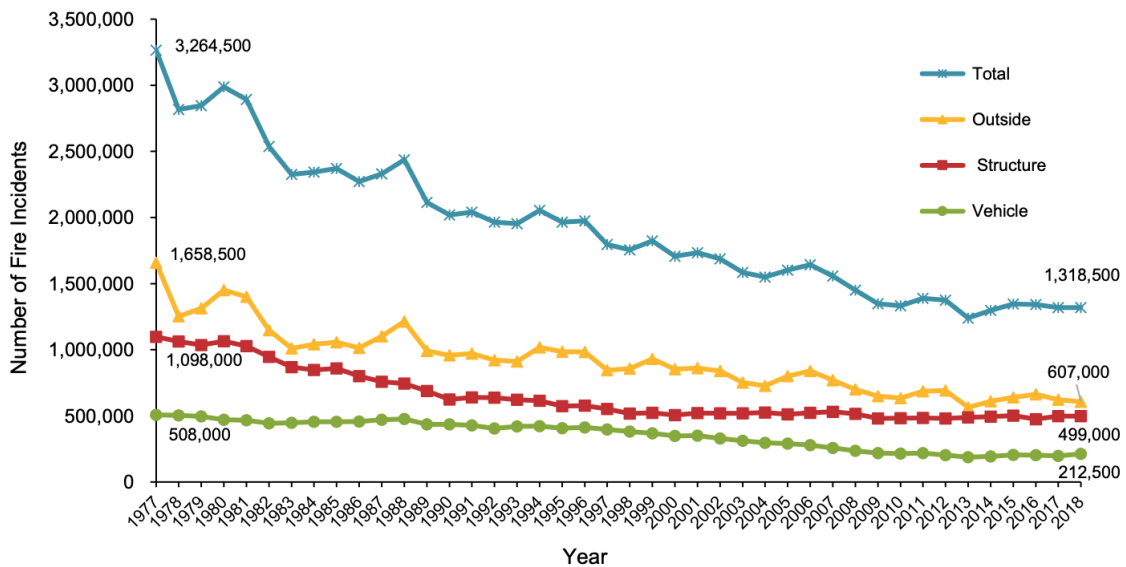


**Figure 2: Fire loss in the United States – reprinted with permission from [5]**

The National Fire Protection Association (NFPA) recognizes the importance and inherent risk of live fire training in NFPA 1403: Standard on Live Fire Training Evolutions [6] and further mandates that students must meet the minimum standards set forth in NFPA 1001: Standard for Fire Fighter Professional Qualifications [7] prior to participating in this training. In this, there is a requirement for exposure to fire dynamics, particularly as it pertains to compartment fire development. By teaching fire dynamics to firefighters, they can respond more effectively to their changing environment [8]. In addition, live fire training reinforces these concepts while allowing firefighters to improve their techniques in realistic environments [9].

### 2.1.1 Background & Goals of the FKTP Project

The importance of training in the fire service was highlighted in Ottawa through the "near-miss" event known as the Forward Avenue Fire, that occurred in Ottawa on February 12th, 2007 which motivated the FKTP project. During the response to a residential structure fire, five firefighters were forced to jump from second and third storey windows to escape from extreme fire conditions. The Critical Injuries Report [10] written following the incident listed the importance of maintaining a comprehensive fire dynamics course for firefighters and officers that would include a focus on knowledge, skills, and abilities was listed as part of the eighty-five recommendations.

### 2.1.2 Importance of Teaching the Basics

NFPA 1403 requires that fire dynamics, the fundamentals of fire behaviour, and fire development in a compartment be taught to students prior to their participation in live fire evolutions [6]. It is important that firefighters understand fire dynamics [11], both to better perform their duties on the fire ground, as well as to be able to learn from past events [12], even if this understanding is fundamentally qualitative instead of quantitative [13]. Further, and at least as critical to theoretical learning, participation in live fire evolutions reinforces these fundamentals and allows for demonstration and practice in the application of tactics that might be employed at fire incidents. In particular, the stages of fire development, the different mechanisms of fire spread, and the two-zone concept of enclosure fires must be reinforced through an effective firefighter training curriculum.

### 2.1.3 Importance & Risks of Live Fire Training

Unfortunately, there have been many documented line of duty deaths (LODDs) associated with live fire evolutions, and as such, safety is a major concern. This safety must be managed by understanding the fire environment, designing a suitable training facility, choosing an appropriate fuel load, properly training instructors, and maintaining appropriate safety and hygiene standards. Further, the learning objectives of the training must be achieved by taking into consideration the limitations and potential drawbacks inherent in any live fire evolution. The National Institute of Occupational Safety and Health (NIOSH) maintains a list of LODD reports for firefighters in the United States which provide excellent guidance on the causes, and proposed solutions to past critical injuries. Within this database are a number of fatalities that occurred during live fire training. While any LODD within the fire service is a tragedy, it is particularly so when the loss of life occurred not while responding to an emergency, but during training. Five NIOSH reports were reviewed, four of which recommended better adherence to NFPA 1403 [14, 15, 16, 17], and one [18] that referenced a need to institute a rehabilitation program as per NFPA 1584: Standard on the Rehabilitation Process for Members During Emergency Operations and Training Exercises [19]. While all of these reports detail distinct events, in different jurisdictions, at different times, and with a variety of identified causes, there are a set of common denominators in many of these cases. Extreme fire conditions precipitated the loss of life in three of these incidents, all of which occurred in acquired structures [14, 15, 17]. The other two reports stem from incidents that occurred at training facilities, and the victims were both instructors [16, 18]. The first of these resulted from excessive exposure to heat which resulted in the melting of the instructor's facepiece, wherein the lack of a second instructor, proper maintenance of the SCBA, and the use of excess fuel were also listed as causal factors [15]. The final, and most recent incident involved sudden cardiac arrest of a training instructor and listed not only exposure to the heat stress common to wearing and operating in personal protective equipment (PPE) in live fire conditions, but also the fact that the instructor led many other physically challenging evolutions on the same day [17]. The importance of properly trained instructors in leading live fire evolutions was referenced in two of the reports [14, 17]. Finally, the use of excessive and/or non-compliant fuel packages were identified in three of the reports [14, 15, 16]. Taken as a whole, these NIOSH reports show the importance of adhering to the guidance set forth in NFPA 1403 [6]. They clearly identify the importance of maintaining a safe live fire training environment through the use of a

proper quantity of the appropriate fuels, as well as the role that properly trained instructors play in establishing and maintaining the safety of the burn.

Any simulated training will require a compromise between safety, logistical considerations and fidelity, as shown schematically in Figure 3. The goal in designing a training evolution, then, is to ensure that the facility design and fuel load are appropriately matched to the learning objectives. In balancing these three requirements, success must be defined as achieving specific learning objectives while balancing all three [20], not simply by meeting one of the three criteria at the expense of the other two.
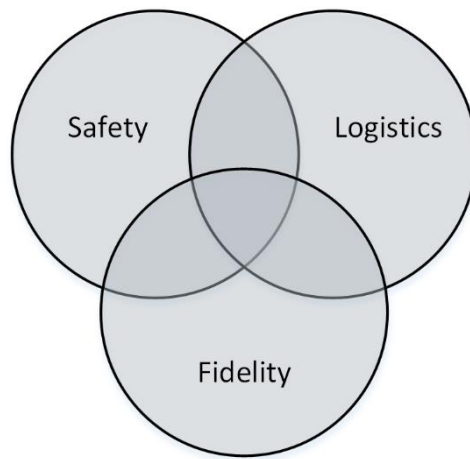


**Figure 3: Simulated training trade-offs**

While safety is of paramount importance, the reality of live fire training is that it inherently does expose participants to a degree of risk. However, this risk is considered reasonable given the unparalleled opportunities to increase participants' understanding of fire behaviour and to practice firefighting techniques that are a critical part of their daily job function. In addition, live fire training builds confidence in dealing with actual fires and builds adaptability under changing circumstances [21]. While the North American fire service has largely relied on fireground experience to provide firefighter development, changes in building construction as well as increased employer responsibilities, liabilities, and worker protections have put an increased emphasis on live fire training [22].

The minimum safety standards for live fire evolutions are set out by NFPA 1403 [6], and as previously reviewed, not adhering to these has resulted in fatalities [14, 15, 16, 17, 18]. The safety document produced by OFS as part of the FKTP project fully complies with NFPA 1403 [6] and

1584 [19] as well as supplementing specific guidance based on the specifics of the site, simulator, lesson plans, and OFS departmental procedures [23].

The logistics of live fire training are such that it involves significant planning, setup, decontamination, and rehabilitation. The duration of the training and number of repetitions of any desired evolutions are limited by the low fuel load that is used to adhere to safety requirements, physiological limitations of participants, and the amount of time that a firefighter's breathing air will last. In addition, many jurisdictions have adopted a 1-3-9 policy for burn frequency:

- 1 burn maximum per day;
- 3 burns maximum per week; and,
- 9 burns maximum per month [24].

Taken together, the implication is that live fire evolutions are costly both financially and logistically. When designing a live fire evolution, it is therefore important to consider whether live fire conditions are actually necessary to achieve the learning objectives. As dictated by NFPA 1403 [6], fire dynamics concepts should be taught prior to the evolution so that concepts are being reinforced rather than introduced during the live fire evolutions. Tactics should be discussed and techniques introduced outside of a live fire environment to lower the logistical requirements, as well as to allow a lower stress environment, which consequently facilitates more effective learning by the student. As an example, the FKTP curriculum includes a number of lesson plans that build the technical skills for tactics such as door control and smoke cooling as groundwork for subsequent live fire evolutions [25, 26]. Even more complicated scenarios and evolutions might be possible using smoke machines and digital simulators that are commercially available [27]. While the fidelity of such evolutions is much lower than that of live fire evolutions, they can still play a significant role in training, particularly if coupled with subsequent training under live fire conditions.

Despite all of these limitations and constraints, live fire training is the only means to achieve first-hand experience with fire behaviour and to practice techniques within an applicable context. For live fire training to be effective, the conditions within the simulator need to achieve a degree of fidelity with actual structure fires so as to demonstrate how a fire would respond to control and extinguishment techniques during an actual incident. Regardless of how well the evolution is

designed to meet the learning objectives, there is also a requirement for well-trained instructors who can relay the concepts and demonstrate techniques competently [20].

Even when safety, logistics, and fidelity have been balanced, learning objectives have been matched to the environment, and the evolution is led by competent instructors, the difference between live fire training and real fire incident environments needs to be reviewed. Where differences exist, the instructor needs to articulate and explain these differences lest the wrong lessons be taught inadvertently [28]. An excellent analogy is that of a flight simulator. No simulated environment can fully replicate the conditions of an actual incident, and a significant danger exists where the instructor or student do not appreciate this fact [9]. OFS addresses this during a comprehensive pre-burn safety briefing that reminds the participants of the differences between the training and incident environments [29]. The dangers of learning the wrong lessons from this type of training are well illustrated by the deaths of two UK firefighters at the Shirley's Towers fire in 2010 [30]. One of the many findings of the investigation into this incident found that crews relied on the "gas cooling using a pulse spray" technique (which is referred to herein as "smoke cooling") to fight the fire despite their inability to make significant progress in suppressing the fire. As will be discussed later, this technique pairs well with metal training structures, and for many jurisdictions it is reinforced as it is a novel technique for most firefighters. However, during the Shirley Tower's fire, crews continued to use this technique despite frustration that it was not effective at extinguishing or facilitating an advance towards the seat of the fire. The report further recommended a review of the live fire training offered by the department to ensure that this technique was introduced as one tactical option among many, and that its uses and limitations were explained [30].

## 2.2 Fire Dynamics for Firefighters

The curriculum developed through the FKTP Project focuses on a basic scientific understanding of fire starting from definitions of energy, work, and power, building on these to describe how basic scientific concepts explain fire development within a compartment [31, 32]. Some of these concepts can be observed during live fire training, particularly the stages of fire development within the compartment, the different types of heat transfer, and the ventilation and two-zone concept often used to describe the general environment in compartment fires [33]. Each of these is discussed in the following sections. Teaching these concepts prior to live fire training provides an

opportunity to engage the student in more focused learning during subsequent evolutions, and transforms the live fire training evolutions from simply technique practice into a chance for first-hand understanding of key fire dynamics concepts.

## 2.2.1 Stages of Fire Development

The development of a fire within a compartment or enclosure can be described as consisting of four stages separated by three transitions [2] as shown by dotted lines and red dots, respectively, in Figure 4:
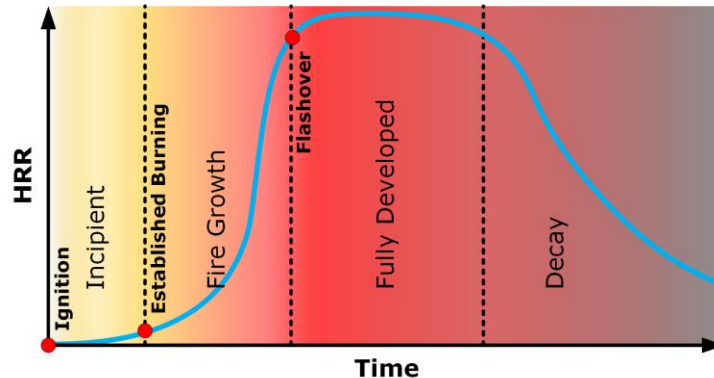


**Figure 4: Fire growth curve**

The four stages of enclosure fire development can be described as below.

1) Incipient: This stage begins with the first transition: either auto or piloted ignition. Following ignition, the fire can either grow until it is self-sustaining, or it can self-extinguish. It is important to distinguish this stage as distinct from the growth phase, as the fire can stay in an incipient stage for a period time without an increase in heat release rate (HRR), also described as an incubation period [34]. This is often associated with a smouldering fire. If this incipient fire continues to grow and becomes self-sustaining, it can be understood as having undergone the transition to established burning. A common benchmark for established burning is a fire reaching a heat release rate of 20kW [35].

2) Fire Growth: This is the growth phase of the fire during which the HRR can be modelled as increasing quadratically with time [36]. The fire will continue to grow as long as it is not limited by either a lack of fuel or ventilation. Work by the Underwriter Laboratory's Fire Safety Research Institute (UL FSRI) has focussed on ventilation limited fires and the fact

that the curve presented in Figure 4 does not show the risk presented to firefighters when changing ventilation conditions transition to those of an under-ventilated fire [37]. As such, an updated curve shown in Figure 5 has been presented to demonstrate this risk [37].
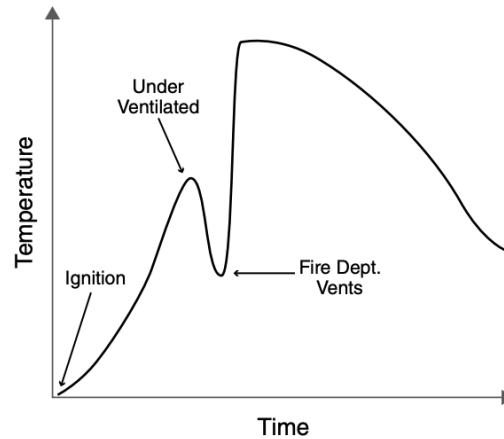


**Figure 5: Modern fire behaviour – reprinted with permission from [37]**

In fact, demonstrating the importance of ventilation in the growth of the fire is a vital learning objective in many live fire evolutions [4]. If there is sufficient available oxygen (supplied via ambient air due to ventilation) and fuel, the fire will continue to grow until the enclosure transitions to a fully developed fire. In the case of a fully developed fire the heat released within the enclosure achieves a maximum value, and the transition to that condition is known as flashover.

3) Fully Developed: Once an enclosure has undergone flashover, the HRR is normally limited by the ventilation available, and the fire can be described as the entire volume of fuel within the compartment being involved in the fire [38]. The HRR of the enclosure fire will continue at roughly this level until the amount of fuel available decreases. Due to the extreme temperatures and heat transfer, it is unsafe for firefighters to train within a compartment approaching flashover or during full room involvement. Extreme phenomena known as Rapid Fire Developments (RFDs), including Flashover, Backdraft and Smoke Explosions pose high risks to firefighters. While it is possible to create these conditions within training structures, it is critical that firefighters remain exterior to the compartment [21].

4) Decay: The final stage of the fire growth curve describes an enclosure fire where the HRR of the fire will decrease as the amount of fuel available is depleted. As previously discussed, this decay stage is not the same as the under-ventilated conditions possible during the growth stage. It should also be noted that the decay stage can occur without an enclosure having previously reached flashover. It is therefore still possible to demonstrate certain features of a fuel-limited decay phase of an enclosure fire without exposing firefighters to flashover conditions.

## 2.2.2 Heat Transfer

Fire spreads through the three methods of heat transfer: conduction, convection, and radiation. During the ignition stage, the primary method of fire spread is due to conduction and convection between the growing flame plume and adjacent, uninvolved fuels. As the fire grows, radiation becomes more important to flame spread as fuels that are not directly in contact with the fire plume can pyrolyze and ignite. The different heat transfer mechanisms, and their relative contribution to flame spread can be demonstrated to students during live fire training evolutions.

## 2.2.3 Ventilation and the Two Zone Model

As the fire moves into the growth stage, a layer of hot combustion products forms in the upper portion of the enclosure. A simplified model for the conditions within an enclosure consisting of two, uniform zones: a hot upper layer, and a cool lower layer [13, 39]. These two layers are separated within the compartment by an interface layer. The upper and lower layers are shown in Figure 6, as well as the interface layer shown by the lower black line.

The height of the interface above the floor is important for firefighters for the following reasons:

- The ambient temperature below the interface is much lower, and so convective and conductive heat transfer to firefighters is substantially reduced if they are operating below the interface;

- If there is little turbulence to mix smoke from the upper layer, visibility can be greatly improved below the interface; and,

- In structure fires, the height of the interface, and any changes of this height can provide firefighters with clues as to the location, severity, and development of the fire.
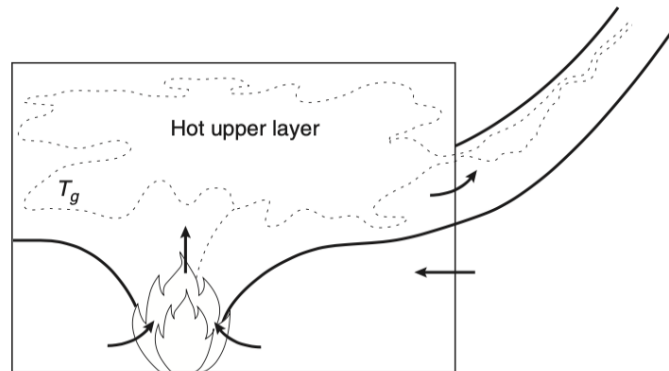


**Figure 6: Two-zone model – reprinted with permission from [33]**

Within the training environment, the ventilation conditions of an enclosure fire training simulator should be able to show the effects of differing ventilation configurations on the interface height. Additionally, lowering the interface height allows instructors to demonstrate an increase in conductive and convective heat transfer. An understanding of these concepts as they relate to the fireground, as well as to observations of smoke density and turbulence patterns in the upper layer, are important in teaching firefighters to make more informed decisions on the fireground [4].

Given the importance of teaching the above fundamental concepts through both theory and practical evolutions, as well as relating them to the two-zone concept of compartment fire development and fire ground tactics, the question arises as to what is the most beneficial type of structure in which to conduct safe and effective practical live fire training. To this end, the next section contains a review of existing live fire training structures, as well as the fuel types and loads used in various structures and the consequent thermal exposure, and thus safety, of participants in each situation.

## 2.3 Live Fire Training

Live fire training structures can be divided by the type of structure as well as the fuel they use. This research project was based on a structure built from steel shipping containers burning class A, wood-based fuel. While live fire training plays a vital role in training firefighters within the fire service, it is not without its risks, and increased realism involves an increased potential for

accidents and injuries [11]. There have been a number of fatalities during live fire evolutions, and additionally, all participants are exposed to the toxic products of combustion. Nonetheless, the importance of live fire evolutions becomes more critical as the number of fires that firefighters respond to declines [5]. As such, there are many different types of full-scale live fire training structures, all with their own benefits and drawbacks. Regardless of the type of structure, training must be delivered with a focus on achieving pre-defined learning objectives while maintaining adequate safety for both the students and instructors. Further, it is not necessary to expose students to high heat conditions to achieve any of the realistic learning objectives, rather it is important to use live fire training to teach the appropriate tactics and techniques as well as appropriate responses to different compartment conditions [4]. In the end, it is important that the fidelity, logistic feasibility, and safety of the structure, fuel load, and goals of the training evolution must all be balanced. With this in mind, the different types of training structures are very briefly reviewed, followed by focused discussion on the version of the live fire training structure that was chosen for the FKTP project and that is characterized in this research project.

### 2.3.1 Types of Structures

Live fire training structures can be broadly broken into four categories:

1) Acquired;

2) Purpose built temporary;

3) Concrete; and,

4) Steel

In addition, each structure may be constructed with only one or with multiple compartments. If the goal is to demonstrate fire dynamics concepts, or to practice simple nozzle skills, a single compartment structure is appropriate. However, if longer tactical exercises are the goal, then a multi-compartment structure is required. In the past, agencies have reproduced different realistic conditions by using acquired structures, varied fuels, and multiple fires as identified in the NIOSH LODD reports [14, 15, 16, 17, 18]. As mentioned in the previous Section, a number of LODDs have occurred in acquired structures, although there is no inherent risk in using these for training that was identified in any of the reports. The use of acquired structures does, however, require

significant work to make them NFPA 1403 compliant [6, 28]. Additionally, it can be difficult to procure these structures, and they do not provide a consistent training environment nor training options that are available on an ongoing basis [9].

Garcia and Kauffman have advocated for purpose-built structures for live fire training evolutions, indicating that they can be built for relatively low cost, and provide a training environment that most closely resembles actual residential fires [28], which made up 85% of the fires in Ontario between 2008 and 2017 [40]. It should be noted that both acquired structures as well as the model proposed by Garcia and Kauffman are built with combustible materials. Therefore, given the overall variability of the fire growth and development in any structure, there is always a risk that the training structure itself can become involved in the fire and contribute to an excessive fuel load resulting in dangerous conditions.

Concrete training structures have generally been shown to suffer from long-term damage from continued use. While this has been attributed to use of large fires, it is generally accepted that all burn compartments should be shielded by other materials which adds significant cost and maintenance to the structure [28]. They do offer a number of advantages, namely their long-term viability and resistance to damage if not exposed to extreme temperatures. However, concrete training structures take more time and fuel to heat up, and then retain this heat longer when compared to steel structures [41] so repeating comparable evolutions for multiple groups of participants in a single day becomes much more difficult.

As a result of the above assessment and drawbacks detailed with each of the other options, it was determined that the FKTP training structure would be built of steel. Specifically, the structure would be based on designs manufactured through the modification of intermodal shipping containers through extensive consultation with international fire training instructors [42]. Further, the design would be based on those used in Compartment Fire Behaviour Training (CFBT) throughout the world. Examples of CFBT designs are shown in the background of Figure 7 [43], with the interior of a multi-container design shown in Figure 8 [44]. CFBT began in the Swedish and British fire services, but has spread to many other countries around the world. While the basic cell design is the same, the CFBT single burn cells have also been integrated into larger structures [20].

**Figure 7: CFBT in Australia – reprinted with permission from [43]**



**Figure 8: FRTC large-scale simulator**

Steel structures have been criticized with respect to size and configuration of training facilities for lacking the potential to create realistic live fire conditions as well as the size and configuration of the facilities produced [28]. For the purposes of combined theoretical fire science training with associated practical live fire evolutions, however, this criticism is not well-founded and can be mitigated by adjusting the learning objectives of the training to focus more on complementing training in fire dynamics as outlined above, and less on tactical training in the case of single compartment trainers. These concerns can also be addressed by creating composite, multi-container training facilities [9] such as the ones shown above in Figure 8 as well as in Figure 9, or the one built in Ottawa shown in Figure 10 to facilitate additional tactical training evolutions.



**Figure 9: Dublin Fire Brigade Training Centre**
**– reprinted with permission from [45]**

These larger facilities can be constructed entirely of intermodal shipping containers, or can rely on a central concrete structure with steel containers added to it. A common low-cost configuration is called a "T-Cell", which is constructed using two shipping containers. This adds the ability to teach hose advancement techniques within the fire environment [46]. The use of steel containers as cost effective sacrificial burn rooms can mitigate the damage done to concrete structures over time [4, 9]. The addition of gypsum board to the interior of steel training structures can also increase realism. The thermal conductivity of metal is much higher than gypsum board and therefore the

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fire development in steel structures is altered when compared to fires in purpose built structures, although it has been found that the addition of gypsum lining can also result in higher temperatures experienced by participants [4].



**Figure 10: Multi-container training facility in Ottawa**

Due to the high thermal inertia and conductivity of steel, if water is applied to the steel containers, it will result in significantly more steam generation when compared to gypsum lined simulators [4]. When safety, logistics, and fidelity are considered as a whole, learning objectives can be set to use the impact of this steam generation on the compartment fire environment to enhance the overall training experience, while at the same time mitigating potential negative safety implications of steam generation on participants. By teaching techniques that limit the application of water onto the interior surfaces of the shipping container, an important learning objective can be met. If water is converted to steam in the upper layer, rather than through contact with enclosure linings, the upper layer will contract due to cooling more than it will expand as a result of the vaporization of the water as shown in Figure 11 which illustrates the relative volume and temperature of the upper layer following applications of water with different efficacies. The different lines in this graph show the ratio of applied water that is vaporized by the upper layer to that vaporized by the compartment linings. When all the applied water is directed at the linings, the

upper layer expands significantly (the dark blue line) while a contraction of the upper layer is achieved for applications where more than 50% of the applied water is vaporized by the upper layer (orange and yellow lines). This demonstrates the improved effects in terms of lowered temperatures and contraction of the upper layer, both of which are beneficial to effective and safe firefighting operations, when techniques are used that minimize contact of the applied water with the compartment linings. Teaching smoke cooling techniques – short bursts from a combination nozzle set to a 40°- 60°  fog setting [47] – as part of the evolutions in steel training structures can therefore limit the expansion of the upper layer and the resulting increase in heat transferred to the participants.
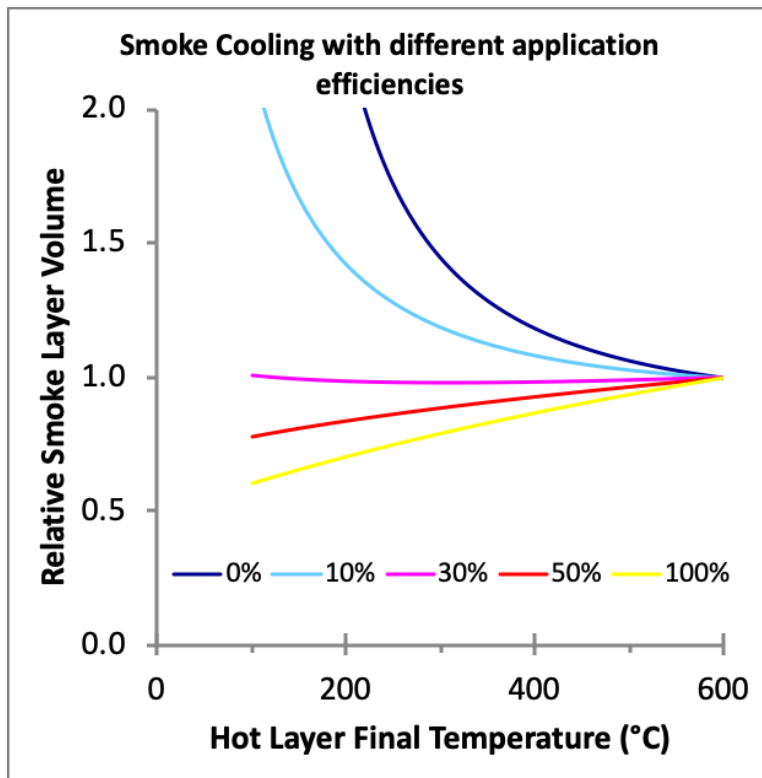


**Figure 11: Relative upper layer volume as a function of the percentage**
**of water evaporated in the upper layer (as opposed to compartment linings) [48]**

When all aspects of potential interactions between the configuration of a training structure and the training scenario to be taught are understood, the focus should be on achieving important learning objectives that relate the fire science and dynamics of the environment as they respond to appropriate tactics and techniques, rather than achieving conditions representative of a residential structure fire. Therefore, for the present research, the EFDS live fire training simulator is based on

a bare-walled steel structure manufactured through modification of an intermodal shipping container.

## 2.3.2 Fuel Type and Load

Equally important to the fire training structure are the fuel types that are chosen for training, the subject of this Section. Currently, the fuels available for fire training simulators can largely be divided into either gaseous or solid fuels, with liquid fuels being prohibited by NFPA 1403 [6]. A gaseous fuel could be one of a number of flammable gases, but is most commonly propane. For solid fuels there are many variations in both the fuel type as well as configuration that could be used, though in reality, the options, amongst other constraints are limited by NFPA 1403 [6].

Due to strict design, safety, and installation regulations, gas-based training simulators would usually be purchased directly from a manufacturer rather than being built by the host jurisdiction. These simulators can be very expensive, do not offer the possibility of producing backdraft or flashover [21] and due to their small size and limitations on flexibility of gas burners, the environment becomes very predictable [28]. Further, there is concern that gas-based simulators do not produce realistic fire phenomena or react appropriately to water application or ventilation in terms of realism. As such, the skills and techniques learned in gas-based simulators do not transfer effectively to the fireground [9]. Hybrid simulators such as the one shown in Figure 12 are also available with the claimed advantage of improved realism, lower emissions, and increased safety [49]. There are other ways to address environmental concerns about the smoke produced by simulators as these can also be mitigated by containing the simulator within a building equipped with smoke cleaning equipment such as at the Frankfurt Training Centre shown in Figure 13.

Unlike gas simulators, simulators using solid wood fuel loads can produce more realistic compartment fire environments as well as flashover and backdraft conditions for evolutions (provided participants are exterior to the compartment for safety) [41]. Due to the numerous types and configurations of solid fuel that are possible, they also offer greater flexibility in design of different fuel loads for different evolutions, removing predictability in training that can be encountered with gas fueled simulators. In reality however, NFPA 1403 dictates that the solid fuel used shall only be wood products and further, that "pressure-treated wood, rubber, plastic,

polyurethane foam, tar paper, upholstered furniture, carpeting, and chemically treated or pesticide-treated straw or hay shall not be used as part of the fuel load" [6].



**Figure 12: LION Class A hybrid simulator [50]**



**Figure 13: FRTC smoke handling – reprinted with permission from [51]**

In recent years, there has been work to further refine these requirements to exclude the use of oriented strand board (OSB) as well given the presence of formaldehydes and other binders and

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sealers that release toxic by-products when exposed to heat and burned [52]. There is no question however that Class A fuels have been shown to provide the best physical and functional fidelity [9], although the exclusion of OSB has been advised by the IAFF [52]. Finally, NFPA 1403 also forbids the use of any flammable liquids, and propane lighters must only be used to ignite the fire provided they are removed immediately following ignition [6].

In order to achieve good training conditions in steel container training structures, it has been found that the fuel should be loaded as close to the ceiling and walls as possible to promote combustion on the side facing into the burn compartment, decreasing the HRR and increasing the amount of smoke produced [24]. For safety and cost, the amount of fuel should also be limited to the minimum required to achieve the learning objectives [21]. Further, while wood based fuels do not provide a realistic environment when compared to the synthetics and foam plastics that form the main fuel load in today's residential fires, it has to be recognized that they can still produce high enough heat to be a risk to participants [4].

With the above considerations in mind, the fuel load for the research was based largely on the fuel loads used for live fire training evolutions conducted in steel containers in other jurisdictions with one exception being the wood crib, which was taken from literature [33]. During testing, as well as during training, the fuel load was ignited using either a propane burner or torch, in accordance with NFPA 1403 [6]. The base fuel load mirrored that of the typical CFBT fuel load, as is shown in Figure 14. Instead of the OSB pieces seen in the figure, a wood crib made of pine was used in this research, while the board used was either fibreboard (FB) or particleboard (PB). The particleboard was chosen in an attempt to limit the amount of formaldehyde that would be generated in the products of combustion.

The wood crib design was taken from the example provided in SFPE Handbook of Fire Protection Engineering and shown in Figure 15 [33]. Each crib was built from 2"x2" (38.1 mm x 38.1 mm) softwood lumber, which was cut into 2' (61 cm) long sections and stacked with 76.2 mm spacing between each piece. The crib was constructed from six layers, each containing six pieces, for a total of 36, 61 cm long pieces. These were cut from 9, 8' long 2"x2"s. The heat release rate of this crib is described by Obach as shown in Figure 16, with the HRR of a single crib peaking just above 200kW and maintaining close to this level for approximately five minutes [53]. In addition to this HRR, the fuel loading from the boards is the less predictable contribution to the overall

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HRR in the training structure. Characterization of the energy release from the combined fuel load and its impact on the environment within the steel training structure therefore formed an important part of the overall characterization of the EDFS trainer and is discussed further in Section 3.3.2.
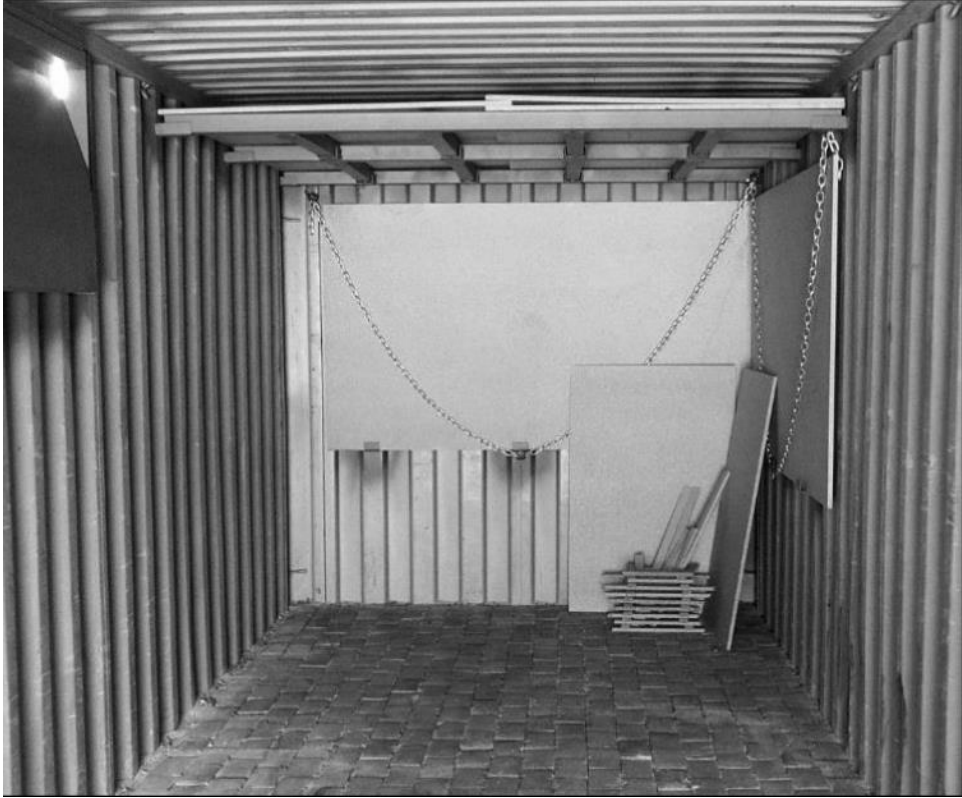


**Figure 14: CFBT fuel load – reprinted with permission from [24]**
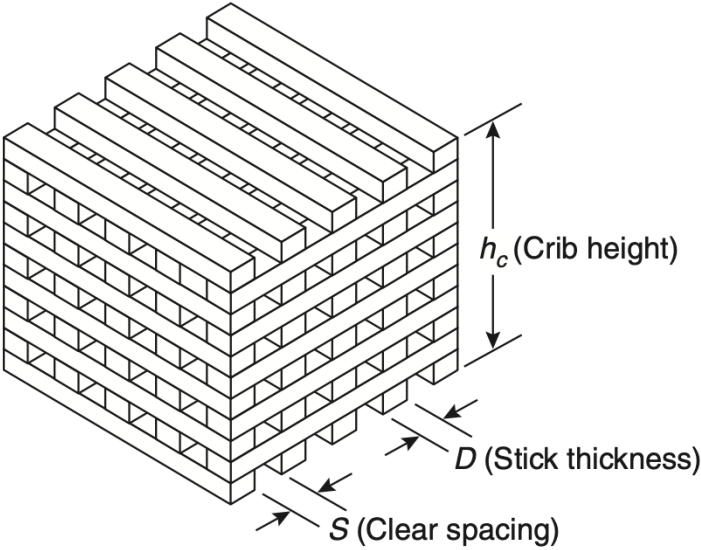


**Figure 15: Crib design – reprinted with permission from [33]**
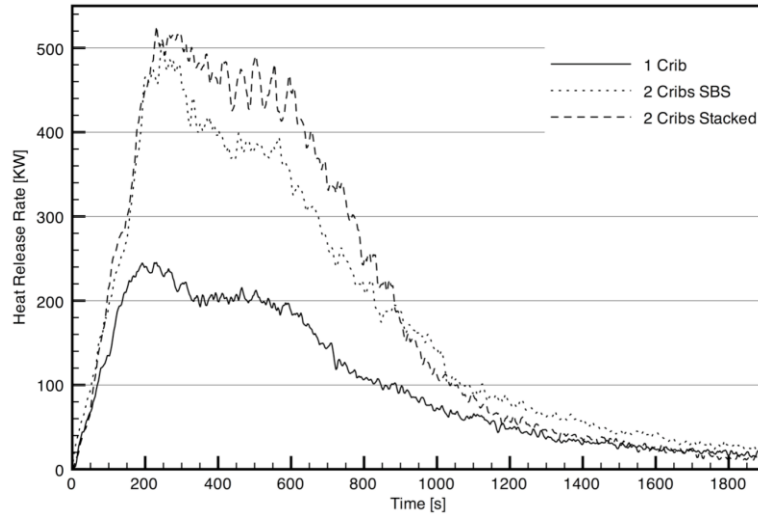
**Figure 16: Crib HRR – reprinted with permission from [53]**

### 2.3.3 Thermal Exposure of Firefighters in Live Fire Training

Due to the highly variable environment experienced by firefighters during incidents [54] and live fire training, it is non-trivial to define what constitutes safe and appropriate thermal conditions for training. One metric is to examine the NFPA standards that set the minimum testing criteria that apply to the various elements of a firefighter's personal protective equipment (PPE). Those standards are as follows:

- NFPA 1971: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting [55];
- NFPA 1981: Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services [56]; and,
- NFPA 1982: Standard on Personal Alert Safety Systems (PASS) [57].

The difficulty in relying on these standards with regard to firefighter safety is that their criteria differ from each other, and they are related to specific PPE component failures rather than defining what a safe operating environment is for firefighters. In reviewing the documents, it was found that facepieces are tested to a less stringent standard than PPE. Further, under testing it has been determined that exposure of the facepieces to a radiant heat flux of 5 kW/m$^2$ for 20 minutes resulted in damage to some test samples while an exposure to 8 kW/m$^2$ resulted in damage to all samples tested. Under a higher radiant heat flux of 15 kW/m$^2$, holes formed in all samples between 1.5 and 3.9 minutes [54]. By contrast NFPA 1971 defines a battery of tests and requirements for

the protective clothing, such as requiring stitching that will not melt below 260°C [55]. Perhaps the most relevant requirement is the thermal protective performance (TPP) which is defined as twice the amount of time that results in injury due to heat transfer through a garment when exposed to a 84 kW/m$^2$ radiant heat source. It should be noted that this TPP time reflects time to second degree burns, and that injury can occur before the TPP time.

However, it is not clear how this metric applies to longer exposures at lower heat fluxes, or how the TPP is affected by different heat transfer mechanisms since these tests are typically designed to replicate the short-duration, extreme conditions firefighters would experience at incidents rather than the longer less intense conditions more typical during training. Further, while TPP requirements have been effective in improving the performance of garments to short duration, high heat flux exposures, it has been shown that many firefighter burns and injuries occur well below the threshold for degradation of firefighting PPE [41]. There has been little scientific work aside from experiential studies done to predict the thermal performance of PPE over the range of conditions usually experienced by firefighters [58]. One attempt to define these environments was undertaken by the National Institute of Standards and Technology (NIST) as it applied to electronic equipment used by firefighters [59]. The report defined four thermal classes for survival of the equipment, each defined by a range of air temperatures and heat fluxes. They then set an amount of time that a firefighter could operate under each set of conditions. The first two classes were based on previous work by Foster and Roberts [60], while the third class was consistent with conditions in a short term working environment for firefighters (temperature and heat flux) that might be expected to result in pain or burning of the skin [61]. The fourth class represents extreme conditions that firefighters should only operate in for very brief durations.

A recent UL study attempted to better quantify the operating conditions that firefighters experienced in training as well as defining the current limitations of the testing mechanism used for monitoring that environment. The study used both static and participant mounted thermocouples and heat flux gauges. Heat flux measurements showed more extreme exposures than temperature measurements did. This can be partially explained given firefighters attempt to operate beneath the interface in the cold layer to limit their exposure to conductive and convective heat transfer from the hot layer. While the ambient temperature can be relatively low while operating in the cold layer, the radiant heat flux from the hot layer can still lead to significant heat

transfer. Therefore, simply measuring the temperature is not sufficient to characterize the thermal environment during training, particularly if thermocouples are positioned so that they are not exposed to radiant heat from the fire or the full extent of heat from the upper layer. Though they did not advance a new method, the UL FSRI study on concrete training structures recommended that the most appropriate method of characterizing participants' exposure would be to develop a time-dose relationship that would take into consideration the variability of the training environment, noting that a cumulative energy transfer model would be applicable for longer exposures, and that the duration of exposure is as important as the peak thermal conditions [41].

The topic of thermal conditions experienced by firefighters is also the topic of a report completed for the UL's Research Foundation by Dan Madrzykowski in 2017 [62]. Both this report, as well as the UL study reference work presented by Utech in 1973 defining three thermal classes for firefighter protective clothing [63]. This work defines three ranges of operating conditions: routine, ordinary, and emergency as well as setting forth rough guidelines for how long firefighters should be able to work in these conditions. Whereas the NIST thermal classes are to be applied to electronic equipment, Utech's thermal operating conditions concern the firefighter. It should also be noted that firefighting PPE has improved considerably since 1973, with its performance governed by numerous NFPA standards [55, 56, 57]. The NIST thermal classes along with Utech's operating conditions are summarized in Table 1 and shown graphically in Figure 17.

**Table 1: Thermal classes/operating conditions [59] [63]**

| Thermal Class/ Operating Conditions | Temperature Range (°C) | Heat Flux Range (kW/m$^2$) | Maximum Exposure Time (min) |
|---|---|---|---|
| I | < 100 | < 1 | 25 |
| II | 100 - 160 | 1 – 2 | 15 |
| III | 160 - 260 | 2 – 10 | 5 |
| IV | ≥ 260 | ≥ 10 | ≤ 1 |
| Routine | 20 - 70 | 1- 2 | no limit |
| Ordinary | 70 - 200 | 2 – 12 | 10 – 20 |
| Emergency | ≥ 200 | ≥ 12 | Seconds |
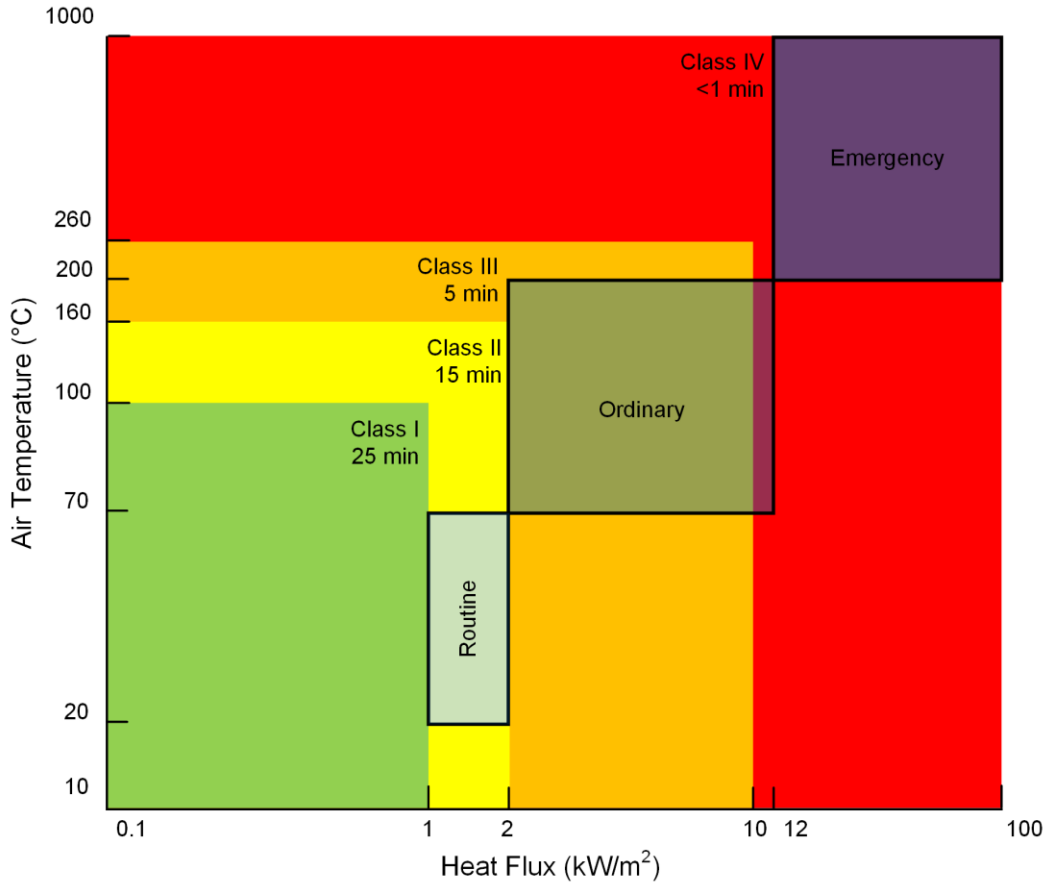
**Figure 17: Thermal classes/operating conditions [59] [63]**

It should be pointed out that NIST's thermal class III and Utech's ordinary operating condition have very broad heat flux ranges extending from 2 to 10 and 12 kW/m², respectively. The lower limit of 2 kW/m² is only double that experienced on a sunny day [64], while 10 kW/m² results in pain to exposed skin in only 3 seconds [36]. At an exposure of 4.5 kW/m², roughly half of the NIST upper limit for thermal class III, exposed skin can sustain an exposure for 30 seconds before second degree burn injury, falling to only 8s an exposure of 6.4 kW/m² [55].

The physiological effects of activity while wearing PPE must also be considered. PPE not only protects the firefighter under extreme conditions, it also adds to the physiological stress by increasing core temperatures and adding weight while performing firefighting duties. The heat stress associated with wearing PPE, even under normal ambient conditions, is an important criteria given the large amount of time that firefighters wear this equipment even while they are not exposed to extreme temperatures or heat fluxes [65]. In a training environment this must be taken into account by limiting the amount of time that participants are in full PPE prior to the start of live

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fire evolutions, and limiting the amount of physical work required before the burn. Proper hydration also plays a role in reducing heat stress. Ultimately, training participants are at risk of being burned as well as succumbing to heat stress due both to their environment and heat build-up while operating in PPE. Without better guidance, the four thermal classes proposed by NIST [58] and Utech [63] offer the best quantitative guidance, although the subsequent work by UL demonstrates its limitations [41]. As such, observations during training, even if anecdotal should be considered, particularly when they impose more stringent criteria on the training. It should also be noted that well designed training programs and competent instructors have many ways to mitigate both heat exposure and heat stress such as:

- moving participants within the live fire environment to reduce exposure to peak heat transfer areas;
- ensuring that participants compress their PPE as little as possible, since compression of the gear decreases its TPP;
- ensuring students are comfortable during evolutions, and that their physical output is minimized while still achieving the learning objectives;
- allowing rest time in cooler environments between highly demanding evolutions; and,
- fostering an environment where the student feels free of repercussions if they mention they are being exposed to too much heat, or feel the effects of heat stress.

## 2.4 Summary

Training, both theoretical and live fire, is important for both new firefighters as well for experienced firefighters to provide ongoing skills maintenance. Theoretical training introduces firefighters to important concepts that make them more effective on the fireground, particularly as it relates to decision making. Live fire training allows firefighters to learn, practice, and master tactics and techniques as well as to reinforce theoretical concepts.

While there are inherent risks involved in live fire training, these can be mitigated. Careful adherence to guidance provided by the NFPA can reduce unnecessary risks to both participants and instructors, and careful design of the curriculum and training evolutions can ensure that important learning objectives are achievable [6].

Ultimately, the safety of participants is dependent on the fire conditions that are present during evolutions. An understanding of the characteristics and risks associated with the type of structure and fuel load is a vital component to ensuring a consistent and safe environment, as is the knowledge and experience of the instructors setting and maintaining the live fire conditions.

This research project focuses on experiments undertaken to characterize the EFDS, with a simulator design and fuel load that were based on CFBT designs from around the world. While there is considerable experience and expertise on the part of the SMEs that were involved in the FKTP Project, there is no known quantitative characterization or comparison of the interior fire conditions, fuel loads, or competing simulator designs. Therefore, the evidence-based analysis to be proposed in Chapter 3 would add considerably to knowledge and understanding of these training simulators.

The following Chapter will review how the EFDS was designed, both in how it was based on previous designs, as well as what new design features were introduced and why as well as the experimental location and facilities. Prior to this work, there was no body of work that characterized the fire environment in a similar training simulator. Given the risks, and given the understanding of thermal exposure to firefighters during live fire training, the characterization of the EFDS over a variety of conditions can provide important understanding of the safety of this training simulator as well as provide guidance for its design and operation. Quantification of the live fire environment offers a unique opportunity to mitigate risk to training participants.

# Chapter 3: Experimental Apparatus & Technique

The goal of the FKTP Project, as outlined in the previous Chapters, was to provide a curriculum for the Canadian Fire Service that addressed perceived gaps between the fire science community and frontline firefighters. The EFDS, along with guidance on fuel loads, training evolutions, and safety recommendations, are intended to complement an in-class curriculum of fundamental Fire Dynamics for the fire service. As such, the lessons learned through the EDFS characterizations undertaken during this research project are intended to inform other agencies if they choose to construct similar training simulators and use those in conjunction with lesson plans developed for the combined theoretical and practical curriculum. With this in mind, it was necessary to characterize the environment in the EFDS under a range of conditions; for example, different weather conditions, that reflect some of the variations that could be anticipated during practical fire service training exercises. Similarly, characterizing the response of the unit to changes in the design and materials making up the fuel load addressed the potential sensitivity of the environment to different instructors, and their effectiveness in setting up and operating the unit for various training situations.

Controlling and varying a large range of such variables independently might have more systematically demonstrated their effect on the internal fire environment in the simulator. However, the limited number of tests that were possible would have necessarily meant that the range of conditions would have been much more narrowly focused and less representative of how the EFDS will actually be used in the field. The priority of this research project however was not the characterization of the interior fire conditions to develop a quantitative model or correlations. Rather, the primary motivation was to generate guidance for the Canadian Fire Service in the safe use of live fire simulators to achieve the learning objectives that support the FKTP curriculum. As such, the goals in characterizing the EFDS are summarized in more detail below.

1) Test and characterize different fuels and fuel configurations to achieve a learning environment that meets the learning objectives of certain training evolutions.
2) Understand how sensitive the fire environment is to a range of different fuel types and configurations and thereby recommend a fuel type and configuration for the fire service end users.

3) Characterize and document the range of conditions that are experienced by both instructors and students during the test burns to ensure that the training environment meets safety requirements.

4) Based on objectives 1) through 3), recommend a design for the EFDS including improvements to interior and exterior features seen in comparable training units and specifically with respect to ease of use related to operation in Canadian weather.

5) Develop and provide guidance on a simple instrumentation plan that can improve safety for participants and be reviewed to help to achieve learning objectives and improve instructor capabilities. Such instrumentation is currently required in the United Kingdom, but not in other jurisdictions [21], although recent work by the UL FSRI recommends instrumentation as well [41].

6) Determine that the final design is in full compliance with the existing guidance laid-out in NFPA 1403 for live fire training [6], as well as anticipating future developments that may be required to improve safety and hygiene of both instructors and trainees.

With the above objectives in mind, the following Sections will review the details of how the EFDS was constructed and instrumented, the location and facilities where testing occurred, what test variables were present during testing, and how firefighters interacted with the interior live fire environment during these tests.

## 3.1 Construction of the Enclosure Fire Dynamics Simulator (EFDS)

The EFDS, shown in Figure 18, was constructed from a regular tall shipping container [66] that was bought as a "single-use" shipping container due to the advantages described in Section 2.3.1. The specifications of the shipping container are shown in Table 2. As shipping containers are manufactured in Asia, unused containers cannot be purchased. Instead, units can be purchased as single-use, having been used once when shipped to North America. The decision to purchase single-use containers was made to limit potential issues related to structural damage or unknown contamination arising from extended previous use.

**Figure 18: The Enclosure Fire Dynamics Simulator – reprinted with permission from [67]**

**Table 2: Shipping container specifications**

| Specifications | | |
|---|---|---|
| Tare Weight | 3940 | kg |
| Cubic Capacity | 76.4 | $m^3$ |
| Internal Width | 2.35 | m |
| Internal Height | 2.7 | m |
| Internal Length | 12.3 | m |
| Door Width | 2.34 | m |
| Door Height | 2.58 | m |

The use of intermodal shipping containers as the basic design element of an EFDS offers the advantages below.

- The design of the apparatus, and hence training environment could be based on ample other examples from the United States [9], Sweden [20], Australia [43], Frankfurt [44], Dublin [68], and Vancouver [69]. This allowed not only the design of the structure, but also the fuel load, training evolutions, complementary teaching, applied tactics and techniques, and safety procedures to be predicated on a broad knowledge base.

- Intermodal shipping containers are available in almost every jurisdiction in Canada and throughout the world given they are intermodal and can, by design be shipped by sea, highway, or railway.
- The purchase price of single shipping containers is relatively low (approximately $C5,000), and the required modifications are also relatively low cost (approximately $C20,000).
- Modifications can be done by a welder with limited specialized training or guidance.
- The use of shipping containers can allow the construction of larger composite structures built entirely of shipping containers, or by integrating them into concrete structures.
- Shipping containers integrated as the fire enclosure into larger structures, either concrete or steel, can mitigate damage to the structures, and their relatively low cost means they can be replaced when worn out while saving the overall structure.
- Shipping containers lack the thermal mass of concrete structures and therefore allow upper layer temperatures to rise more quickly with less fuel. Conversely, they also retain this heat for less time, allowing activities to resume with less downtime and with lower residual heat exposure.

A standard shipping container was modified to facilitate safety, durability, ventilation, and to accommodate training objectives. An overview of the top and side views of the final layout for the EFDS are shown in Figure 19a) and b), respectively, and the different features will be described in this section. The origin for the coordinate system is also shown and will be described later. As the EFDS was based on several designs from different jurisdictions, many features were originally incorporated, some of which were not utilized during testing, and some of which have subsequently been eliminated in the final layout for the EFDS units that are located at the OFS training facility (shown in Figure 10). In general, the container is divided into three main sections from back to front: a vestibule section in the back 7'10.5" (2.40 m), and the fire compartment from there forward, which also includes the fuel burn area in the front 14'7" (4.44 m) of the container.

Figure 20 shows a coordinate system that is used for locating the features of the EFDS that are listed in Table 3 and this coordinate system is also referenced in Figure 19. Features are located from the floor of the EFDS, forward from the vestibule bulkhead, and right from the inside of the left wall. This same coordinate system is used when describing the locations of any instrumentation and for any subsequent discussions.

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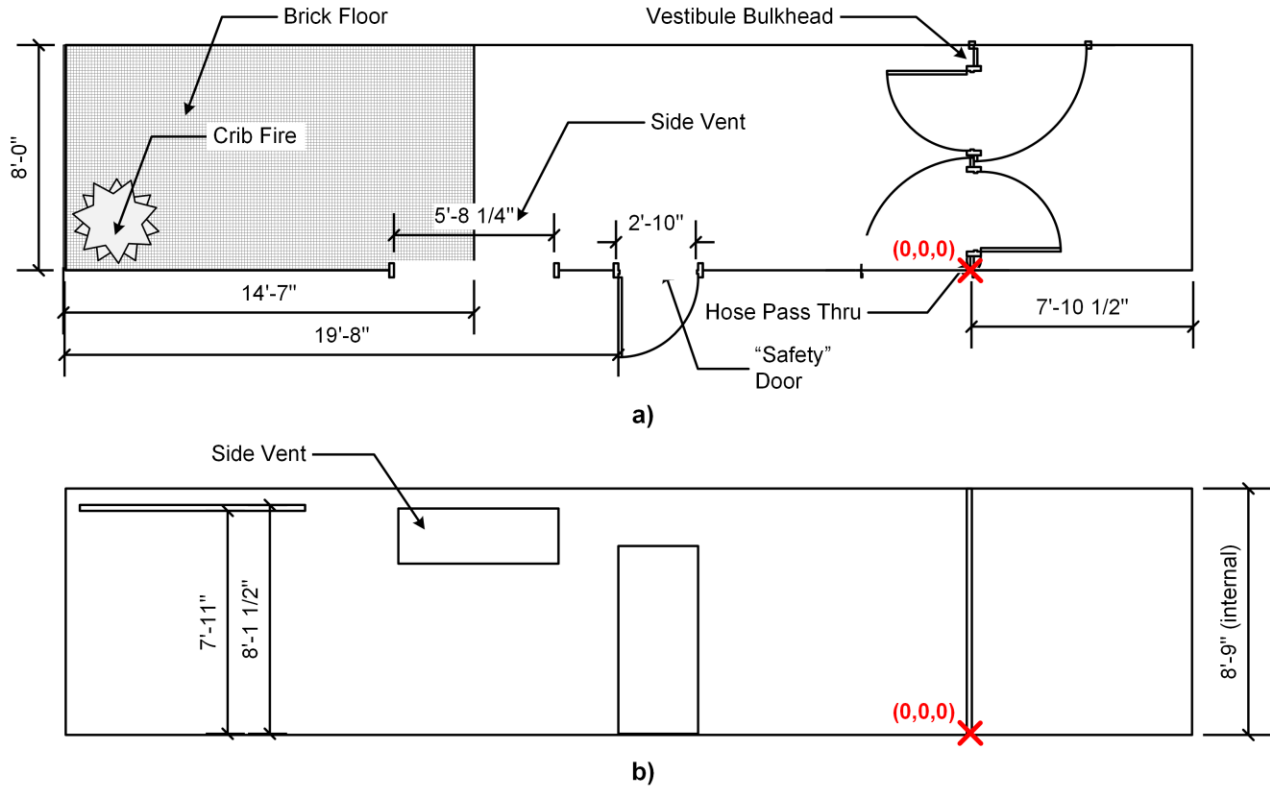
**Figure 19: EFDS Design overview: a) top view; and, b) side view**
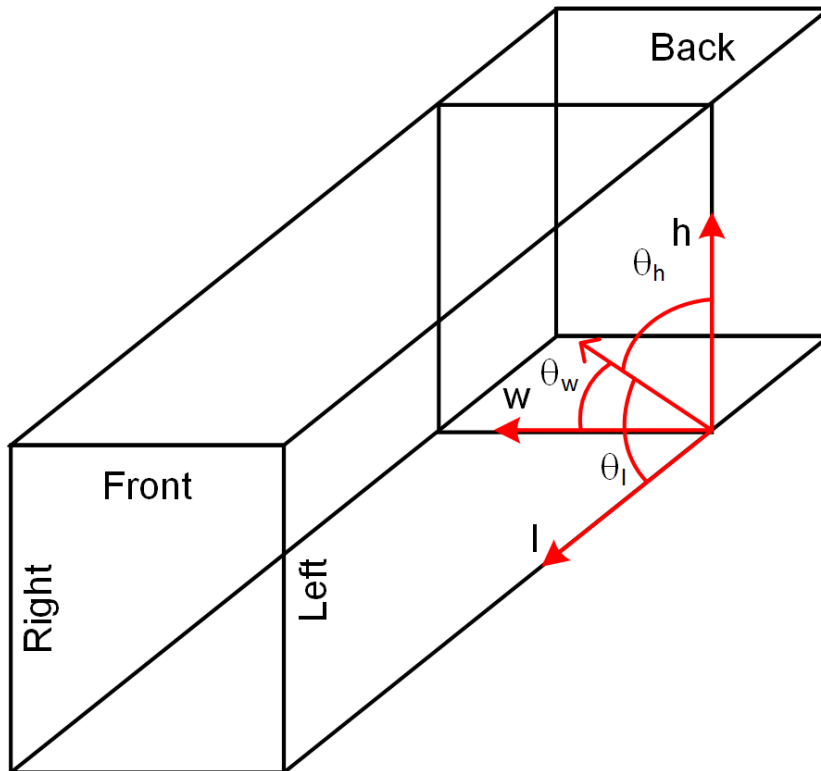


**Figure 20: EFDS coordinate system**

When describing the orientation of the EFDS, the front is taken as the end of the EFDS where the fuel is loaded and burned (i.e., the seat of the fire), as this is the direction that participants typically face during training evolutions. Using this reference, the side vent and safety door (shown in Figure 19) are on the left side of the EFDS. Any features located within the vestibule area will then be located at a negative length. Features are located by their rear, bottom, leftmost point.

**Table 3: EFDS modification specifications**

| Feature | Dimensions (m) | | | Location (m) | | |
|---|---|---|---|---|---|---|
| | h | l | W | h | L | W |
| Vestibule Door (Right) | 1.98 | - | 0.86 | 0.00 | 0.00 | 1.21 |
| Vestibule Door (Left) | 1.98 | - | 0.86 | 0.00 | 0.00 | 0.10 |
| Vestibule Bulkhead | 2.70 | - | 2.35 | 0.00 | 0.00 | 0.00 |
| Safety Door | 1.98 | 0.86 | - | 0.00 | 3.91 | 0.00 |
| Side Vent | 0.60 | 1.73 | - | 2.00 | 4.65 | 0.00 |
| Brick Floor | 0.10 | 4.44 | 2.35 | 0.00 | 5.45 | 0.00 |

The construction details of the EFDS will be reviewed beginning from the back of the EFDS where participants enter and exit the simulator, proceeding through to the front where the seat of the fire is located. Exterior features will then be described, followed by features that were included but did not play a role in the experiments.

### 3.1.1 Rear Doors

The main doors (which are a standard feature of shipping containers) at the back of the EFDS were cut horizontally slightly above the halfway point as shown in Figure 21. This modification is intended for a similar purpose as the bulkhead discussed further in the section below: to retain hot smoke to build-up an upper layer. However, the usefulness of this feature is not as pronounced in a design that contains a vestibule bulkhead, such as that used in these tests as well as by OFS for their training simulators. While the doors of the EFDS were modified in this way, ventilation was controlled by adjusting the opening of the inwards swinging door in the vestibule bulkhead. It should be noted that this modification requires significant work as the door clasps have to be modified, and it makes locking the EFDS when not in use more difficult, so this feature was not implemented in the EFDSs used for training. During testing, the rear doors of the EFDS were left

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fully open and ventilation into the main area was instead controlled through the vestibule bulkhead.



**Figure 21: Rear door detail**

### 3.1.2 Vestibule Bulkhead

For the initial design, the fuel load was based on fuel loads used by CFBT [20] and by the New South Wales Fire Brigade [70] in Australia The vestibule bulkhead design, and shown in Figure 22 was modified from designs of the New South Wales Fire Brigade [71] in Australia.
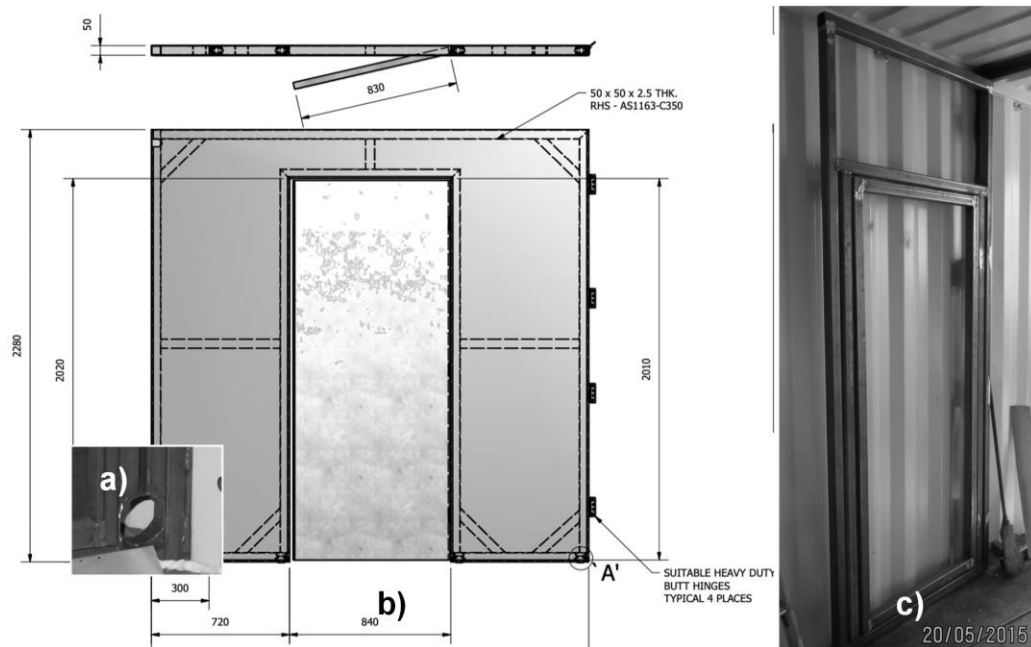


**Figure 22: Vestibule details: a) hose pass-through; b) CFBT design – reprinted with permission from [71]; and, c) EFDS under construction**

The vestibule bulkhead was split into two portions, hinged in the middle and each containing a door that was 34" (0.86 m) wide by 78" (1.98 m) high, as shown in Figure 19. One of these modifications, the hose pass through was also modified to reduce pinching and is detailed in Figure 22a.When unhinged from one another, the bulkhead halves can be moved out of the way entirely so that the EFDS can be used in different configurations. This allows instruction to a wide variety of learning objectives through different training evolutions [72, 73, 74]. For example, since the doors in the bulkhead sections open in opposite directions, training evolutions can be done on inwards and outwards-swinging doors. During the testing, the right hand, inward swinging door (shown during training evolutions in Figure 23) was used as the primary ventilation opening for the instrumented burns.



**Figure 23: Door entry training evolutions – reprinted with permission from [75]**

### 3.1.3 Safety Door

A safety door is located on the same side of the EFDS as the side vent as shown in Figure 19 as well as Figure 24. This door was 34" wide by 78" (0.86 m wide by 1.98 m high), a standard North American door size, and was divided horizontally into two equal upper and lower sections. The primary purpose of the safety door is to provide a secondary egress point during training evolutions. The division of the safety door into two sections allows this door to be used more effectively as an inlet for ventilation as shown in Figure 25 as well.



**Figure 24: Side vent and safety door**

While the doors in the vestibule were more commonly used for ventilation, both during testing as well as during evolutions there are a few conditions where the safety door can be used for ventilation.

- During training evolutions where participants are using the vestibule doors to practice door-entry techniques (as shown in Figure 23), and ventilation is required without interfering with these learning objectives.

- When the EFDS is attached to a larger training structure (such as the training facility in Ottawa, as seen in Figure 10) and the training evolution involves participants advancing

through a central structure. For these evolutions, the rear doors of the EFDS are kept as closed as possible so that the smoke produced in the EFDS will migrate into the central structure shown in Figure 10 so the evolutions can take place in limited visibility conditions. This situation means that the vestibule doors that normally provide ventilation (through the rear doors) are no longer as good a source of non-vitiated air.

- During longer training evolutions involving the larger training structure shown in Figure 10. These evolutions tend to be longer in duration, and so instructors might control fire conditions from outside of the EFDS to limit their exposure to the high-heat environment.

### 3.1.4 Side Vent

A louvered vent was located on the side of the EFDS as one method by which to control ventilation and smoke layering within the container during both testing and training. This vent was 0.6 m high and 1.73 m long and louvered in the middle so that when open, the upper half opens outwards and the lower half opens inwards. The side vent is operated using handles located on the interior and exterior of the EFDS (shown in Figure 24). The vent midpoint was aligned approximately with the end of the bricked floor in the EFDS. Vent dimensions are shown in Figure 25a, the vent in its open position is shown in Figure 25b, while an interior view of the closed vent is shown in Figure 26.
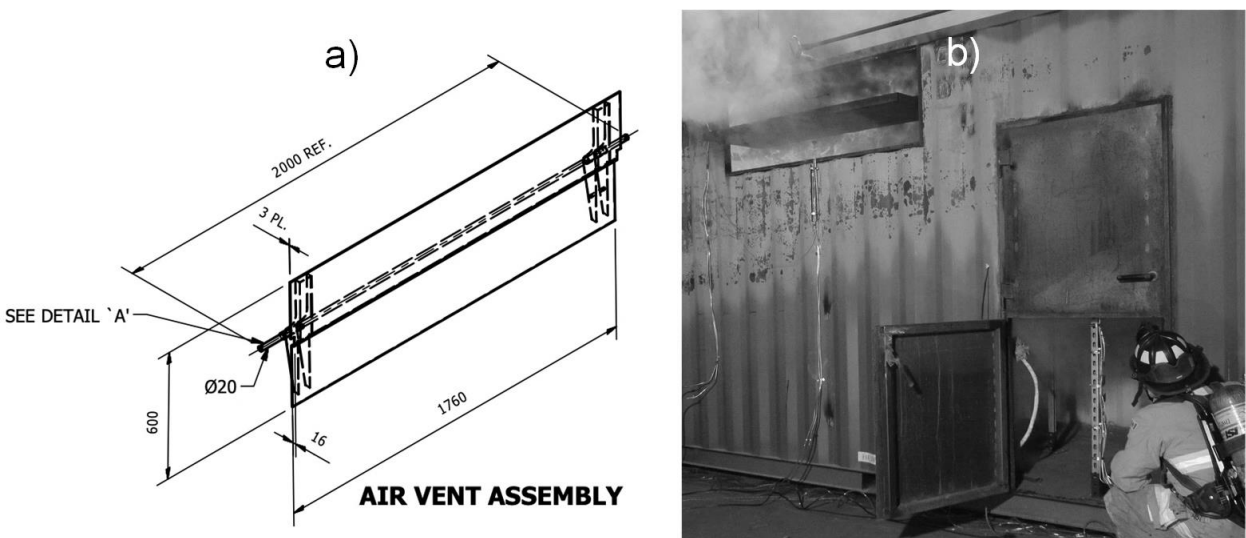


**Figure 25: EFDS side vent: a) design; and, b) operation**
**– reprinted with permission from [76, 77]**

Given its proximity to the fire, as well as its position near the ceiling of the EFDS, this vent provides a good outlet for smoke during training. In particular, it is often used when an abundance of moisture is present in the EFDS as a result of excessive water application during training evolutions. Excessive water application occurs more commonly during training than it did during experiments as more water is applied when allowing participants to practice techniques, particularly as applying short bursts of water takes practice, thus inexperienced students tend to apply longer duration applications. These applications tend to introduce more water into the interior fire environment than when more experienced instructors are either controlling the fire or demonstrating techniques. Given the test burns did not include participants, fewer water applications were made during the burns, and they tended to be shorter bursts. Another cause of excessive water application is during evolutions where participants enter the EFDS and make several water applications from their firefighting hoses as they advance towards the seat of the fire [74]. When the louvered vent is used in conjunction with one of the doors in the vestibule as an inlet, smoke and moisture can be quickly moved out of the EFDS and the smoke-air interface layer within the container will lift. At the same time, however, the increased ventilation will result in a higher heat release rate for the fire.

### 3.1.5 Brick Floor

A layer of interlocking brick was installed to cover the floor of the fuel burn area and held in place using a piece of angle iron. It extended the first 14'7" (4.44 m) of container length as shown in Figures 19 and 26. This has been done in designs from New South Wales [78], detailed in Figure 27, and many other fire training facility applications to protect wood floors of the containers from the seat of the fire and from the higher radiant and convective heat flux environment anticipated closer to the seat of the fire.

A section of the floor of the EFDS at the front end of the EFDS was removed and replaced with steel grating as shown in Figure 28. This section lies underneath the brick and allows for water used during testing and training burns to be captured from drains in the EFDS. The capture of water used during testing and training evolutions is important to limit the environmental impact of training, and reduces the requirements for groundwater assessments as well as the risk that the OFS training site might suffer the same fate as the NRC's National Fire Laboratory (which will be discussed in Section 3.1.9) [79, 80].

**Figure 26: EFDS – various interior features**
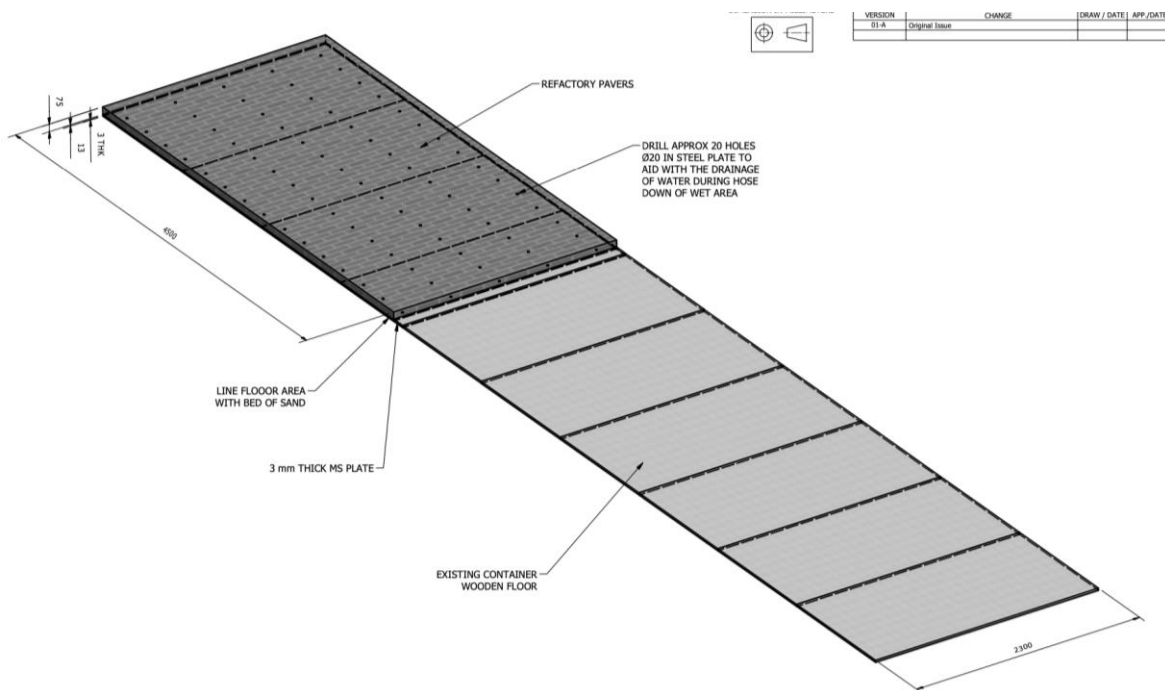


**Figure 27: Brick floor design from NSW – reprinted with permission from [78]**

**Figure 28: Water drainage**

## 3.1.6 Supports for Fuel Loading

The front end of the EFDS had to be configured in a way to support an appropriate fuel load for the characterization, and after a necessary refinement during characterization, for final training purposes as well. The final fuel type and configuration will be discussed in Section 3.3.2, but construction of the EFDS supporting elements for the fuel will be explored here. For the initial design, the fuel load was based on fuel loads used by CFBT and New South Wales Fire Brigade [70] in Australia as well as that of Ian Bolton in North Vancouver [69], although similar fuel loads are used in a variety of other jurisdictions as well [44, 81]. This loading, and the typical supports, are shown in Figure 29.

Sheets of fuel are supported near the ceiling of the EFDS by a framework made of hollow structural steel members, while additional sheets are supported next to the front and side walls of the EFDS on individual brackets and held in place with chains. The fibreboard fuel used in early experiments was found to have poor structural integrity, and as such the sheet fuels were reinforced using steel mesh on both the walls and ceiling. On the walls, bracing material was used to hold the mesh together with the fibreboard as shown in Figure 30. While the steel mesh was not

required for tests when particleboard was used instead of fibreboard on the walls, it was still used on the ceiling for tests with particleboard as fuel.
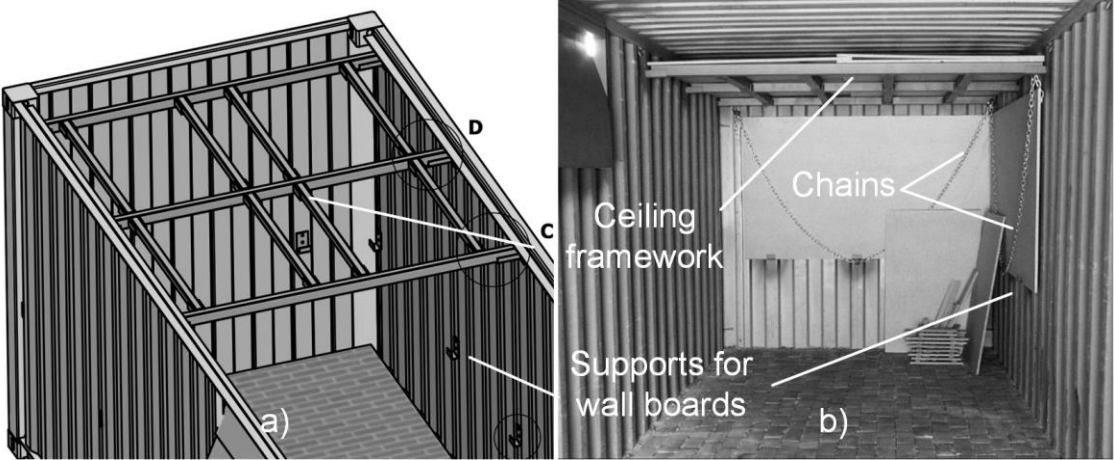


**Figure 29: Fuel supports: a) details of ceiling supports – reprinted with permission from [70]; and, b) wall and ceiling**



**Figure 30: Mesh reinforcement for fibreboard**

Through iterations on the design during the characterization tests, an updated design was established and used to secure the fuel on the walls for the EFDS at the OFS training site. This design involved a piece of hollow structural steel resting on brackets on either side of the fuel. This design, which can be seen in Figure 31, is more effective at retaining the fuel on the walls as the structural integrity of the fuel disintegrates during a fire, and also allows for mounting of, and holding steel mesh next to the fuel if so desired, with the side benefit that it is also easier to load the fuel before each burn.



**Figure 31: Final fuel support design for OFS training**

### 3.1.7 Roof

The EFDS was initially built without a roof external to the top surface of the container. A roof was added when the testing was moved from inside at the National Research Council's (NRC) National Fire Laboratory to the OFS training site. During training, participants and instructors had noted

that it took an extremely long time for the EFDS to build-up sufficient upper layer temperatures to show phenomena such as rollover which is characterized by flames issuing through hot combustion gases accumulated along the ceiling on the compartment. The time taken was observed to be greatest when water had accumulated on the EFDS and ambient temperatures were low. The importance of adding a roof, both to the EFDS used in this research as well as to those used in training, was also informed by the example of the training units used by the Dublin Fire Brigade [81] and shown in Figure 32.



**Figure 32: Roof (Dublin Fire Brigade)**

These roofs are not uniformly used in all jurisdictions. Most notably, they are not used in Australia (as can be seen in Figure 7) where in these jurisdictions improved training conditions were actually reported [82] when water had built-up on the training units. It is important to note, however, that the ambient conditions in the Australian jurisdictions are both considerably hotter, and less humid, than in Ottawa [83, 84], and therefore, the example from Dublin [85] would seem to be more applicable to Ottawa. In addition, it was felt that adding a roof to the EFDS would aid in keeping

the testing conditions consistent, both between the tests conducted indoors and outdoors, as well as from test to test outdoors.

The roof used in Dublin was asymmetrical due to the presence of a roof vent in their container training unit design. While the EFDS was initially built with a roof vent, it was quickly determined that the side vent would be used instead, and so no venting from the top vent was required. Therefore, in the present research a symmetrical design of roof was settled on as shown in Figure 33. A series of supports were constructed of hollow structural steel over which corrugated sheet metal was attached. The roof extended over the sides of the EFDS and the gable ends and eaves were left open to allow for air circulation. In addition, the roof had an open ridge cap to increase ventilation of the air above the roof of the intermodal container.
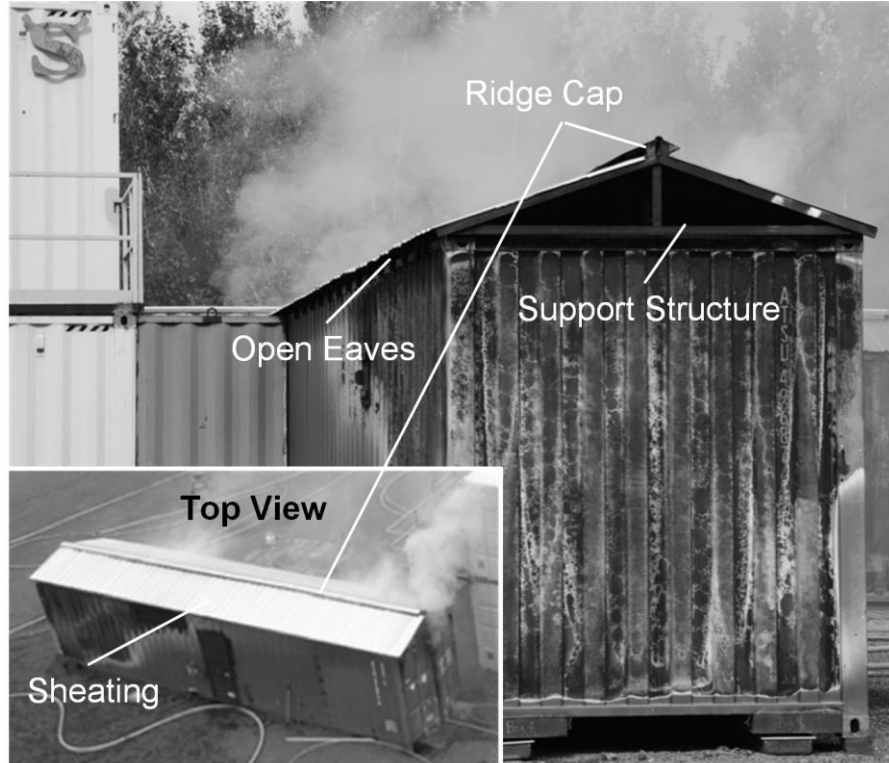


**Figure 33: EFDS roof details (inset: top view)**

### 3.1.8 Other Features

There are several other modifications made to the EFDS that, although they did not impact testing, should be noted. Firstly, a second door, with the same design and dimensions as the safety door was also installed in the vestibule area of the EFDS as shown in Figure 34a, on the right side, as

the safety door. The purpose of this door is to allow for an EFDS to be connected to a central training structure through this door as shown in Figure 34b. In the EFDS instrumented for testing, this door was divided into two horizontal halves in the same way as the safety door. However, when implemented into the training structure, the doors were not cut in half so as to not add another safety concern if this door is being used as a means of egress in limited visibility.

A moveable radiation shield was installed in the EFDS (shown in Figure 26). While it was installed in the instrumented EFDS, it was not used during testing. This shield serves mostly to obscure the seat of the fire from advancing fire crews during longer training evolutions [74]. Because the size of the fire in the EFDS is relatively small, it can be extinguished easily with only a moderate volume of water. Since extinguishing the fire means that further evolutions would not be possible, it is necessary that participants not extinguish the fire during training. However, when this is used as part of the instruction, it runs the serious risk of teaching the participants that extinguishing the seat of the fire is not an important part of firefighting. Such an undesired learning outcome has been shown to pose a serious risk to firefighters responding to actual incidents [30]. By moving the radiation shield into place, participants are able to advance towards the seat of the fire with hot gases and fire phenomena occurring above them in the upper layer, but without being able to see the seat of the fire. The result is that they are being trained to observe and deal with the general environment, and the instructor does not need to reinforce the idea of not extinguishing the seat of the fire. Hopefully, in this way the danger of teaching the undesired learning outcomes is mitigated.

A moveable bulkhead, which is 60 cm deep and located just behind the side vent, is shown during construction in Figure 35 which is located just behind the side vent. This bulkhead is intended to help with the build-up of a hot upper layer during training evolutions by retaining smoke close to the ceiling. This feature is more important in designs were there is no vestibule bulkhead, which effectively accomplishes a similar goal. This bulkhead was never used in testing, was not included in the four EFDSs that are used for training at the OFS training site, and is therefore not a part of the developed training curriculum.

**Figure 34: Side door: a) used to connect to larger structures; and, b) details**
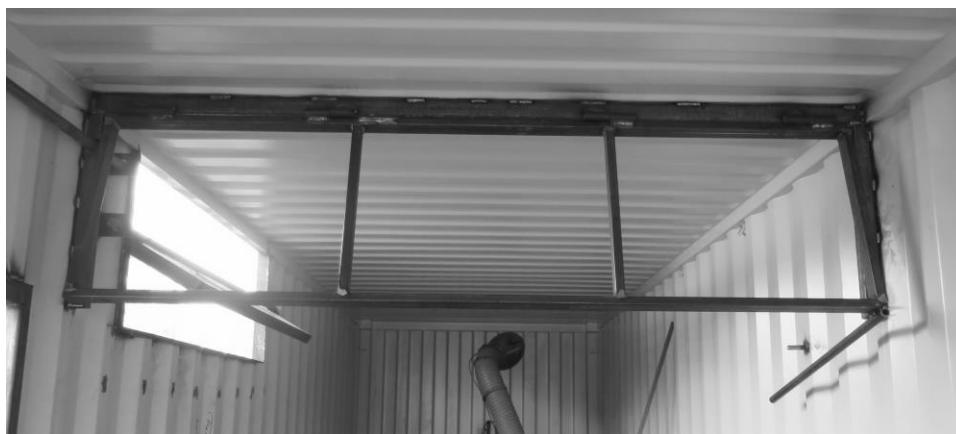


**Figure 35: Moveable bulkhead**

A moveable radiation shield was installed in the EFDS (also shown in Figure 26). While it was installed in the instrumented EFDS, it was not used during testing. This shield serves mostly to obscure the seat of the fire from advancing fire crews during longer training evolutions [74]. Because the size of the fire in the EFDS is relatively small, it can be extinguished easily with only a moderate volume of water. Since extinguishing the fire means that further evolutions would not be possible, it is necessary that participants not extinguish the fire during training. However, when this is used as part of the instruction, it runs the serious risk of teaching the participants that extinguishing the seat of the fire is not an important part of firefighting. Such an undesired learning outcome has been shown to pose a serious risk to firefighters responding to actual incidents [30]. By moving the radiation shield into place, participants are able to advance towards the seat of the fire with hot gases and fire phenomena occurring above them in the upper layer, but without being

able to see the seat of the fire. The result is that they are being trained to observe and deal with the general environment, and the instructor does not need to reinforce the idea of not extinguishing the seat of the fire. Hopefully, in this way the danger of teaching the undesired learning outcomes is mitigated.

### 3.1.9 Location & Facilities

The EFDS was initially installed and instrumented for testing at the NRC's testing facility in Mississippi Mills (Figure 36).



**Figure 36: NRC site (Mississippi Mills) [79]**

This facility was chosen as it had a large enclosed area that would allow for indoor testing of the EFDS (as shown in Figure 37), which had the benefits of limiting the effects of changing ambient wind conditions and precipitation on the characterization results, as well as including the NRC's participation in the research (a copy of the City of Ottawa's Purchase Order can be found in Appendix B) [86]. Testing began on the EFDS in the summer of 2015 at this site, but was put on hold in early 2016, due to the closure of the Mississippi Mills Facility over water contamination detected in a nearby neighbourhood and traced back to the historical use of firefighting foams at the facility [79, 80]. This resulted in the permanent closure of the facility and the need for OFS to

build an alternate facility to allow for continuation of both characterization testing as well as to install the final units for ongoing training planned for the FKTP Project.



**Figure 37: Testing at the NRC facility – reprinted with permission from [87]**

A new site was prepared in the spring of 2016, under jurisdiction of the City of Ottawa to support both the ongoing training activities of the FKTP Project as well as remaining EFDS testing. The EFDS was relocated to the newly prepared site in the summer of 2016 and while many options were considered, the remaining testing was conducted outdoors. Efforts then had to be made to mitigate, insofar as possible, the effects of wind and precipitation on the characterization results. To mitigate the effects of wind, a three-sided containment area was constructed using intermodal shipping containers stacked two containers high and oriented to block the dominant winds from the southwest [88]. A picture of this structure [89] is overlaid on the site map for the training facility showing its orientation in Figure 38. A roof was also installed on the EFDS to reduce the effects of water and snow accumulation on the simulator since it had been previously determined during training that significant build-up of water on the EFDS acted as a significant heat-sink and negatively affected the internal training environment, particularly if ambient temperatures were closer to freezing.
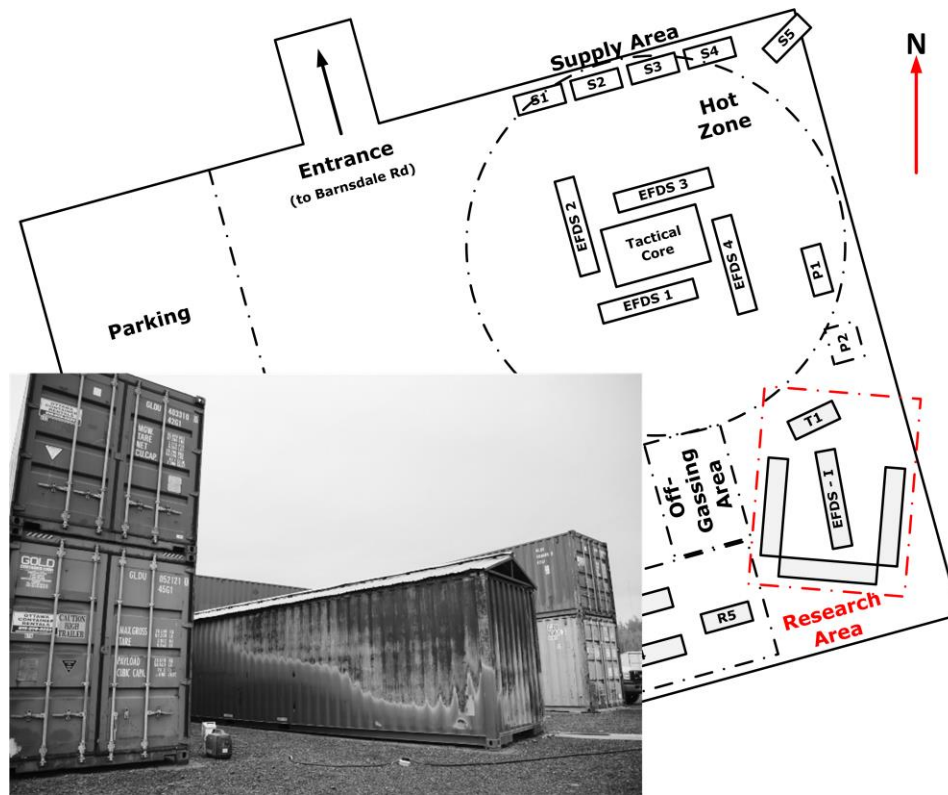
**Figure 38: Testing at the OFS training facility – reprinted with permission from [89]**

## 3.2 Instrumentation and Measurement Uncertainty

Instrumentation of the EFDS that was characterized in this research, along with design of the data acquisition system, was performed, in close consultation with the author, by staff from the National Research Council of Canada under contract with Ottawa Fire Services [86] as part of the CSSP grant for the FKTP Project [1]. Instrumentation consisted of the following:

- thermocouples to measure a variety of internal and external temperatures;

- heat flux gauges to measure heat flux from the interior fire environment to locations that would provide useful characterization of the environment;

- bi-directional probes to measure ventilation through the side vent as well as the safety door;

- cameras to record the burns so that they could be reviewed and visual phenomena might be correlated with other data; and,

- a data logging system that captured all of the data and recorded measurements to a central computer which are shown as configured at the NRC's lab in Figure 39 as well as a mobile

office (ATCO trailer) that was used to house this instrumentation when testing moved to the OFS training facility as shown in Figure 40.



**Figure 39: Data collection setup (NRC labs) – reprinted with permission from [77]**



**Figure 40: Instrumentation trailer at OFS site [90]**

The instrumentation was positioned to best characterize the fire environment and its effect on the EFDS. The research project eventually focussed on a characterization of the interior fire environment based on video observations, temperature measurements, and heat flux measurements. The velocity measurements from the bi-directional probes were not analyzed in this characterization of the fire environment so results from those will not be discussed further here.

A variety of measurement uncertainties exist for the different measurements collected. In general, these uncertainties can be considered as either precision or bias uncertainties, and the components of these must be combined to give an overall uncertainty for each measurement.

Precision uncertainties are random, occurring from variations in the measurement [91], while bias uncertainties are systematic, resulting from the experimental setup, and are taken here as the values given by the respective manufacturers. The overall bias uncertainty is achieved by assuming that the different contributions are not covariant, and therefore can be combined using equation 3.1:

$$b_{tot} = \sqrt{\sum_{i=1}^{n} b_i^2}$$ 

<div align="right">3.1 [92]</div>

where $b_i$ are the individual contributions to the total bias uncertainty. Precision uncertainty will be discussed as it relates to the specific transducers in subsequent Sections. The total uncertainty, which includes both bias and precision uncertainties can be calculated using equation 3.2:

$$u = \sqrt{p^2 + b_{tot}^2}$$ 

<div align="right">3.2 [92]</div>

The calculation of uncertainty for temperature and heat flux will be specifically discussed in the subsequent Sections.

### 3.2.1 Temperature Measurement

Temperatures were measured using Omega, K Type thermocouples. Within the compartment, 18-Gauge stainless steel shielded and grounded thermocouples were used (model HKQSS-18G-400 [93]), while 24-Gauge glass braided thermocouples were used for exterior measurements (model GG-K-24-SLE-1000 [94]). Each thermocouple was connected to thermocouple K Type extension wire [95] and run back to a Portable Data Logger connected to a computer (model OM-SQ2040 [96]). Temperature measurements were recorded once every second.

The EFDS was instrumented with a total of 27 thermocouples distributed as follows, shown in Figure 41 and with their positions further detailed in Table 4.
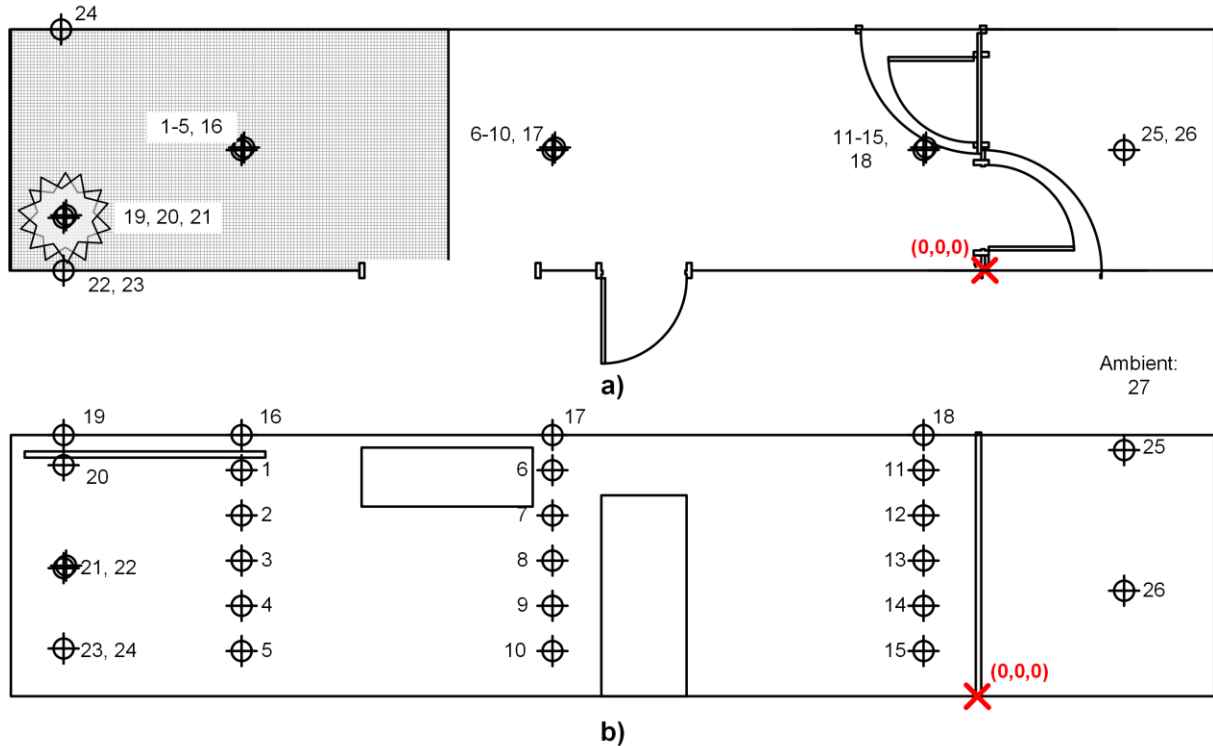
**Figure 41: Thermocouple placement: a) top view; and, b) side view**

- Thermocouples positioned above the crib at heights of 2.59 m (T20) and 1.83 m (T21) to provide information on the growth of the fire plume emanating from the crib during the early stages of fire growth.
- Three thermocouple rakes (the first two of which are shown in Figure 42) – with thermocouples positioned at heights above the floor of 2.59 m, 1.98 m, 1.37 m, 0.76 m, and 0.15 m – along the centerline of the EFDS positioned:
  - Rake #1 (T1-T5): In the middle of the section of the EFDS where the floor is protected by interlocking brick;
  - Rake #2 (T6-T10): Just ahead of the safety exit door, behind which all participants should be positioned for the majority of the evolution, as well as representative of conditions where emergency egress would occur; and,
  - Rake #3 (T11-T15): Just inside the interior vestibule, as far away from the seat of the fire that participants could be positioned, where participants would enter and exit the EFDS under normal circumstances, and exposed to more convective heat transfer due to ventilation using these doors.

- Two thermocouples positioned near the ceiling (T25) as well as 0.91 m (T26) above the floor in the vestibule area.
- External thermocouples positioned:
  - Above each rake on the roof of the EFDS (T16, T17, and T18);
  - Above the crib on the roof of the EFDS (T19);
  - The exterior of the EFDS on the side adjacent to the crib at a height of 1.83 m (T22) and 0.91 m (T23) to characterize the heat stress experienced by the shipping container; and,
  - The exterior of the EFDS of the side opposite to the crib at a height of 0.91 m (T24) to characterize the heat stress experienced by the shipping container.
- A thermocouple positioned near the instrumentation trailer to measure ambient temperature (T27).

Bias uncertainties for the thermocouples arise from three sources.

- Thermocouple uncertainty (for stainless steel shielded or glass braided K Type thermocouples) of ±2.2°C or 0.75% above 0°C, whichever is greater within a 95% confidence level [97, 98]. The maximum temperature measured during the testing was 982°C, and therefore an uncertainty of ±7.4°C.

- Thermocouple extension wire uncertainty of ±2.2°C or 0.75% above 0°C, whichever is greater within a 95% confidence level [97]. This is taken as ±2.2°C as this uncertainty value is larger than the 0.75% uncertainty at 293°C, well above the temperature the extension wire would be subjected to.

- An uncertainty associated with the data acquisition module of ±0.05% for the reading (once again using the maximum temperature of 982°C) and ±0.025% (assuming an upper operating temperature of 30°C) for the range within a confidence level of 95% [96].

These bias uncertainties combine for an overall bias uncertainty of ±7.7°C within a confidence level of 95% using equation 3.2.

**Table 4: Thermocouple placement**

| # | Description | Internal/External | H | L | W |
|---|---|---|---|---|---|
| 1 | Rake #1 | I | 2.59 | 7.92 | 1.18 |
| 2 |  | I | 1.98 | 7.92 | 1.18 |
| 3 |  | I | 1.37 | 7.92 | 1.18 |
| 4 |  | I | 0.76 | 7.92 | 1.18 |
| 5 |  | I | 0.15 | 7.92 | 1.18 |
| 6 | Rake #2 | I | 2.59 | 5.84 | 1.18 |
| 7 |  | I | 1.98 | 5.84 | 1.18 |
| 8 |  | I | 1.37 | 5.84 | 1.18 |
| 9 |  | I | 0.76 | 5.84 | 1.18 |
| 10 |  | I | 0.15 | 5.84 | 1.18 |
| 11 | Rake #3 | I | 2.59 | 0.3 | 1.18 |
| 12 |  | I | 1.98 | 0.3 | 1.18 |
| 13 |  | I | 1.37 | 0.3 | 1.18 |
| 14 |  | I | 0.76 | 0.3 | 1.18 |
| 15 |  | I | 0.15 | 0.3 | 1.18 |
| 16 | Rake #1 External | E | 2.74 | 7.92 | 1.18 |
| 17 | Rake #2 External | E | 2.74 | 5.84 | 1.18 |
| 18 | Rake #3 External | E | 2.74 | 0.3 | 1.18 |
| 19 | Crib | E | 2.74 | 0.3 | 2.35 |
| 20 | Crib | I | 2.59 | 9.60 | 2.05 |
| 21 | Crib | I | 1.83 | 9.60 | 2.05 |
| 22 | Plume Side | E | 1.83 | 9.60 | 2.35 |
| 23 | Plume Side | E | 0.91 | 9.60 | 2.35 |
| 24 | Opposite Side | E | 0.91 | 9.60 | 0 |
| 25 | Vestibule | I | 2.59 | -1.20 | 1.18 |
| 26 | Vestibule | I | 0.91 | -1.20 | 1.18 |
| 27 | Ambient | E | - | - | - |
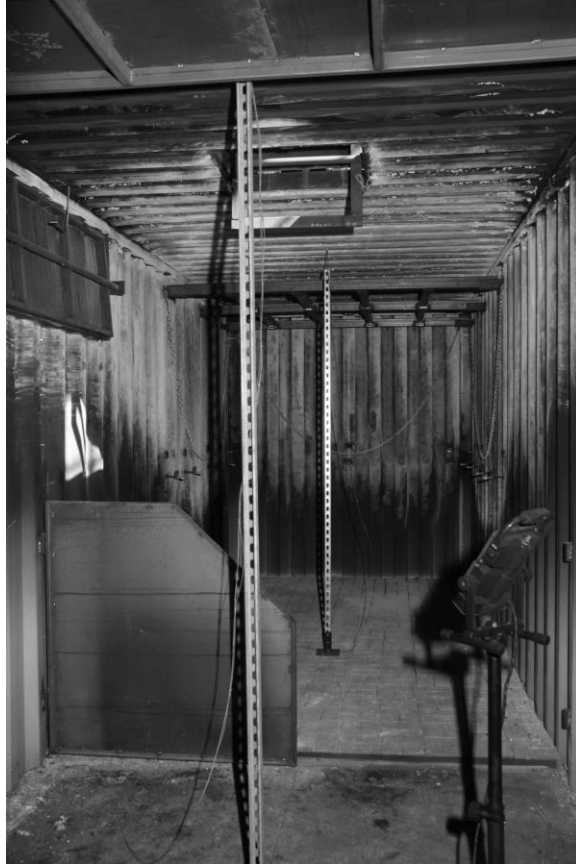
**Figure 42: Thermocouple rakes #1 & #2**

The precision of temperature measurements was approximated looking at measurements taken prior to ignition of the first and last burns in the series of characterization experiments and using equation 3.3:

$$p = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad \text{3.3 [92]}$$

where $n$ is the number of samples, $x_i$ is each individual measurement, and $\bar{x}$ is the arithmetic mean of the sample. This was a period when conditions could be considered to be steady-state and those tests were chosen to account for any drifts that might have occurred over the course of testing as well. Due to the nature of the evolutions, data acquisition started well before ignition for each test, resulting a relatively large number of measurements on which to base the analysis.

While this attempt to characterize the precision of the measurements is far from rigorous, it does allow comparison of the precision to the overall uncertainty. Data from the ceiling-height thermocouple in the vestibule area was used as this area had very little traffic prior to the evolutions as well as being inside the EFDS and therefore less subject to changes in ambient temperature. The estimated precision within a confidence level of 68% determined in this fashion is shown in Table 5,and is not important when compared to the bias uncertainty.

**Table 5: Thermocouple precision**

| Test Date | Mean Temperature (°C) | Number of Data Points | Estimated Precision (°C) |
|---|---|---|---|
| August 6th, 2015 | 25.7 | 576 | ±0.003 |
| July 11th, 2017 | 25.1 | 296 | ±0.008 |

The total uncertainty, when considering the estimated precision uncertainty and combining it with the bias above, is ±7.7°C within a confidence level of 95%.

### 3.2.2 Heat Flux Measurement

Heat flux was measured using four model #TG1000-1 Gardon gauges, each with a 180° view angle, manufactured by Vatell Corporation [99]. The water-cooled bodies of the gauges are made of copper and have a length and diameter of 1" (25.4 mm), with a 4.7 mm constantan foil disc mounted in the center of the upper face. Gardon gauges were selected due to availability for the experiment and familiarity on the part of the NRC staff.

In the gauge, the temperature difference between the center and the circumference of the foil disc is measured and a corresponding voltage output generated. Via an energy balance on the gauge, the differential temperature is proportional to the convective and radiative heat flux incident on the face of the gauge. The gauges are calibrated by the manufacturer so that each voltage measurement can be converted to kW/m$^2$ by applying a predetermined calibration curve. A high-temperature, low-emissivity paint is applied by the manufacturer to the surface of each gauge, since the measured value of heat flux is very dependent on the emissivity of the front face of the sensor. As a result of their sensitivity, the sensors were regularly cleaned of any material build-up from the

burns during the present tests, and a high-emissivity coating was re-applied once following an inspection which showed some degradation [100].

Two heat flux gauges (HFGs) were mounted in the floor of the EFDS, one was mounted near the safety exit, and a final one was mounted at the rear vestibule wall. Figure 43 shows both the position and the view angle for each gauge with positions and orientations, along with their calibration factors, in Table 6.
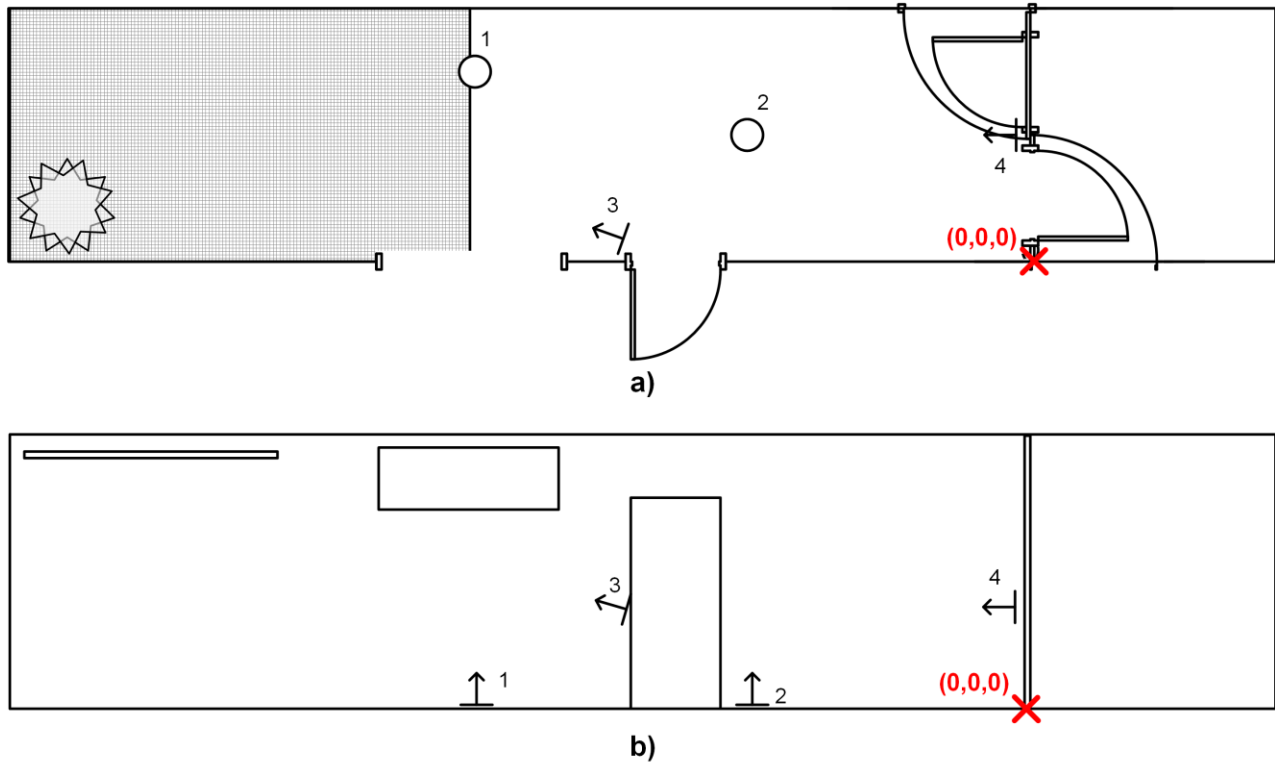


**Figure 43: Heat flux gauge placement: a) top view; and, b) side view**

**Table 6: Heat flux gauge calibration constants and placements**

| # | Description | Calibration Constant (kW/m$^2$·mV) | Relative Position (m) | | | Relative Angle (deg.) | | |
|---|---|---|---|---|---|---|---|---|
| | | | H | l | w | $\theta_h$ | $\theta_l$ | $\theta_w$ |
| H1 | Forward – Floor | 20040 | 0.00 | 5.33 | 1.73 | 0.0 | 90.0 | 90.0 |
| H2 | Mid – Floor | 20220 | 0.00 | 3.37 | 1.18 | 0.0 | 90.0 | 90.0 |
| H3 | Exit Door | 19380 | 1.00 | 4.41 | 0.30 | 73.8 | 25.9 | 70.4 |
| H4 | Rear | 20530 | 1.00 | 0.50 | 1.18 | 90.0 | 0.0 | 90.0 |

The two HFGs mounted in the floor (H1 and H2) were positioned just past the end of the section covered with interlocking brick, as well as just behind the safety door. They were mounted flush with the floor and protected by a steel pipe, with all wiring external to the EFDS and therefore amply protected. The locations were chosen to determine heat flux at the position of maximum forward advance of participants to the fire area in the container during a test, as well as locations where participants were likely to spend most of their time during the evolutions, respectively. The choice was made to mount these sensors at floor level facing towards the ceiling so as to allow for comparison of measured heat flux data to the heat flux threshold of 20 kW/m$^2$ at the floor that is often used to represent the onset of flashover in compartment fire scenarios [33, 36].

The third HFG (H3) was mounted just in front of the safety door at a height of 1 m off the floor to approximate the height of a kneeling firefighter and oriented to face into the fire area toward the opposite top corner of the EFDS. It was protected with a length of steel pipe and the body was insulated using glass fiber insulation. The position and orientation for this HFG were chosen to approximate a worst-case scenario for heat flux to a firefighter who might be using the safety door as an emergency point of egress.

The final HFG, H4, was mounted at a height of 1 m and oriented to face the middle of the front wall (fire compartment) of the EFDS. As with sensor H3, this sensor was protected with a length of steel pipe as well as insulated using glass fiber insulation as is shown in Figure 44. The position and orientation were chosen in an effort to measure the heat flux that participants would be exposed to from the compartment at the furthest distance away from the fire. It turned out that there was considerable air flow, and thus convective heat transfer, in this area as the rear doors were used as the primary source of ventilation for the compartment which greatly affected the values of incident heat flux measured by H4.

In terms of uncertainty, the HFGs have a bias uncertainty of ±3% and a precision uncertainty of ±1% within a confidence level of 95% as supplied by the manufacturer [101]. Other work suggests that an additional uncertainty of ±8% might also be present due to contribution of convective heat transfer [4, 102]. While this is unlikely to have a significant effect on H1 and H2 which are mounted in the floor, the contribution to measurements recorded by H3 is unknown, and the effect is likely significant for H4. Given that the flow velocities varied significantly over the course of the fire, as well as due to firefighter interactions with the ventilation in most areas of the test

enclosure, this additional bias error is included in the calculations here. Thus, a total bias uncertainty of ±8.5% was calculated using equation 3.1 and an overall uncertainty of ±8.6% was calculated using equation 3.2 within a confidence level of 95%.
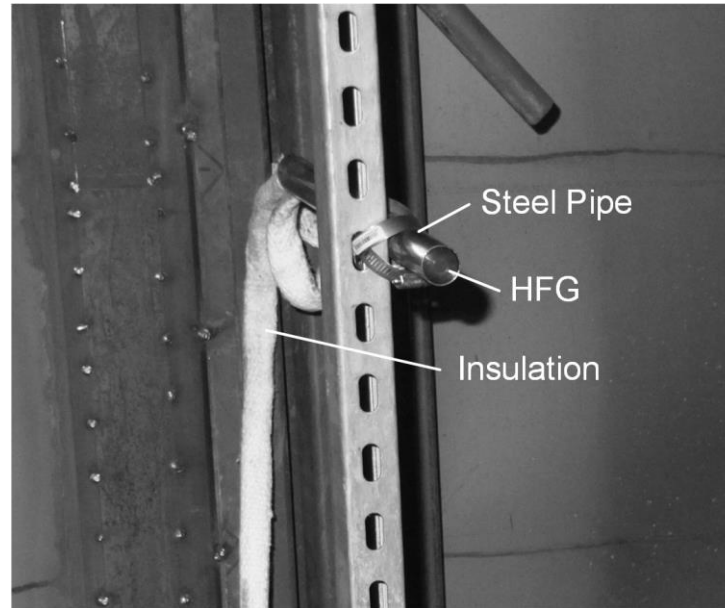


**Figure 44: Heat flux gauge protection**

## 3.2.3 Heat Flux Modelling

Heat flux to the four HFGs described in the previous Section was modelled to determine what modes of heat transfer predominated for each sensor. This model also allows for an analysis of the association between the heat flux at each of the four HFGs and select temperature measurements that will be presented in Section 4.5.3.

### 3.2.3.1 Radiant Heat Flux

In an attempt to validate a radiant heat flux model for all the heat flux gauges (HFGs), the radiation view factors were calculated for all four sensors based on radiation from all six interior surfaces, the interface layer, and the fire plume. This analysis was undertaken in an attempt to model the relative contributions of different elements within the EFDS to the radiant heat flux at each of the HFGs.

The coordinates for the EFDS, the HFGs, and the various elements are shown in Figure 45:
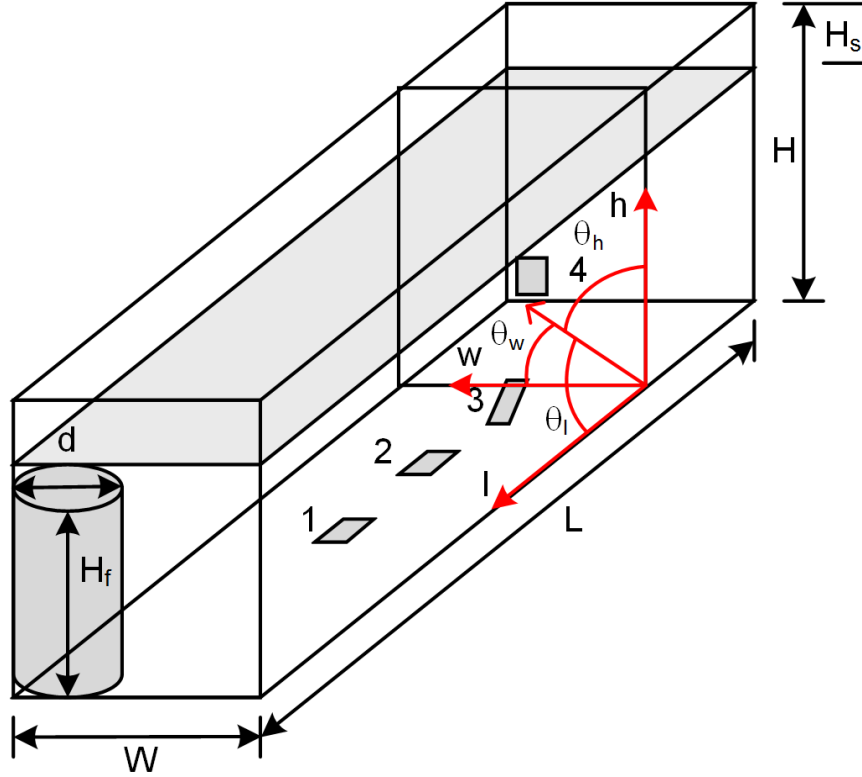
**Figure 45: Heat flux view factors**

In general terms, radiant heat flux from an element 2 to an element 1 can be expressed as:

$$E_{d1-2} = F_{d1-2}\varepsilon\sigma T^4 \qquad \text{3.4 [33]}$$

where $F_{d1-2}$ is the radiation view factor between the two elements, $\varepsilon$ (a dimensionless unit) is the emissivity of surface 2, $\sigma$ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m$^2$K$^4$), and T is the temperature of surface 2 in degrees Kelvin.

The radiation view factor from a parallel rectangular surface to the center of an infinitesimal element at a set distance away from a corner of the surface is given in equation 3.5:

$$F_{d1-2} = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right] \qquad \text{3.5 [33]}$$

60

where $X=a/c$, and $Y=b/c$, $a$ is the height of the rectangular area $A_2$, $b$ its width and $c$ the distance to the receiver (all in meters) as shown in Figure 46:
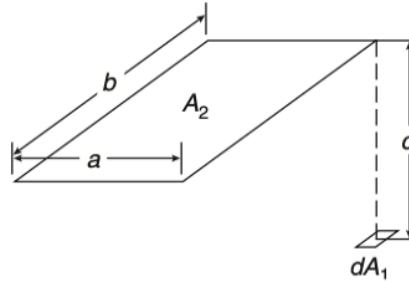


**Figure 46: Radiation view factor to a perpendicular definite rectangle – reprinted with permission from [33]**

The radiation view factor from a perpendicular rectangular surface to an infinitesimal element, again joined to the corner of the surface, is given in equation 3.6:

$$F_{d1-2} = \frac{1}{2\pi}\left[\tan^{-1}\left(\frac{1}{Y}\right) - \frac{Y}{\sqrt{X^2 + Y^2}}\tan^{-1}\left(\frac{1}{\sqrt{X^2 + Y^2}}\right)\right]$$ 

3.6 [33]

where $X=a/b$, and $Y=c/b$ as shown in Figure 47:
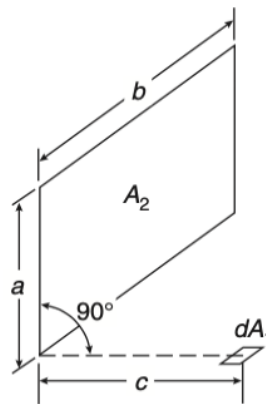


**Figure 47: Radiation view factor to a parallel definite rectangle – reprinted with permission from [33]**

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A more generalized view factor for a rectangular element at an arbitrary angle, still referenced to the corner of the surface, is given in Equation 3.7:

$$F_{d1-2} = \frac{1}{2\pi} \left[ \left( \tan^{-1}\frac{b}{c} \right) \cos\theta_i + \left( \tan^{-1}\frac{a}{c} \right) \cos\theta_j \right.$$
$$+ \frac{a\cos\theta_k - c\cos\theta_i}{\sqrt{c^2 + a^2}} \tan^{-1}\frac{b}{\sqrt{c^2 + a^2}}$$
$$\left. + \frac{a\cos\theta_k - c\cos\theta_j}{\sqrt{c^2 + b^2}} \tan^{-1}\frac{a}{\sqrt{c^2 + b^2}} \right]$$

3.7 [103]

where $\theta_i$, $\theta_j$, and $\theta_k$, are the angles of surface $dA_1$ with respect to the $x$, $y$, and $z$ axes, respectively as shown in Figure 48:
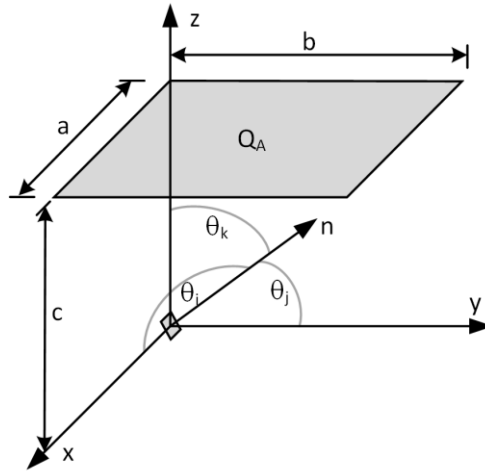


**Figure 48: Radiation view factor to a rectangular element at arbitrary angle**

The total view factor from any plane rectangular surface to an element situated at other than the corner of the surface can be obtained by using Equation 3.7 and summing the four quadrants of a rectangle, depending on the relative position of the receiver, using equation 3.8 as shown in Figure 49:

$$\phi_{total} = \phi_A + \phi_B + \phi_C + \phi_D$$

3.8 [36]

Equations 3.7, and 3.8 were used to calculate the view factors from the walls, ceiling and floor to the detectors, and in the cases of H1, H2, and H4, these results were cross-checked with the more specific cases presented in equations 3.5 and 3.6 to ensure the accuracy of equation 3.7, given this

equation was from an online source [103], and not from a reviewed textbook as were equations 3.5 and 3.6 [33].
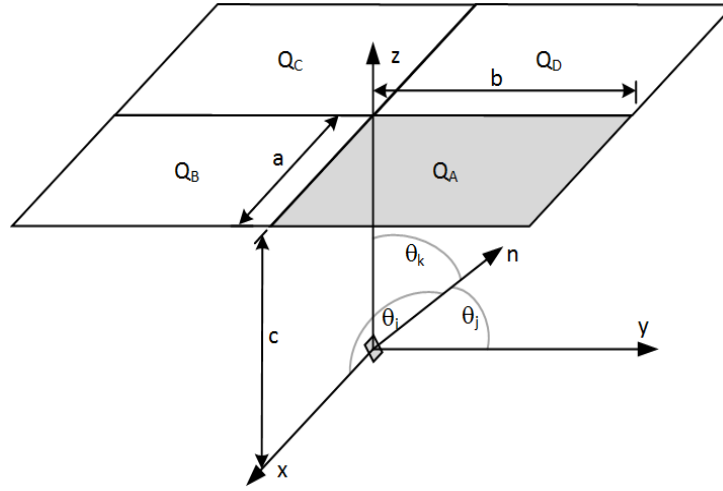


**Figure 49: Generalized radiation view factor to a definite rectangle (using quadrants)**

The radiation from the fire plume is modelled as a cylindrical source, assuming homogeneous flame, over all wavelengths, and is given as equation 3.9:

$$F_{cyl-2} = (1 - e^{-\kappa_m S})\sigma T_f^4 (F_1 + F_2 + F_3) \qquad\qquad \text{3.9 [33]}$$

where $\kappa_m$ is the effective absorption of soot in m$^{-1}$, $T_f$ is the temperature of the flame plume in Kelvin, $S$ physical path length through the plume in meters and the different components $F_1$, $F_2$, and $F_3$ are given by equations 3.10, 3.11, and 3.12 respectively:

$$F_1 = \frac{u}{4\pi}\left(\frac{r}{L}\right)[\pi - 2\theta_0 + \sin(\theta_0)] \qquad\qquad \text{3.10 [33]}$$

$$F_2 = \frac{v}{2\pi}\left(\frac{r}{L}\right)[\pi - 2\theta_0 + \sin(\theta_0)] \qquad\qquad \text{3.11 [33]}$$

$$F_3 = \frac{w}{\pi}\left(\frac{r}{L}\right)\cos{\theta_0}^2 \qquad\qquad \text{3.12 [33]}$$

where $r$ is the radius of the plume in meters, $L$ is the distance from $dA$ to the center of the plume in meters, $H$ is the height of the flaming zone of the fire,

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$$\theta_0 = \tan^{-1}\left(\frac{L}{H}\right) \qquad\qquad 3.13\ [33]$$

and $u$, $v$, and $w$ are the components of the normal unit vector $\vec{n}$ of the receiving element $dA$:

$$\vec{n} = u\vec{i} + v\vec{j} + w\vec{k} \qquad\qquad 3.14\ [33]$$

Provided that the condition

$$\frac{L}{r} > 3 \qquad\qquad 3.15\ [33]$$

is met. These variables are all shown graphically in Figure 50.
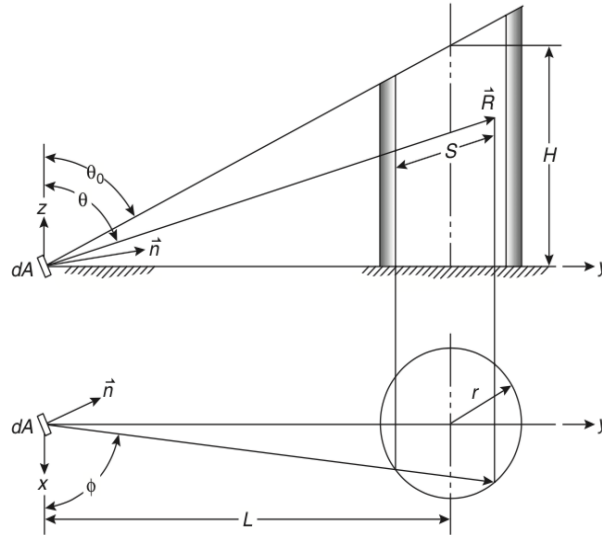


**Figure 50: Radiation view factor from a cylindrical flame plume – reprinted with permission from [33]**

Given the complexity of these calculations, the summation rule [33] was used to ensure the calculations were correct:

$$\sum_j F_{i-j} = 1 \qquad\qquad 3.16\ [33]$$

Where $F_{i\text{-}j}$ is the view factor from all surfaces $j$ to $i$. This rule implies that the total view factor at any given point within a closed area will equal 1. By considering the ceiling, walls, and floor of the

EFDS, this provides a means to check the accuracy of the calculations using equations 3.5, 3.6 and 3.7. The inclusion of the fire plume was not considered in this accuracy check given its geometric complexity with regards to these other six surfaces. The locations of the HFGs are listed in Table 6, while the dimensions for the EFDS were previously listed in Table 2 and Table 3 (Section 3.1). The radiation view factors for each of the HFGs, not considering either the flame plume, nor the upper layer are shown in Table 7:

**Table 7: Radiation view factors with no upper layer**

| Sensor | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| Ceiling | 0.3601 | 0.3685 | 0.2458 | 0.1856 |
| Front Wall | 0.0199 | 0.0082 | 0.1289 | 0.0223 |
| Left Wall | 0.3842 | 0.2913 | 0.2787 | 0.2604 |
| Right Wall | 0.2221 | 0.2913 | 0.2479 | 0.2604 |
| Rear Wall | 0.0137 | 0.0407 | 0.0000 | 0.0000 |
| Floor | 0.0000 | 0.0000 | 0.1100 | 0.2714 |
| Total | 1.0000 | 1.0000 | 1.0114 | 1.0000 |

As shown by the sum of the view factors, the calculations appear to be correct with only a 1.1% inaccuracy in the case of H3. H3's view factor is complicated by the fact that it is neither normal to any of the interior surfaces of the EFDS, nor is it located at any of these surfaces.

In reality, an upper layer forms during the evolutions, and so radiation from this upper layer should be considered. While radiation from this layer is complicated by the transmission through a participating medium, when considering the view factors, it is appropriate to consider the inclusion of the upper layer as replacing the ceiling, but at an adjusted height above the floor. The radiation view factors of each of the HFGs considering the upper layer as an effective ceiling 1 m below the EFDS ceiling are shown in Table 8. H3 shows an inaccuracy of 1.8%, while the other 3 sensors show none. This analysis demonstrates the importance of radiation from either the ceiling or the upper layer on all of the HFGs. The side walls also contribute significantly to the total radiation view factor, while the front and rear walls are relatively less important, except in the case of H4 where the floor represents approximately 27% of the total view factor of the HFG. The presence of

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the upper layer reduces the contribution of radiation from all four walls due to their effective size being reduced accordingly.

**Table 8: Radiation view factors including an upper layer**

| Sensor | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| Upper Layer | 0.5180 | 0.5524 | 0.4311 | 0.3260 |
| Front Wall | 0.0093 | 0.0036 | 0.0840 | 0.0142 |
| Left Wall | 0.3265 | 0.2115 | 0.1846 | 0.1942 |
| Right Wall | 0.1400 | 0.2115 | 0.2083 | 0.1942 |
| Rear Wall | 0.0062 | 0.0210 | 0.0000 | 0.0000 |
| Floor | 0.0000 | 0.0000 | 0.1100 | 0.2714 |
| Total | 1.0000 | 1.0000 | 1.0180 | 1.0000 |

As stated earlier, for simplicity, radiation from the fire plume was not considered, however this was not calculated to be a significant contributor with respect its view factor to any of the HFGs as shown in Table 9:

**Table 9: Radiation view factor from the fire plume**

| Sensor | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| Fire Plume | 0.0084 | 0.0029 | 0.0120 | 0.00001 |

The small contribution of the fire plume to the view factor of all of these sensors is surprising. A HFG positioned near the end of the brick section of the EFDS, and oriented towards the plume might have yielded interesting data of what the radiation from the plume is like for participants closer to the fire (this position is occupied by one of the instructors, and, unlike the students, the instructor does not rotate during live fire training evolutions, making this contribution even more important). In an attempt to estimate this, a model was devised in which a sensor was oriented the same way as H4, but was moved forward to the edge of the brick floor. While the contribution of the plume to the total view factor of this sensor was still not significant, the relative contribution of the front wall rose to 7% from 1%. However, this was still far below the 31% relative contribution from the upper layer. This does not however look at the effects of the temperatures of these elements, which is an important factor given the $T^4$ dependence of radiative heat transfer. One

simple approximation would be to use the peak temperatures of thermocouples, but this wouldn't account for the fact that the temperature of the plume will rise earlier in the burn than those of either the upper layer or the ceiling or walls of the EFDS. Given the temperatures of each element will vary as the interior fire conditions develop, there is no straightforward way to weight their relative contributions to the total heat transferred without also considering time-dependent temperature measurements. Given the geometrical complexity of the fire plume, its low radiation view factor to all four HFGs, as well as the complexity of considering time-dependent temperatures of the different radiant elements, this analysis will proceed by simply adding the plume to the overall view factor for each HFG and adjusting the view factors from the upper layer, walls, and floor down proportionally.

The importance of different surfaces and elements on the radiant heat flux isn't only dependent on the view factor, but also on the emissivity of each the elements. The emissivity for the ceiling and walls of the EFDS was taken to be 0.97, the upper range of rough steel [36], while the emissivity of the floor was taken as 0.9, that of planed oak [36].

Calculating the emissivity from the upper layer is a bit more complicated. The simplest approximation would be to consider the interface layer as an emitter with the same emissivity as used with the ceiling. There are a few problems with this approximation, however:

- The emissivity of smoke is likely to be lower than the value of 0.97 previously taken for the ceiling [33]; and,
- The EFDS ceiling temperature does not match that of the upper layer due to the significant thermal mass of the EFDS when compared to the upper layer (which will be demonstrated in Figure 67 in Section 4.1).

The effective emissivity of the interface of a soot-filled upper layer is given by equation 3.17:

$$\varepsilon_t = 1 - e^{-\kappa S} \qquad\qquad 3.17 \ [33]$$

where $\varepsilon_t$ is the effective emissivity of the smoke layer, $\kappa$ is the effective absorption coefficient of soot (taken as 0.8 m$^{-1}$ for wood smoke [33]) and $S$ is the pathlength in meters (taken as 1 m for this calculation). This produces an emissivity of 0.45 for the interface layer, and this can also be

considered as related to the absorption of radiation in the upper layer according to a special case of Kirchoff's Law

$$\alpha_t = \varepsilon_t \qquad\qquad 3.18\ [33]$$

where the incident radiation is independent of the angle, which will be considered as an approximation, thereby neglecting the interaction of the walls above the interface layer. It should be noted that this value for emissivity is consistent with values presented by De Ris [104]. Using the calculated values in Table 8, the inclusion of the ceiling will be approximated by reducing the view factor of the ceiling by the absorption of the upper layer:

$$F_{eff} = F_{ceil}(1 - \alpha_t) \qquad\qquad 3.19\ [33]$$

where $F_{eff}$ is the effective view factor of the ceiling, $F_{ceil}$ is the original view factor as listed in Table 7, and $\alpha_t$ is the absorption of the upper layer. This value is then subtracted from the view factor of the interface layer in Table 8. The results of this rough approximation are presented in Table 10:

**Table 10: Radiation view factors including the ceiling and an upper layer**

| Sensor | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| Ceiling | 0.1981 | 0.2027 | 0.1352 | 0.1021 |
| Upper Layer | 0.3199 | 0.3497 | 0.2959 | 0.2239 |
| Front Wall | 0.0093 | 0.0036 | 0.0840 | 0.0142 |
| Left Wall | 0.3265 | 0.2115 | 0.1846 | 0.1942 |
| Right Wall | 0.1400 | 0.2115 | 0.2083 | 0.1942 |
| Rear Wall | 0.0062 | 0.0210 | 0.0000 | 0.0000 |
| Floor | 0.0000 | 0.0000 | 0.1100 | 0.2714 |
| Total | 1.0000 | 1.0000 | 1.0180 | 1.0000 |

The emissivities for the surfaces, plume, and upper layer are shown in Table 11, as well as those listed below.

- The relative contribution from each element to the overall view factor for each of the sensors.
- The effective emissivity of each element (with the exception of the plume), which combines both the emissivity and its relative view factor. While this isn't a physically important quantity, it will be used in Section 4.5.3 to validate a heat flux approximation using temperatures measured by limited thermocouple measurements.

The effective absorption for both the plume and upper layer was taken as 0.8 (that of wood smoke [33]), the radius of the plume was taken as 30 cm, half the width of the crib, and the depth of the upper layer was taken to be 1 m.

**Table 11: Relative radiative heat flux contributions**

| Surface | Emissivity | View Factor | | | | Effective Emissivity | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | H1 | H2 | H3 | H4 | H1 | H2 | H3 | H4 |
| Upper Layer | 0.45 | 20% | 20% | 14% | 10% | 0.192 | 0.197 | 0.131 | 0.099 |
| Ceiling | 0.97 | 32% | 35% | 30% | 22% | 0.144 | 0.157 | 0.133 | 0.101 |
| Front Wall | 0.97 | 1% | 0% | 8% | 1% | 0.009 | 0.003 | 0.081 | 0.014 |
| Side Walls | 0.97 | 33% | 21% | 18% | 19% | 0.317 | 0.205 | 0.179 | 0.188 |
| Back Wall | 0.97 | 14% | 21% | 21% | 19% | 0.136 | 0.205 | 0.202 | 0.188 |
| Floor | 0.97 | 1% | 2% | 0% | 0% | 0.006 | 0.020 | 0.000 | 0.000 |
| Flame Plume | 0.38 [33] | 1% | 0% | 1% | 0% | - | - | - | - |

Table 11 shows the importance of both the ceiling and the upper layer to radiant heat flux at all four HFGs. While the side walls also have significant view factors and effective emissivities, their temperatures are much lower than either the ceiling or upper layer, and as such their contribution to the overall heat flux is expected to be comparatively lower. Radiation from the flame plume is minor, although it should be noted that the effective emissivity of the front wall is expected to be more important given the fuel configuration.

This approximation of the view factors from the various surfaces as well as the plume, and the subsequent calculation of effective emissivities relies on numerous assumptions and approximations. Were this the basis of a model without additional data taken from actual measurements, the method would need to be far more rigorous. However, this model is being

considered to investigate the utility of a calculation of heat flux based on thermocouple measurements that will be described in Section 4.5.3. As such, the assumptions and approximations are sufficient to act as a basis for this effort.

### 3.2.3.2 Convective Heat Flux

A purely radiant heat flux model is almost certainly appropriate for HFG H1 and H2 given their position on the floor and therefore the relatively low local temperatures and air flow. HFG H3 is still expected to be below the interface layer, and given its orientation, is exposed to high radiant heat fluxes from the upper layer as well as the seat of the fire. Therefore, the measurements are again anticipated to be predominantly governed by radiant heat transfer.

H4 is located below the expected interface layer, but due to its position near the vestibule door that is operating as the primary inlet and outlet during the experiment, the neutral plane at this opening could be below the interface layer, and an increase in the temperatures and velocity of gases at this position could increase the contribution of convective heat transfer to measurements obtained by this HFG. Conversely, the distance of H4 from the fire, as well as it's orientation with respect to the upper layer would minimize the contribution of radiant heat flux to this sensor. While a radiant heat flux model was considered for this sensor, a convective model was considered as well. Convective heat flux in kW/m² is given by:

$$\dot{q}'' = h\Delta T \qquad\qquad 3.20\ [36]$$

where $h$ is the convective heat transfer coefficient (in kW/m²·K), and $\Delta T$ is the temperature difference in either K or °C between the transmitting medium and the receiver. Calculating the convective heat transfer coefficient can be complicated, as it is dependent on the fluid properties and the velocity of the fluid, as well as the geometry of the object. As such, an in-depth calculation will not be attempted here. As with the radiative heat transfer model, the goal is to provide a comparison for association of heat transfer with temperature measurements taken using thermocouples in Section 4.5.3. While the EFDS was instrumented with bi-directional probes, data from these instruments was not analyzed. For later comparison, typical values for h are given in the range of 5-50 kW/m²·K for free convection and 25-250 kW/m²·K for forced convection [36].

## 3.2.4 Video Recording

Two GoPro© cameras [105] were installed in the EFDS with their locations shown in Figure 51 and representative images recorded from the cameras shown in Figure 52. While these cameras were not used for quantitative measurements, they provided valuable data in terms of monitoring the evolutions and interpretation of the collected data.
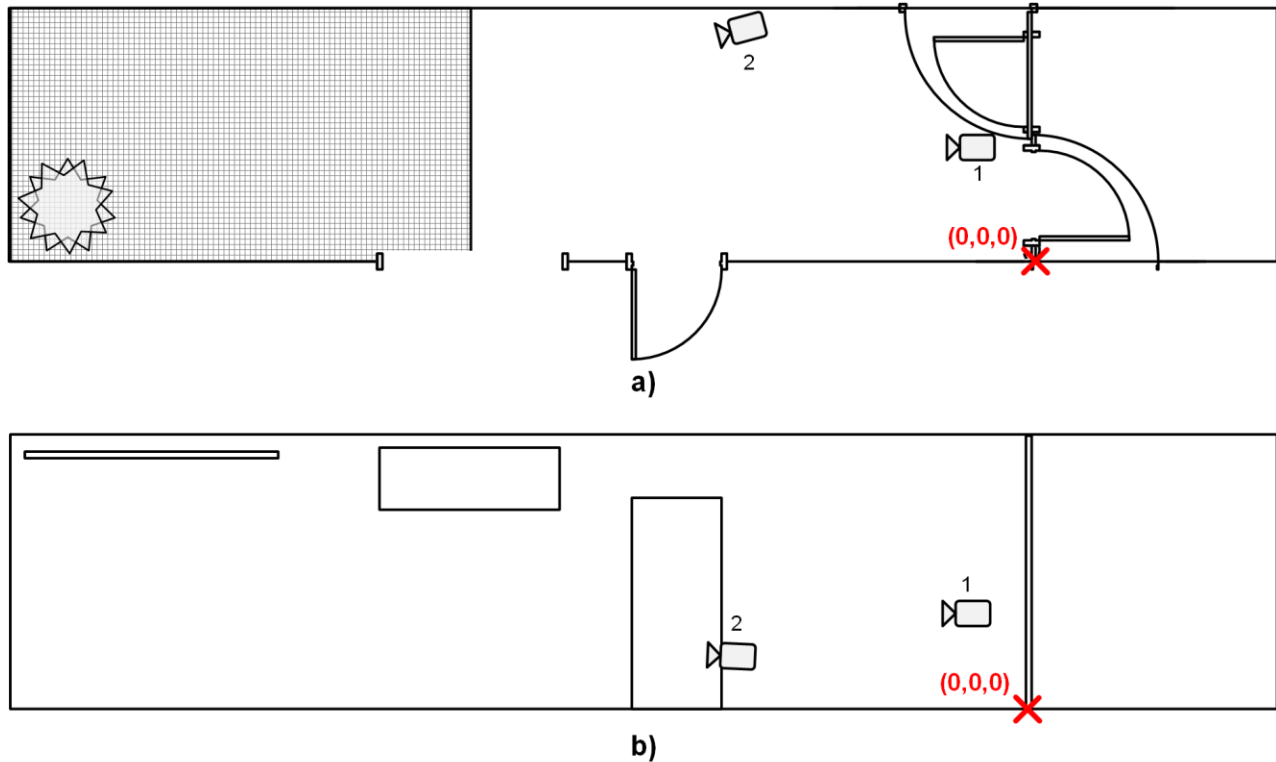


**Figure 51: Video camera placement: a) top view; and, b) side view**

Still images could be captured from the video files and used for analysis. In addition, the records provided a degree of safety, since the internal conditions could be reviewed by both firefighters and NRC staff while the characterization experiments were taking place. After the tests and through time-syncing of images, the videos provided a qualitative record of fire phenomena and firefighter actions that could be correlated with data measurements. This further allowed for qualitative analysis of the training conditions, and particularly the quality of smoke production as well.

**Figure 52: Views from EFDS video cameras: a) Camera #1 – bulkhead wall; and, b) Camera #2 – forward left side of compartment**

## 3.3 Testing Variables

Large-scale oxygen depletion calorimeter tests were completed by the NRC [106] to characterize the heat release rate of the crib as well as the additional sheet fuel. In addition, 22 instrumented burns were conducted in the EFDS unit as part of this research project. Many variables were

introduced into the tests. Some were intentionally introduced by the author for research purposes and others resulted from either the testing environment or inherent variability due to the nature of the training evolutions being modelled. The key variables that influenced the testing are listed here and each is discussed in more detail in a following Sections.

- Ambient Conditions: With the closure of the NRC's National Fire Laboratory, the EFDS testing was moved to a new location. Importantly, testing moved from inside the NRC test facility to outdoors. This change introduced impacts of ambient conditions on the results, particularly with wind as a variable. In addition, the move required re-instrumenting of the EFDS, which resulted in problems in data acquisition for several burns.

- Wood Fuel Crib Design: Early testing used a standard crib [33], with individual pieces nailed together, that was elevated so that a burner could be used for ignition. While this produced repeatable conditions for ignition of the crib, it did not match an actual configuration of crib that would be used in training. As the characterization research moved to investigate conditions that more closely resembled those anticipated during training, particleboard cribs were used. As with the standard nailed cribs constructed of 2"x2" pine, these were subsequently deemed too labour intensive and so a jig was designed, and tested as part of this research. All three of the crib designs were placed on the floor of the EFDS and ignited using a propane torch, while the standard pine crib was also ignited using a burner, for a total of four different configurations:
    - o Elevated nailed-together pine ignited with a burner;
    - o Nailed-together pine ignited with a torch;
    - o Particleboard ignited with a torch; and,
    - o Pine in a steel jig ignited with a torch.

- Fuel Load: Both the fuel type and configuration were adjusted based on a preliminary analysis of data and feedback from training evolutions that were run concurrently with the testing. In total, two different fuels were used: fibreboard and particleboard, and these fuels were tested in different configurations.

- Firefighter Interactions: It was important to characterize the EFDS not only in terms of a standard fire, but as it would be used in training. This introduced the necessity to include firefighter interactions with the fire and their consequent impacts on the environment in the EFDS as a variable during testing. The author participated in all the burns discussed in this

thesis, but two other firefighters were needed as well: one to control water application, and the other to control ventilation. There were naturally differences in the water application techniques of these firefighters, even if their tactical goals were the same. A larger variable is that the effectiveness of water application which is highly dependent on training and experience, with excess water application being a common result of a lack of experience. The firefighters involved in this research testing were learning as the testing proceeded, and as such their effectiveness improved over this period.

### 3.3.1 Ambient Conditions

The weather conditions and testing locations for all of the EFDS tests are detailed in Table 12. Ambient temperature was measured using thermocouple T27, remote from the EFDS. To cross check these measurements, temperature was also determined, along with humidity, wind direction, and wind speed from historical data from the MacDonald-Cartier International Airport weather station available online through Environment Canada [107]. Indoor tests occurred over a temperature range of 15.0°C to 25.5°C as measured by the thermocouple or 15.2°C to 26.8°C as recorded from Environment Canada. Outdoor tests occurred over a temperature range of 2.1°C to 25.6°C as measured by the thermocouple or 1.7°C to 25.8°C as recorded from Environment Canada. Humidity varied between 44% and 59% for the indoor tests, and between 38% and 94% for the outdoor tests. The highest wind speed recorded during the outdoor tests was 33km/h on October 18th, 2016. The wind in this case was from the SSW and so would have largely been blocked by the structure built around the EFDS. During the test on June 15th, 2017 however, the wind speed was 23km/h from the East meaning the EFDS would have largely been unprotected by the structure built around it.

**Table 12: Weather and location of EFDS testing**

| Date | Location | Roof | Temperature (°C) | | Relative Humidity (%) | Wind | |
|------|----------|------|---------|---------|---------|---------|---------|
| | | | On-Site | Weather | | Direction (deg.) | Speed (km/h) |
| 6-Aug-15 | NRC Lab | No | 23.9 | 26.8 | 44 | 120 | 12 |
| 10-Aug-15 | NRC Lab | No | 25.5 | 26.8 | 44 | 120 | 12 |
| 21-Aug-15 | NRC Lab | No | 24.2 | 22 | 62 | 220 | 16 |
| 5-Oct-15 | NRC Lab | No | 14.9 | 15.2 | 59 | 310 | 6 |
| 6-Oct-15 | NRC Lab | No | 15.0 | 15.2 | 59 | 310 | 6 |
| 12-Oct-16 | OFS Site | No | 12.8 | 13 | 46 | 170 | 16 |
| 18-Oct-16 | OFS Site | No | 24.5 | 22.8 | 68 | 200 | 33 |
| 19-Oct-16 | OFS Site | No | 20.5 | 14.6 | 59 | 27 | 14 |
| 20-Oct-16 | OFS Site | No | 10.9 | 10.6 | 93 | 10 | 3 |
| 21-Oct-16 | OFS Site | No | 9.7 | 9.9 | 90 | 360 | 16 |
| 3-Nov-16 | OFS Site | Yes | 8.3 | 8.6 | 94 | 330 | 8 |
| 4-Nov-16 | OFS Site | Yes | 2.1 | 1.7 | 72 | 30 | 13 |
| 7-Nov-16 | OFS Site | Yes | 6.2 | 6.3 | 76 | 200 | 10 |
| 9-Nov-16 | OFS Site | Yes | 8.6 | 4.3 | 53 | 220 | 23 |
| 31-May-17 | OFS Site | Yes | 23.0 | 19.6 | 53 | 220 | 23 |
| 6-Jun-17 | OFS Site | Yes | 14.8 | 11.3 | 88 | 60 | 19 |
| 13-Jun-17 | OFS Site | Yes | 24.2 | 15.2 | 59 | 310 | 6 |
| 15-Jun-17 | OFS Site | Yes | 21.4 | 20 | 38 | 90 | 23 |
| 19-Jun-17 | OFS Site | Yes | 22.9 | 21.9 | 61 | 230 | 14 |
| 5-Jul-17 | OFS Site | Yes | 25.0 | 24.8 | 38 | 50 | 1 |
| 6-Jul-17 | OFS Site | Yes | 25.6 | 25.8 | 54 | 210 | 11 |
| 11-Jul-17 | OFS Site | Yes | 24.5 | 23.7 | 74 | 220 | 12 |

### 3.3.2 Fuel Load

The fuel load and configuration are critical elements in defining the operating conditions and interior fire fighter training environment in the EFDS; therefore, significant care was taken to establish an appropriate combination of fuels, as well as optimal layout, for the fuel during this study. Based on the training requirements, the general concepts behind tailoring of the fuel load are listed below.

1. A gaseous ignition source is needed to accelerate the initial growth of the fire. This is important as participants are using air provided by their Self-Contained Breathing Apparatus (SCBA), and as such the duration of the training evolution is limited. After two minutes, which is sufficient time for established burning of the crib, the ignition source is removed from the EFDS.

2. The gaseous ignition source is used to ignite a crib of combustible material, most often a wood-based product, which is placed in a corner of the EFDS in close proximity to an additional 'fuel load' and provides a point of origin for the fire.

3. The crib must be designed to provide enough convective and radiative heat transfer to pyrolyze the additional fuel load on the walls and ceiling of the EFDS, and then to ignite this fuel, which provides most of both heat release rate and smoke for the training evolutions.

4. Additional material should be added either beside or on top of the crib to form a bridge for flaming combustion to spread to the additional fuel load and therefore accelerate the ignition of the fuel on the walls and the ceiling of the EFDS as well.

5. The additional fuel load referred to above is provided in the form of sheets of combustible material, in these tests comprised of either wood fibreboard or particleboard. These are positioned close to the walls and ceiling of the EFDS. The positioning of this fuel should be such that it allows for heating by the crib fire, as well as providing a source of both heat and smoke to the interior compartment to establish the desired environment for training evolutions. During firefighter training, it is important to generate not only heat, but also to establish an upper layer of smoke with sufficient optical density to provide reasonable fidelity and by which to teach important concepts related to the formation of the hot smoke-clear air interface layer in compartment fires. By placing fuel high on the walls, and

particularly near the ceiling, combustion of this additional fuel occurs in a localized ventilation-limited environment that promotes the production of more optically-dense smoke.

A summary of the crib type, additional fuel load type, fuel configuration and ignition method for all 22 EFDS tests are listed in Table 13:

**Table 13: Fuel load EFDS testing variations**

| Date | Crib | Ignition | Fuel Type | Configuration |
|---|---|---|---|---|
| 6-Aug-15 | Pine | Burner | Fibreboard | DNVFRS |
| 10-Aug-15 | Pine | Burner | Fibreboard | DNVFRS |
| 21-Aug-15 | Pine | Burner | Fibreboard | DNVFRS |
| 5-Oct-15 | Pine | Burner | Fibreboard | DNVFRS |
| 6-Oct-15 | Pine | Burner | Fibreboard | DNVFRS |
| 12-Oct-16 | Pine | Burner | Particleboard | CFBT |
| 18-Oct-16 | Pine | Burner | Particleboard 0E | CFBT |
| 19-Oct-16 | Pine | Burner | Particleboard | DNVFRS |
| 20-Oct-16 | Pine | Burner | Fibreboard | DNVFRS |
| 21-Oct-16 | Pine | Burner | Fibreboard | DNVFRS x 2 |
| 3-Nov-16 | Pine | Burner | Fibreboard | DNVFRS x 2 |
| 4-Nov-16 | Pine | Burner | Particleboard | DNVFRS |
| 7-Nov-16 | Pine | Burner | Particleboard 0E | CFBT |
| 9-Nov-16 | Pine | Burner | Particleboard | CFBT |
| 31-May-17 | Pine | Torch | Particleboard | CFBT |
| 6-Jun-17 | Particleboard | Torch | Particleboard | CFBT |
| 13-Jun-17 | Jig | Torch | Particleboard | CFBT |
| 15-Jun-17 | Pine | Torch | Particleboard | DNVFRS |
| 19-Jun-17 | Particleboard | Torch | Particleboard | DNVFRS |
| 5-Jul-17 | Jig | Torch | Particleboard | DNVFRS |
| 6-Jul-17 | Jig | Torch | Particleboard | DNVFRS |
| 11-Jul-17 | Jig | Torch | Particleboard | DNVFRS |

Additional discussion of the different variations of each parameter provided in the Sections below. As a starting point, the two fuel configurations were based on those used by CFBT [9] and District of North Vancouver Fire and Rescue Services (DNVFRS) [69]. The fuel type, as well as its configuration, were then varied during different tests based on feedback from the ongoing training associated with the FKTP Project by participants from different jurisdictions. Initially, a wood fibreboard was used that contained no additional binders or adhesives. It was hoped this would reduce the toxicity of the smoke that participants were exposed to; however, feedback indicated that this fuel did not achieve interior conditions that supported the learning objectives and therefore, the fuel was changed to particleboard. A variety of different configurations of particleboard were then also tested to see if any quantitative difference between these configurations existed.

For all tests, the initial wood cribs were built from lengths of 2"x2" (nominal) dimensional pine lumber, cut to 2' (61 cm) lengths and stacked six rows high, with each row six lengths across, and alternating rows stacked perpendicular to one another. In later tests, cribs were built using two slats of particleboard cut to 30.5 cm lengths, 50.8 mm wide, then stacked 18 slats high, with each row having the slats approximately 15 cm apart, and alternating rows stacked perpendicular to one another. The cribs were ignited either by a burner or a propane torch. A jig was introduced in later tests that simplified the construction of the cribs.

### 3.3.2.1 Wood Cribs

In total, four wood crib designs were used in the testing as shown in Figure 53. These different designs are listed below.

1) The standard wood crib was used in the first 14 tests, from August 6th, 2015 to November 9th, 2016, with all three fuel types, and all three fuel configurations. The crib is constructed of 2"x2" dimensional pine lumber, cut into two-foot-long pieces stacked six across and six high as shown in Figure 53b and assembled using nails. This crib was initially chosen given its description in the literature [33], as well as the availability of heat release rate data for the specific configuration used [53]. Initially, the crib was elevated as shown in Figure 53a and ignited using a propane burner so that the ignition was consistent between tests and

because this would allow for association with the large-scale calorimeter tests conducted by the NRC [106].

2) The standard crib described above was also ignited using a torch in the tests conducted on May 31st and June 15th, 2017 as shown in Figure 53b.

3) A particleboard crib as shown in Figure 53c was ignited using a torch was used in the tests conducted on June 6th and June 19th, 2017.

4) A crib assembled using a jig as shown in Figure 53d and ignited using a torch was used in tests conducted June 13th, July 5th, July 6th, and July 11th, 2017. It should be noted that this is the crib configuration currently used in training by OFS.
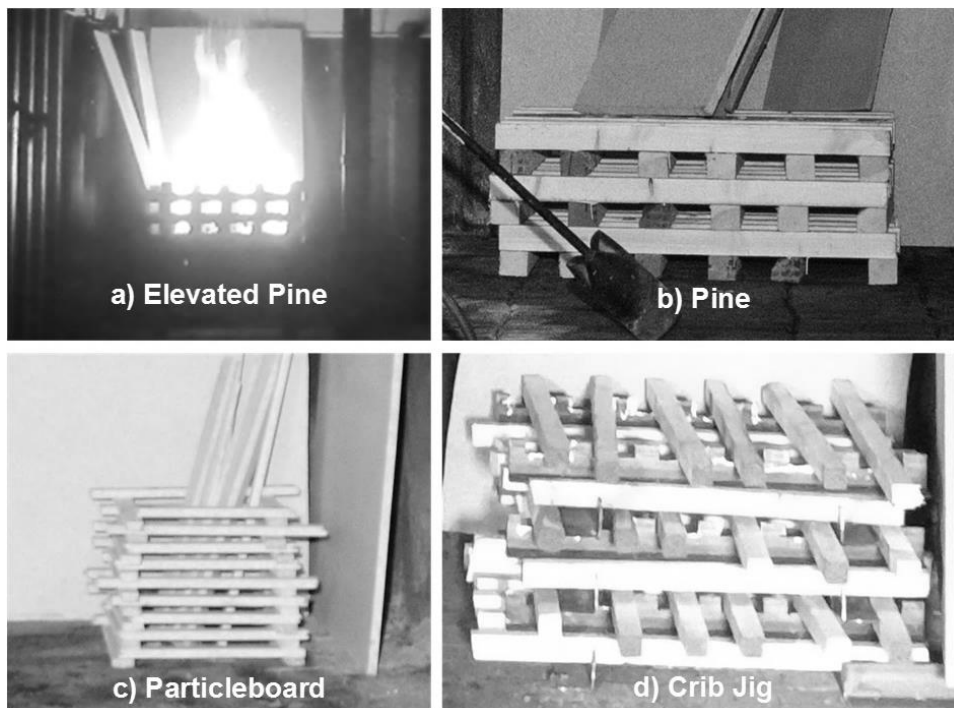


**Figure 53: Crib designs: a) Elevated Pine; b) Pine; c) Particleboard; and, d) Crib Jig**

The standard crib design used extensively in this research project was carefully characterized, from a fire performance standpoint, by the NRC prior to instrumentation of the EFDS [106]. Single and double cribs were tested (Figure 54) and it was determined that the flame plume established during burning of a single wood crib was sufficient to provide the conductive and radiative heat transfer required to pyrolyze and ignite the additional fuel load without involving the additional fuel too quickly. The large-scale calorimeter at the NRC National Fire Laboratory was used to characterize the HRR of this crib, when it was mounted on a stand 30 cm above the ground. Results of the test

are shown in Figure 55 for the single crib with the contribution of the propane burner subtracted from the measured heat release rate plotted. None of the cribs used in the tests were conditioned prior to their respective tests. Rather, the cribs, or the material made to assemble them, were kept in a storage container at the respective test sites. Given the amount of variability in other testing parameters, it was felt that humidity in the crib material would not be a significant variable.
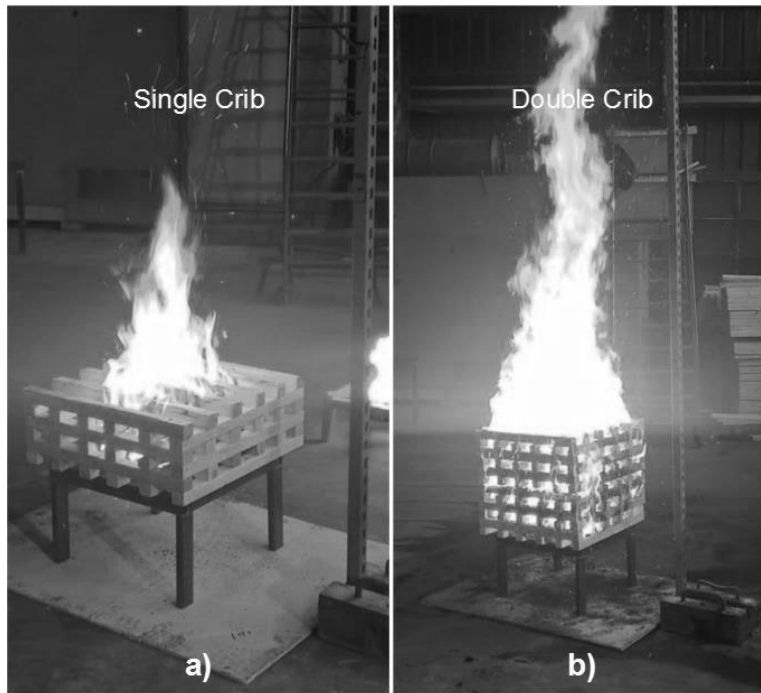


**Figure 54: Crib testing [106] – reprinted with permission from [106]**
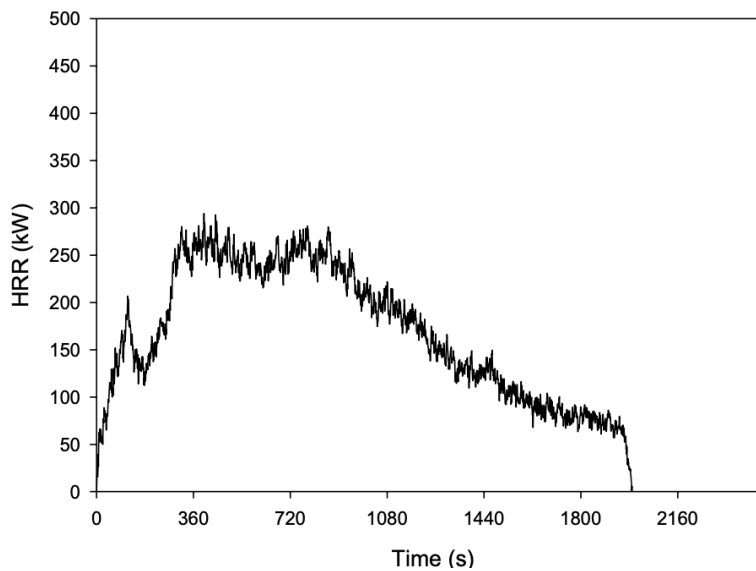


**Figure 55: NRC crib HRR results – reprinted with permission from [106]**

These results differ from those from Obach [53], indicating both a higher peak HRR (above 250kW) as well as a longer overall duration of burn, potentially due to differing internal flow of air to the individual pine pieces because the crib in the NRC research was elevated above the ground [106] whereas that in Obach was not [53]. Overall, this crib design provided a heat source that was easy to ignite, with energy output that did not peak at values that were too high and with a reasonable duration for the total burn, which in this work ensured that reignition of the additional fuel could occur if flaming combustion was extinguished either due to under-ventilated conditions or through the inadvertent excessive application of water during an evolution.

Initially, a propane burner was used for ignition of the wood crib, with the burner being operated at a controlled flow rate for two minutes to ignite the crib. This method allowed for subtraction of the heat release rate from the ignition burner in the case of the large-scale calorimeter tests, and in the field helped to ensure ignition and initial fire growth were uniform from test to test.

In later stages of testing, another crib design was suggested by some SMEs [108] and used in two of the tests. This crib was constructed of particleboard and is shown in Figure 53c. With this crib, the original propane burner ignition method was no longer feasible, and a propane cylinder with a torch was used instead. It was felt that this crib design provided a higher peak heat release rate earlier in the burn than was experienced when standard cribs were used instead. This led to earlier ignition of the additional fuel in the EFDS. However, this crib is consumed more quickly than the standard wood crib or crib-jig design (below), a drawback that is often compensated by adding a 1/3 piece of particleboard during burns in, for example, the CFBT training jurisdictions. While this 1/3 piece of particleboard does form an element of the additional fuel load configuration used in the present study, the compensation is less likely to be needed when either of the softwood cribs is used. Nonetheless, it is available in either case if the instructors feel it is needed.

Finally, a third crib configuration was designed to circumvent a major drawback with the standard crib related to longer term use of the EFDS for fire fighter training. Since they were nailed together, construction of the standard wood crib and the alternate particleboard crib proved very labour-intensive. While this was not an issue for testing, it requires a significant amount of resources per burn for training. Therefore, as training using the EFDS proceeded, a less labour-intensive solution was sought, and after some iterations a jig was constructed that would maintain consistency of crib construction while also eliminating the need for nailing during crib assembly.

This jig, shown in Figure 56, was made from steel with slots that allowed pre-cut lengths of 2"x2" dimensional pine lumber to be placed in the approximate configuration of the original, standard crib design. The jig greatly increased consistency of construction, reduced the labour required to build each crib, and also, due to built-in stand-offs, ensured that the crib was positioned in a consistent location within the EFDS for each repeat testing or training evolution.
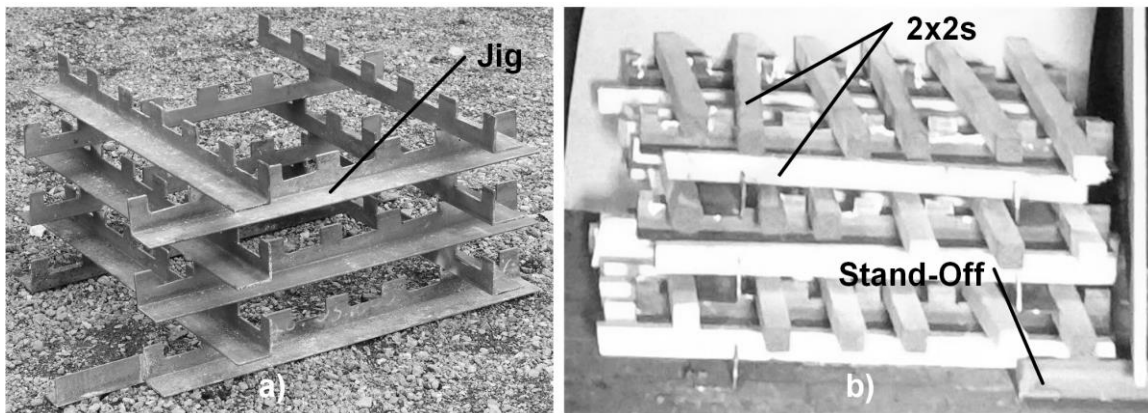


**Figure 56: Crib jig: a) without fuel; and, b) with fuel**

The new design has not come without apparent disadvantages, however. Many of the instructors involved in the FKTP Project, as well as during ongoing training with OFS, have reported that use of this jig to hold and position the wood crib seemed to result in lower peak heat release rate and longer overall burn time of the fuel, likely due to impacts of the thermal mass of the jig itself. While some instructors have expressed an interest in moving back to the original nailed design, the reduction in labour associated with preparing the fuel for use in the new jig appears to outweigh any apparent downsides.

### 3.3.2.2 Fuel Types

The ideal fuel for live fire training would provide the smoke opacity and colour close to that considered typical in a residential fire [109]. However, a balance needs to be found between the quality of the smoke produced, and the health impacts of exposing firefighters to any type of smoke, which contains known carcinogens. Determining how fuel choice and conditions in a given test in this research (or training evolution during longer term use of the EFDS) will impact the toxicity of the smoke is difficult as smoke production depends on many factors aside from fuel choice, including ventilation conditions and ambient temperature. Further complicating the issue is

the difficulty in determining which of the hundreds of chemicals contained in smoke are the most toxic for firefighters, either in the short, or the longer, terms. Smoke toxicity has previously been quantified using the 6-gas method by monitoring the concentration of six gases, which are CO, $CO_2$, HCN, HCl, HBr, and $NO_2$ [110]. These gases were selected based on their impacts when they are ingested through cross-contamination or inhaled, however, which is not applicable to live fire training as firefighters should always be wearing their SCBA. Therefore, reduction of these six gases only mitigates inhalation as a route of exposure, and only during the burn, but does nothing dermal absorption, the other main route of exposure (ingestion, not being considered to be a factor). Instead, more recent work has focused on the carcinogenic effects of exposure of volatile organic compounds (VOCs), particularly poly-aromatic hydrocarbons (PAHs) [111] via skin exposure. A study looking specifically at firefighter exposures to smoke in CFBT training structures found higher levels of VOCs, PAHs and formaldehyde was generated when oriented strand boards (OSB) were used as fuel, in comparison to evolutions fueled by hardwood [112].

Given the guidance provided by the International Association of Fire Fighters (IAFF) on the use of OSB as fuel during testing or training [52], two of the fuels tested in this study were chosen due to their minimized concentrations of glues and other binders. One of these was a fiberboard product that contained only naturally occurring lignin as a binder, and the other was particleboard. The first of these was tested alongside OSB in a small-scale oxygen consumption calorimeter by the NRC under incident heat flux exposures of 25 kW/m$^2$. The data on average smoke production across three tests for each material are shown in Table 14 along with partial data for particleboard gathered from additional sources [38, 97]. Unfortunately, no smoke generation data was available for particleboard under similar test conditions.

**Table 14: Material data [106]**

| Material | Density (g/cm$^3$) | Time to Ignition (s) | Peak HRR (kW/m$^2$) | Mean HC (MJ/kg) | Total Smoke Production (m$^2$) |
|---|---|---|---|---|---|
| Fibreboard | 2.31 | 25 | 145.1 | 15.1 | 74.3 |
| OSB | 6.56 | 116 | 237.1 | 13.8 | 279.5 |
| Particleboard | 6.6 [113] | - | - | 17.5 [33] | - |

Initially, the fibreboard was the preferred fuel given the lower amount of glue and more natural binder it that it contained. When compared to OSB, however, fibreboard is a very low-density

material with comparable heat of combustion, but low smoke production. The low density of the material is advantageous in the sense that the lower overall weight for a sheet makes it easy to load. However, this benefit is more than offset by difficulties and drawbacks with its use in this application.

Initial burns with fibreboard qualitatively showed poor smoke production, poor structural integrity of the fuel during combustion, and difficulty in controlling the fire environment due to the product's tendency to become involved in the fire more quickly than particleboard. This fire behavior was supported by results from the early large-scale calorimeter tests at NRC in which extremely high heat release rates and large flames were observed during fiberboard burns, as shown in Figure 57.
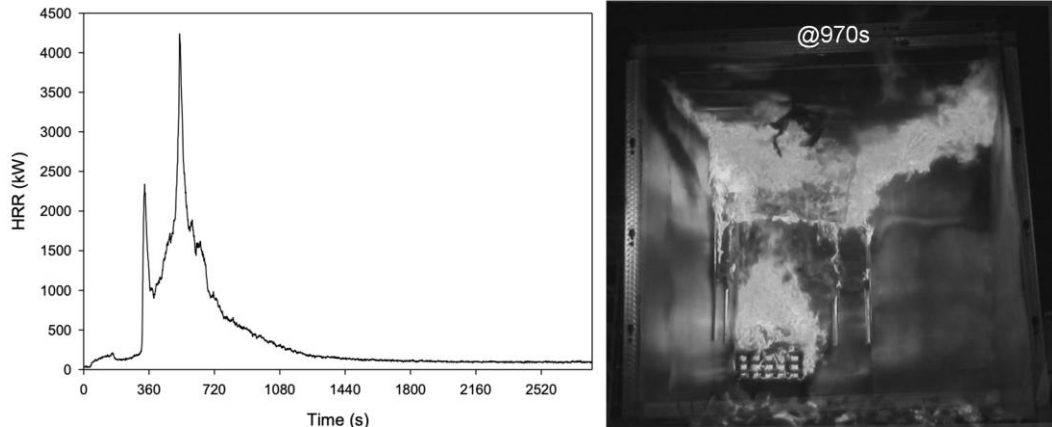


**Figure 57: Initial fibreboard tests (NRC) – reprinted with permission from [106] [106]**

This problem could be partly mitigated through the addition of a steel mesh to support the fibreboard as it lost structural integrity during combustion, as shown in Figure 58. During the large-scale calorimeter testing seen in Figure 57, this mesh was attached to the fibreboard and the walls of the test room using screws. In the EFDS, however, screwing the fiberboard to the walls was deemed to be too labour intensive so pieces of metal were used to wedge the fibreboard and mesh together against the walls as shown in Figure 59. The mounting solution, however, did not address the issue of low smoke optical density during combustion of the fibreboard. In an attempt to address this latter issue and increase smoke production, additional wood, in the form of pallets, was added to some burns as shown in Figure 59 [114]. While this hybrid fuel load did address the smoke quality issues, the use of pallets on a continual bases during fire fighter training raised several other concerns.
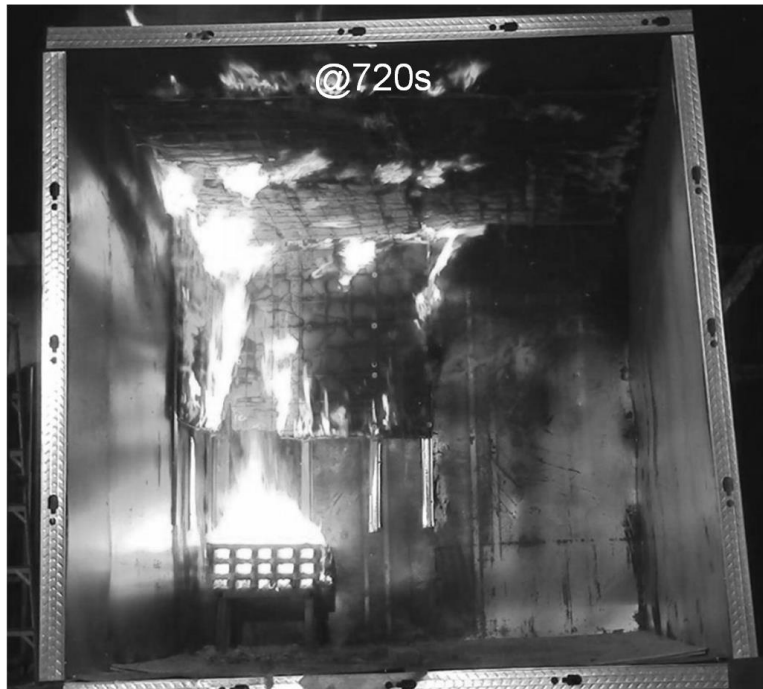
**Figure 58: Mesh reinforcement**



**Figure 59: Hybrid fuel load #1**

These included considerable logistics involved in acquiring and storing the number of pallets required to follow this approach, as well as the observations that the size of slats and wood species used in the pallets was unknown and inconsistent, and the pallets were previously used and often painted implying possible unknown contamination in the burns. The above pointed to two serious issues that precluded use of pallets:

1) the fuel load was not reproduceable for research or training purposes; and,
2) longer term impacts of possible contamination were a significant threat to researchers and trainees.

Therefore, the fiberboard plus pallet fuel load was not used in the testing for this thesis, although it was tried for one round of training in 2015. As both the FKTP and research projects proceeded, the additional fuel load was changed to particleboard, bringing it more in-line with those of other CFBT examples [9]. While there were potentially health and safety advantages to the use of fibreboard, it did not provide the training environment required to meet the learning objectives necessary for effective fire fighter training in the EFDS. Particleboard is considered a reasonable trade-off since while it may produce more emissions during burning than fibreboard, it is of similar density and heat of combustion as OSB, but with less glues and binding agents. In particular, in an attempt to reduce the toxicity of the training environment as much as possible, a low-emission product was sourced for some of the test burns (denoted as 0E in Table 13). The density and heat of combustion of this product is assumed to be the same as for the regular product. Unfortunately, particleboard and related products are not specified by the chemical content of their glues and binding agents, but rather by their mechanical properties as regulated under ANSI A208.1-2009 [115]. There is no guarantee that particleboard purchased at different times will be made at the same factory, and therefore, its composition and burning characteristics can vary, imparting some potential variability in combustion characteristics and emissions between testing and training evolutions.

### 3.3.2.3 Fuel Configuration

The different fuel load configurations (not including material or crib variations, or what if any bridging material was used) are summarized in Table 15, with other specifics of the variations discussed below.

**Table 15: Fuel load configurations**

| Name | Ceiling | | Front Wall | Side Wall (next to crib) | Total # of Sheets |
|---|---|---|---|---|---|
| | Above Crib | Opposite Crib | | | |
| DNVFRS | 2 half sheets + 1 full sheet | 1 full sheet | 2 half sheets | 2 half sheets | 5 |
| DNVFRS x2 | 4 half sheets + 2 full sheets | 2 full sheets | 4 half sheets | 4 half sheets | 10 |
| CFBT | 2 full sheets | 1 full sheet | 1 full sheet | 1 full sheet | 5 |

The initial fuel load, shown in Figure 60, was built from fibreboard in a configuration based on the DNVFRS fuel load provided by Ian Bolton and used by the District of North Vancouver Fire & Rescue Services [69], although particleboard was used in this jurisdiction. A standard pine wood crib was used, and no bridging material (fuel placed above the crib to facilitate flame spread from the crib to the other fuel and designated as #7 in Figure 60) was used. This fuel load, with pieces designated as #1 through #5, was also installed and tested in the large cone calorimeter test facility at the NRC, as shown in Figure 61. The DNVFRS fuel configuration was used in 15 tests, including twice when the fuel was doubled to the DNVFRS x2 configuration. This configuration was used with both fuels: eight fuelled by fibreboard, and seven using regular particleboard as well. The CFBT configuration was used in seven tests, all using particleboard.

Most of the fibreboard tests occurred in 2015 when the EFDS was installed indoors at the NRC Mississippi Mills fire test site. An early test at the outdoor OFS site was configured using the DNVFRS loading with fibreboard as the additional fuel, to provide a comparison test to the indoor tests from 2015. While the fibreboard has a similar heat of combustion per weight as particleboard, its density is close to a third of that of particleboard meaning that the total heat output is much lower when fibreboard is used as shown in Table 14. In addition, the lower overall total heat release produced using the DNVFRS configuration over that normally seen during training with particleboard in other jurisdictions and the known low levels of smoke production from fibreboard became an issue in terms of fidelity of the environment for training. In response, for two tests after the EFDS had been moved outside, the number of fibreboards on the side and back walls of the EFDS were doubled resulting in the DNVFRS x2 configuration listed in Table 15. This was done in an attempt to determine whether increasing the fuel load to align with the total heat output from

particleboard might address some of the previous concerns about fibreboard as a fuel. Doubling the fibreboard brings the total fuel load closer to that of particleboard. However, the smoke production would still be only about half of that anticipated from similar quantities of particle board, even with this change in the number of sheets used. Other than these initial tests with fibreboard after the EFDS was relocated outdoors in 2016, the additional fuel used in the EFDS was switched to particleboard based on feedback from ongoing training being conducted simultaneously with this thesis research.



**Figure 60: Fuel load based on that from District of North Vancouver – reprinted with permission from [69]**

The fuel load used in the training done as part of the FKTP Project was adapted further to align with those used by various CFBT users in the United States [9], Belgium [24], and other jurisdictions. The later fuel configuration, with the exception that the particle board crib was replaced with a pine wood crib in a jig, is shown in Figure 62. The fuel load and configuration that is currently in use by OFS is shown in Figure 63, which, with the exception of the crib, is essentially the same as the CFBT [24] fuel load, both in material and configuration. Many of the later tests still used the DNVFRS [69] fuel configuration however, to determine if there was any significant difference between the DNVFRS and CFBT fuel load configurations.
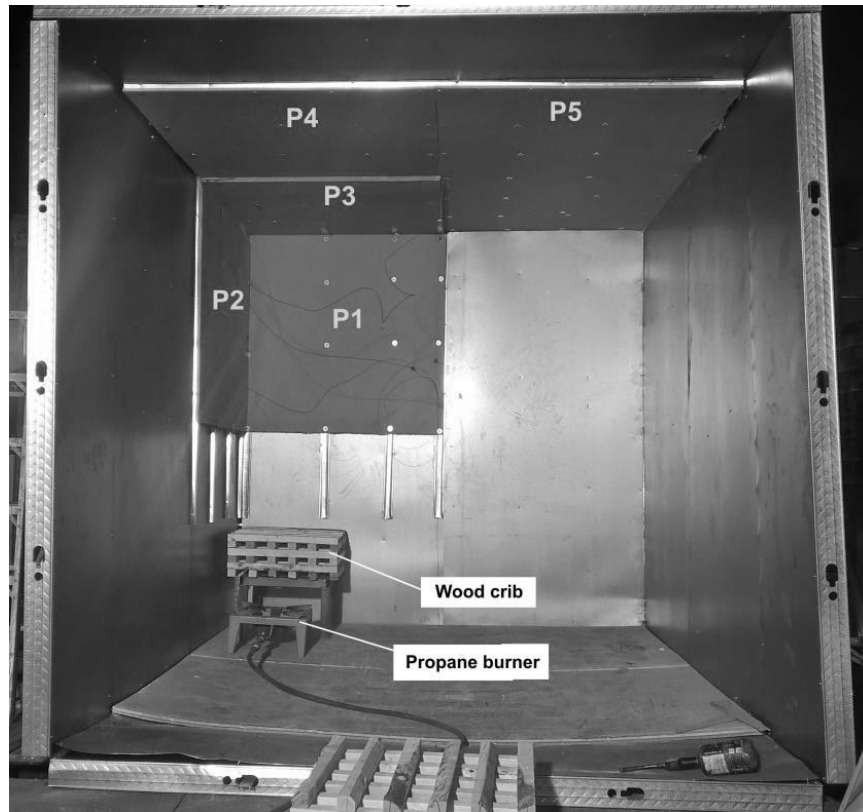
**Figure 61: Fuel Configuration for Calorimeter Testing [106]**
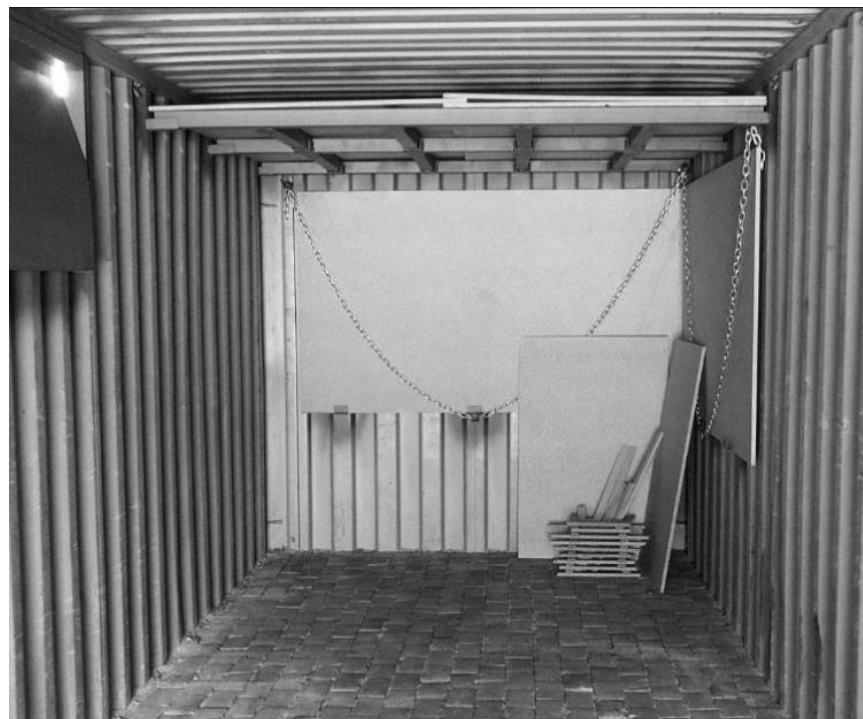


**Figure 62: CFBT fuel load – reprinted with permission from [24]**
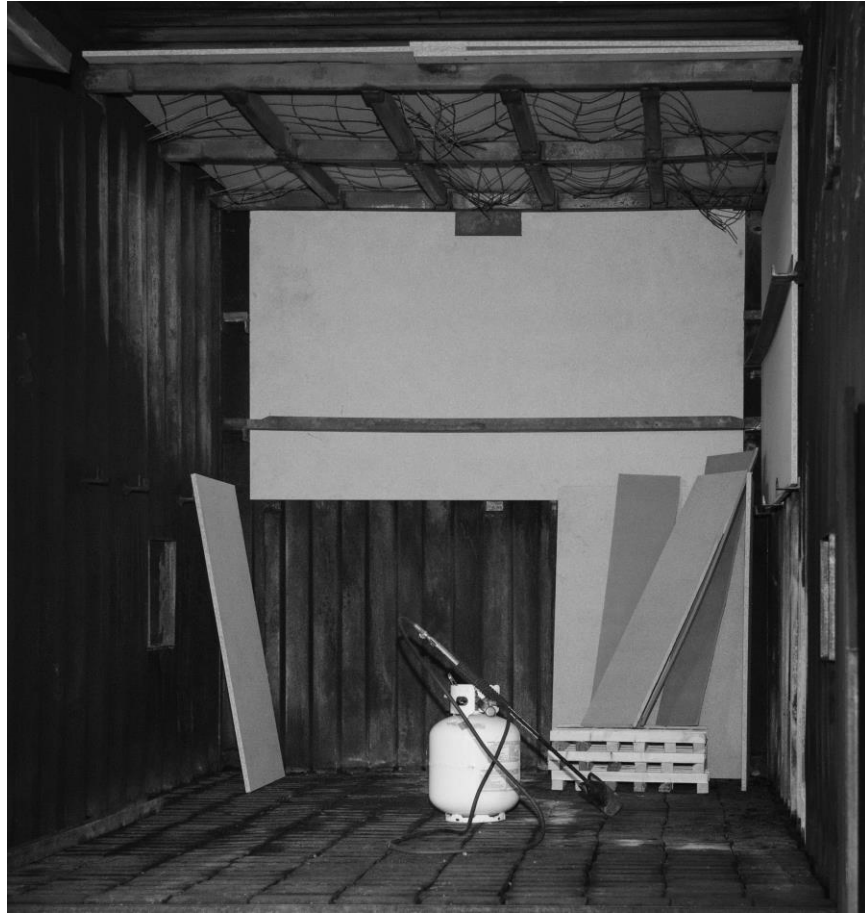
**Figure 63: Current fuel load [23]**

## 3.4 Firefighter Interactions

One important, yet difficult-to-characterize aspect of this research project is the interactions of firefighters with the fire within the EFDS. These interactions occur as a result of either the application of water to the compartment environment, or because of an adjustment of ventilation conditions during a test. It was not possible to dictate the timing of these to be consistent across tests, and it was also very difficult to record them quantitatively, because conditions inside the EFDS and the resultant fire fighter interactions evolve quickly and very differently from fire to fire. That said, there are several practices that can be anticipated during training. For instance, water is used by instructors to control the growth of the fire as well as to promote incomplete combustion and therefore increase the optical density of the smoke in the upper layer. Water is also applied by participants to the upper layer as they practice use of the smoke cooling technique. Both of these water applications were duplicated as closely as possible during testing.

Ventilation is used for two primary purposes during training as well. The first is to adjust the height of the interface layer within the EFDS, and the second is to remove excess moisture, particularly due to excessive water application by participants during training. As with water application, these ventilation actions were duplicated during testing, although the second was not required as often as water application was quite limited.

The test burns conducted for this research project involved firefighters from OFS including the author (who was inside the EFDS for all tests). Setting fire conditions to achieve a live fire environment that is both safe and that meets the learning objectives of the various training evolutions requires considerable expertise that comes almost exclusively from experience. As such, it can be expected that the control of the fire environment improved as testing proceeded, and that more consistent, less extreme conditions might be expected in the later tests in this research.

### 3.4.1 Water Application

In the present tests, water application was accomplished using a Task Force Tips (TFT) G-Force variable flow nozzle, set at 30 GPM @ 100psi and shown in Figure 64a [116]. This nozzle offers selectable flow rates from 30 to 150 GPM. Because of the small size of the EFDS, and the relatively low fuel load when compared to a typical residential fire, the lowest flow rate for the nozzle was selected. This flow rate is very low in contrast to the TFT Metro nozzles used by OFS for their primary attack lines which provide 150 GPM @ 50psi [117] as shown in Figure 64b. The Metro nozzle was not used during testing, nor is it used during training evolutions. The use of different nozzles during training when compared to those used in frontline suppression is problematic because it does not allow for participants to practice techniques using the same nozzle that they will use responding to structure fires. However, this is required as the higher flow rate of the Metro nozzle would overwhelm the relatively small heat release of the training fire.

Use of firefighting nozzles, particularly in the context of live fire training in the EFDS is an acquired skill that takes significant practice. In general, two techniques must be mastered in the training.

The first is smoke cooling which was previously described in Section 2.1.3. This is a technique developed to help firefighters advance towards the seat of fire. While this technique is not considered an extinguishment technique, it can lower the local heat transfer to firefighters, and

adds water to the upper layer to provide feedback on the temperature of the upper layer and to make fire phenomena such as rollover less likely. Water is ideally applied in very short bursts, so the technique takes practice and when executed, its effectiveness is highly dependent on the angle of the water spray (fog angle) an example of which is shown in Figure 65a. If the pulse is too long, or the fog angle too small, water will make contact with the ceiling of the EFDS and as it evaporates, it will reduce the temperature of the shipping container without having a significant cooling effect on the upper layer. In addition, the more water that evaporates on contact with the shipping container, the greater the expansion of upper layer, as was shown in Figure 11 [48]. Given that the testing undertaken during this research project was started before the author or other participants had much experience in use of this technique, our skill improved considerably over the course of testing, and so some variability in technique can be expected to have an effect on the resultant upper layer cooling in the results.



**Figure 64: a) G-Force nozzle; and, b) Metro nozzle  – reprinted with permission from [116] [117]**

The second main water application technique that is used in the EFDS is wetting. This technique is used by instructors to control the fire development during training evolutions and is shown in Figure 65b. It involves applying very small amounts water with a high degree of precision to different parts of the fuel load, allowing the water to run down the surfaces of the fuel that is mounted on the walls of the EFDS. The effectiveness of this technique is highly dependent not only on the skill with which it is applied – both the amount of water applied, as well as where exactly it is applied – but also in anticipating and understanding how it should be applied. It is

commonly considered that the number of training evolutions required to become modestly proficient in this technique is approximately 100, with effectiveness increasing asymptomatically with an instructor's experience [118, 119]. Applying water effectively via wetting decreases the heat release rate of the fuel in the EFDS while adding a minimum of excess moisture to the environment. Thus, effective wetting can prevent excessive heat release rate, limit the necessity to use the side vent (which is used to remove excess moisture, but itself leads to increased ventilation, and therefore higher heat release rate), and produce desired fire phenomena such as rollover.
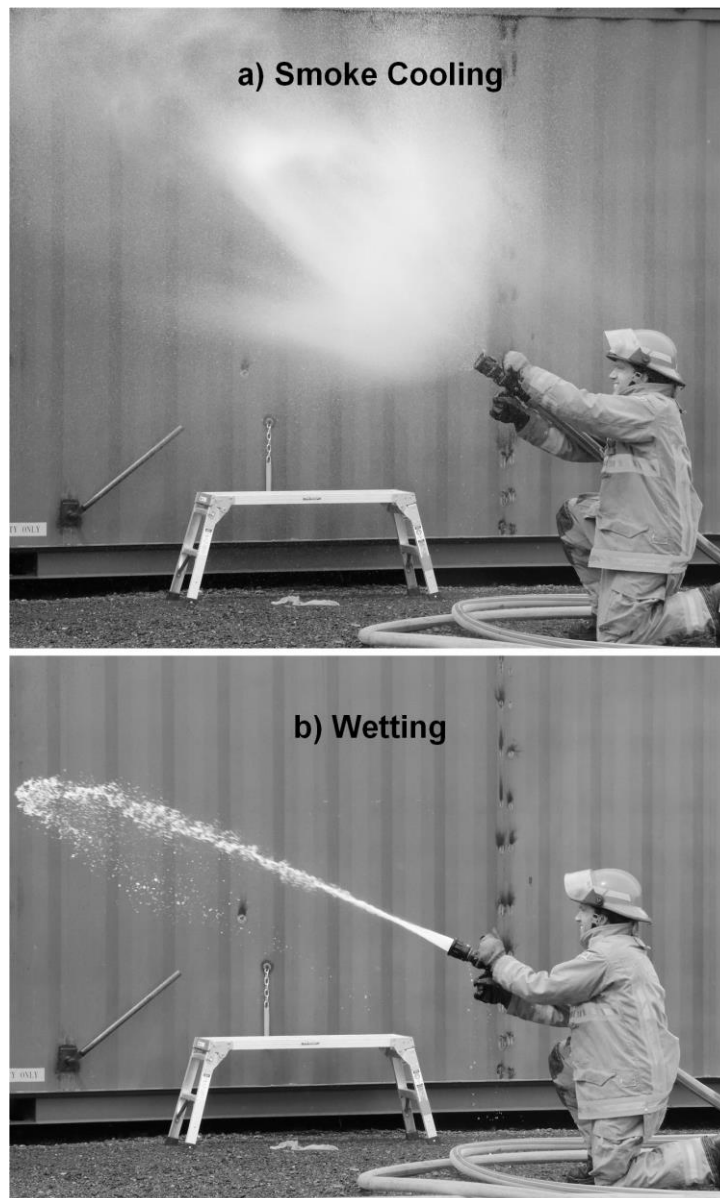


**Figure 65: Water application techniques: a) smoke cooling; and, b) wetting – reprinted with permission from [120]**

Demonstration of some of these fire phenomena is important in achieving the learning objectives of many of the training evolutions. Further, given the participants are often new to live fire evolutions, an effective and experienced instructor can seem to have a supernatural control over the environment, which can increase the confidence of the trainees, as well as their enthusiasm for learning more about fire dynamics.
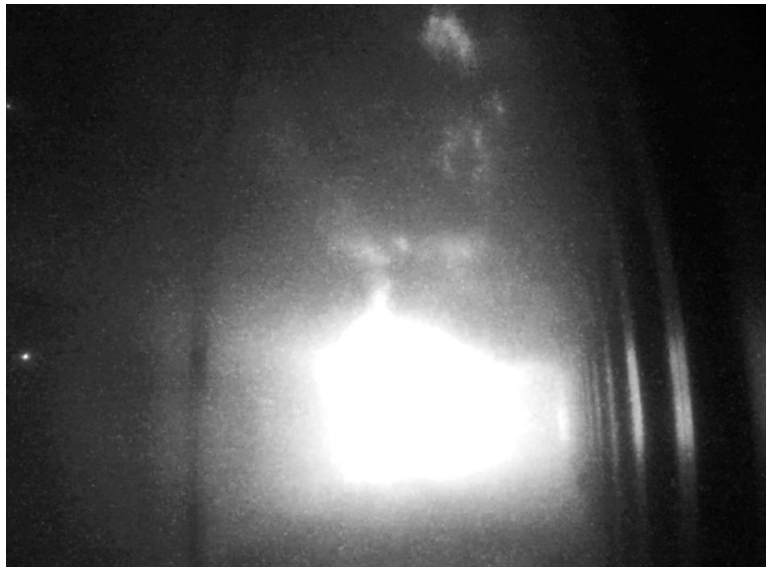


**Figure 66: Fire phenomena in the EFDS**

## 3.4.2 Ventilation

The environment within the EFDS can be influenced by use of two main ventilation openings during training and testing. These are the vestibule doors at the back, and the side vent near the fire compartment in the EFDS unit.

The primary inlet for air to enter the EFDS, both during training evolutions as well as during testing, is through using one of the doors in the vestibule bulkhead. As this is often the only ventilation opening, it operates as both an air inlet and an outlet for the hot layer and smoke building up inside the EFDS during an evolution. Early in the evolution, this opening can be kept mostly closed as the fire is small and less oxygen is required for combustion. Following this, the opening has an important role as an outlet, since it directly affects the volume of smoke that exits the EFDS. Retaining smoke early in the burn allows for an upper hot smoke layer to establish. As the fire grows, the interface between this layer and the cooler lower air layer is allowed to descend, and the EFDS transitions into a ventilation-limited environment. As the heat release rate of the fire

increases, the importance of this opening as an air inlet also becomes more important as the heat release rate is entirely controlled by limiting ventilation. This not only affects the overall heat in the EFDS unit, but also affects how the fuel burns, and depending on details of amount of fuel burning and amount of air into the EFDS, can allow for more production of smoke in the upper layer. The vestibule door can be opened or closed to adjust these conditions, as well as to demonstrate specific learning objectives. Some of the key areas in which ventilation directly interfaces with the necessary learning objectives, are via demonstration of principles such as the influence of convective heat transfer, the impact of ventilation on fire growth and heat release rate, and the impact of moisture (steam) build up in a fire compartment. For instance, by lowering the interface layer to just above the floor, instructors can demonstrate the role that convection has in overall heat transfer to firefighters and clearly reinforce the importance of staying low while fighting fires. Similarly, by systematically adjusting the side vents or vestibule doors, the interaction between level of ventilation and growth and heat release rate of a fire can be demonstrated. Increasing the ventilation will raise the interface layer, which, as discussed above, reduces the convective heat transfer to participants. However, this increased ventilation will support a higher heat release rate within the EFDS, thus increasing radiation to the fuel and surrounding compartment. In a different link between compartment environment and ventilation, the side vent is primarily used to reduce excess moisture within the EFDS during training. This can be required as the result of poor technique in water application, either by instructors or by participants, or due to the need to keep the vestibule doors closed during an evolution [74]. When there is too much moisture in the EFDS, the visibility is severely impacted and heat transfer to participants is increased. The overall ability to demonstrate other fire phenomena is also negatively affected. While the vestibule door could be used to vent excess moisture, the proximity of the side vent to the fire as well as its height above the floor make it an excellent outlet for smoke and moisture that build to excess in the environment. This allows use of the vestibule door as an inlet which is important, for example, during some training evolutions, where participants start the evolutions in the vestibule area, behind the bulkhead, and practice door entry techniques to gain access to the fire compartment. During these evolutions, fire conditions are maintained by two instructors in the EFDS using the side vent for control, and the vestibule door is kept closed for the evolution. As participants advance into the EFDS through the vestibule doors, these evolutions

often involve considerable water application, rendering the side vent even more important to overall success in achieving the appropriate learning objectives.

## 3.5 Summary

The test apparatus for this research project was the Enclosure Fire Dynamics Simulator (EFDS) that has been discussed in this section. The EFDS is constructed by modifying a standard shipping container to improve safety as well as the ability to create and maintain interior fire conditions that will allow training participants to realize the learning objectives specified by different training evolutions. The design of the EFDS was based on previous designs in several jurisdictions with a few new or modified features that were found to improve the performance of the training simulator or better adapt it to a Canadian environment.

The results from these tests are presented in the following section. The EFDS was instrumented with 27 thermocouples and four heat flux gauges to allow for the characterization of the interior fire environment. There were many test variables that were varied during this research project including ambient conditions, fuel load, and firefighter interactions. Typical and extreme conditions will be presented along with a more detailed discussion of the instrumentation and how it can be used to characterize the interior fire environment. The effects of the many variables on fire development and thermal environment will be discussed, as will how best to determine the safety of training participants from this characterization.

# Chapter 4: Results

Overall, 22 days of testing were conducted during this research project, starting on August 6th, 2015 and finishing on July 11th, 2017. There were some problems related to data collection, owing to this task being performed by the NRC: data was only analyzed once it was released, and as such, problems sometimes weren't observed until some later time, allowing problems to persist beyond a single occurrence. In addition, the move from the NRC's facility in Mississippi Mills to the new OFS training site seems to have resulted in problems with heat flux data acquisition.

For this reason, data from several experiments must be excluded from the analysis that follows. Incomplete data was received from the NRC for the test conducted on October 18th, 2015, and so it is excluded from most analyses. Heat flux data were absent or exhibited inconsistencies for the duration of testing in 2016 (October 18th through to November 9th), following the relocation of the testing to the OFS training site. Temperature data for these dates are still available however, and are thus included in the analysis when heat flux data are not involved. However, data for the test on October 19th, 2016 were never received from the NRC, and so are not included. Finally, heat flux data from June 15th, 2017 displayed significant deviations that may be attributed to a test participant occluding heat flux sensor H2 (floor, middle of the EFDS), and so this test is therefore also excluded from analysis involving heat flux.

Data collection was started prior to the ignition of the fire and video was synched to the data by manually recording the reading from a stopwatch in front of each of the cameras. Ignition time was determined during analysis following the burn, and was defined by a 5°C rise in temperature from the thermocouple 1.83m above the crib (T21). This time is noted as 0 minutes and 0 seconds in all the test data.

In total, data were collected from 27 thermocouples and four heat flux sensors at a frequency of once every second and have been analyzed for a period of 30 minutes following ignition. Thermocouple and heat flux sensor data were time-synched with each other through the data acquisition module, while video was synched using stop-watches. The cut-off time of 30 minutes was chosen as it is close to the duration of many training evolutions, and test data collected after firefighters exit the EFDS often show high temperature peaks as the fire development is no longer being controlled. As such, almost 60,000 data points were analyzed for each test, for a total of over

one million data points in total. Presenting this data in a concise and meaningful way poses a challenge as well as an opportunity. While it is impossible to present all of this data, samples of typical and extreme cases are presented, and different data sets are presented in relation to each other to allow for analysis and discussion of some of the more relevant findings.

As has been mentioned previously, there were several test variables involved over the course of testing, some introduced by design, some as a result of ambient conditions, some a result of the fact that the test environment included firefighters who were actively interacting with the fire environment. Fibreboard was initially chosen as a fuel in an attempt to reduce participants' exposure to the toxic products of combustion [52]. However, this fuel did not meet the learning objectives of the training associated with the FKTP Project. Training moved to the use of particleboard, and the decision to mirror this change in the research tests was made to ensure the relevancy of the results. Similarly, the crib was changed in an attempt to provide one that lessened the labour required for assembly. The ambient conditions during testing varied considerably, but are representative of what could be expected during training in Ottawa, as well as in many Canadian jurisdictions. Finally, the interactions of firefighters during the testing was not controlled. Controlling the fire environment to create appropriate conditions required for both safety and to ensure learning objectives are achieved is complicated and requires considerable experience. Unfortunately, this control cannot be prescribed, particularly as differences in fire development arise from ambient conditions and/or fuel load. It should be noted that the experience and skill of the firefighters involved in the testing increased over the course of the experiments. As such, many parameters, particularly peak temperatures might be affected by this improved ability to control the fire environment. While all of these variables limit the ability for an extensive analysis of the effects of a single variable on the fire environment, they are representative of the variability that is present in live fire training.

This Chapter will review the results from the 20 tests with partial or complete data. Temperature data will be reviewed followed by heat flux data including a presentation of typical and extreme cases and measurements. With this data presented in a general fashion, the focus will turn to a more in-depth analysis of the thermal environment experienced by firefighters, what effects can be observed due to the different changes to the fuel load, and whether the effects of ambient conditions can be meaningfully characterized.

## 4.1 Temperature Measurements

The EFDS was instrumented with 27 thermocouples as presented in Table 4. Of these thermocouples, only 24 will be analyzed. T25 and T26 were located in the vestibule area of the EFDS for monitoring the effects of ventilation using the bulkhead door. Ventilation is not being analyzed; as such, evaluation of these results falls outside of the scope of this analysis. T27 was used to measure the ambient temperature prior to the burn and was compared to recorded data [88] as reviewed in Section 3.3.1. The reading from this thermocouple immediately prior to ignition was taken as the ambient temperature of the test. In addition, T22, located at a height of 1.83m from the floor above the crib is located in proximity to the fuel load, and was neither fastened, nor secured, and so data from this thermocouple were found to be inconsistent. Therefore, data from this thermocouple were largely excluded from the subsequent analysis. Finally, the attachment of the thermocouples on the roof seems to have been inconsistent (T16, T17, and T18) resulting in variable measurements at times. However, these data are still used in the subsequent analysis without further adjustment.

The minimum, average, and maximum peak temperatures from each of the 24 thermocouples for all 20 tests are presented in Table 16. Without further context these data are not particularly relevant in and of itself, other than providing a listing of the extremes in temperatures that firefighters might be exposed to. Sample data from a test burn on July 5th, 2017 are shown in Figure 67. This test was chosen as it represented a typical burn with peak temperatures near the average values of those found in Table 16. With a relatively large sample size of 22 test burns, it is hoped that the average temperatures recorded in Table 16 would be representative of future test or training burns under similar conditions, although it is not possible at this time to definitively predict this would be the case. The minimum and maximum temperature extremes seem more likely to provide guidance for extreme conditions for future burns. Again, given the large number of tests conducted, along with the number of different variables involved, it is hoped that the fire environments included in this research represent a representative distribution of conditions that might be experienced in future training evolutions.

**Table 16: Typical and extreme thermocouple measurements**

| Thermocouple | | Peak Temperature (°C) | | |
|---|---|---|---|---|
| # | Description | Max. | Avg. | Min. |
| T1 | Rake #1 - 2.59 m Height | 733.9 | 635.2 | 515.9 |
| T2 | Rake #1 - 1.98 m Height | 536.9 | 371.0 | 267.6 |
| T3 | Rake #1 - 1.37 m Height | 364.2 | 240.6 | 171.1 |
| T4 | Rake #1 - 0.76 m Height | 254.3 | 121.6 | 77.1 |
| T5 | Rake #1 - 0.15 m Height | 260.3 | 85.5 | 54.6 |
| T6 | Rake #2 - 2.59 m Height | 706.2 | 515.1 | 356.0 |
| T7 | Rake #2 - 1.98 m Height | 443.8 | 322.8 | 240.7 |
| T8 | Rake #2 - 1.37 m Height | 278.5 | 217.7 | 151.1 |
| T9 | Rake #2 - 0.76 m Height | 177.2 | 100.3 | 60.9 |
| T10 | Rake #2 - 0.15 m Height | 89.2 | 55.3 | 34.4 |
| T11 | Rake #3 - 2.59 m Height | 450.6 | 369.0 | 253.6 |
| T12 | Rake #3 - 1.98 m Height | 411.7 | 342.0 | 244.6 |
| T13 | Rake #3 - 1.37 m Height | 338.3 | 255.6 | 181.2 |
| T14 | Rake #3 - 0.76 m Height | 157.7 | 117.8 | 59.1 |
| T15 | Rake #3 - 0.15 m Height | 81.6 | 53.5 | 29.6 |
| T16 | Rake #1 - Exterior Roof | 388.9 | 272.5 | 92.2 |
| T17 | Rake #2 - Exterior Roof | 273.5 | 229.0 | 128.1 |
| T18 | Rake #3 - Exterior Roof | 210.5 | 167.2 | 82.2 |
| T19 | Crib - Exterior Roof | 434.1 | 257.2 | 93.2 |
| T20 | Crib - 2.59 m Height | 975.1 | 758.7 | 531.7 |
| T21 | Crib - 1.83 m Height | 981.5 | 674.6 | 228.7 |
| T22 | Exterior - Plume Side 1.83 m Height | 525.1 | 327.4 | 100.5 |
| T23 | Exterior - Plume Side 0.91 m Height | 538.8 | 325.0 | 48.4 |
| T24 | Exterior - Opposite Side 0.91 m Height | 217.0 | 135.7 | 68.3 |
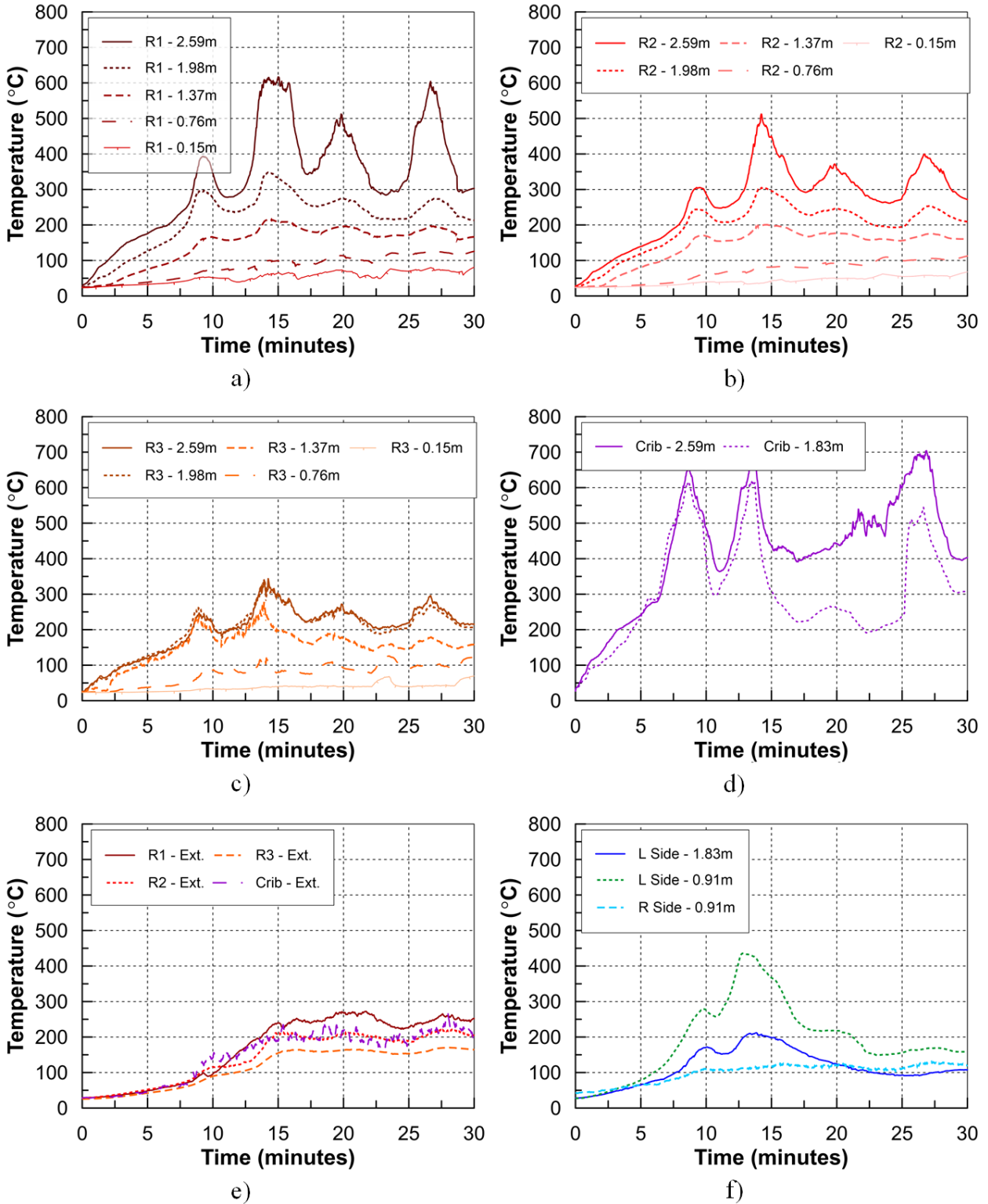
**Figure 67: Sample thermocouple measurements from July 5ᵗʰ, 2017 for: a) Rake #1; b) Rake #2; c) Rake #3; d) Crib; e) Exterior roof; and, f) Exterior sides**

Figure 67a through c show the three thermocouple rakes, demonstrating that temperature increases with height as well as with proximity to the fuel load, although these temperature differences are more pronounced for the thermocouples closer to the ceiling. While the interface height varies during the tests, thermocouples located at 1.37m and higher are considered to be located in the upper layer, while the ones located at 0.76m and at 0.15m are considered to be located in the lower layer for much of the duration of the test burns. An analysis of the interface height was not undertaken, given that it is controlled by firefighters, is sometimes lowered during training evolutions to achieve learning objectives, and similarly was varied during the test burns.

Figure 67d shows the two thermocouples located above the crib. As the data from T21 were inconsistent, they will not be used in subsequent analysis. T20 however will be analyzed, particularly in describing early fire development associated with the crib, and as a potential gauge of the influence of ambient conditions on fire development. Figure 67e shows the thermocouples located on the exterior roof of the EFDS. There might have been some issues with how these thermocouples were attached, and therefore how accurate a measurement of the EFDS ceiling temperature they represent. Despite those concerns these thermocouples will play an important role in the modelling of heat transfer presented subsequently in Section 4.5.3 for reasons that will be explored in Section 3.2.3.1. Figure 67f shows the thermocouples located on the exterior walls which were added to allow for an analysis of thermal stresses on the EFDS as a means to analyze the potential longevity of the trainer. However, this analysis does not form part of the eventual research project.

## 4.1.1 Plume Development

Plume development was analyzed looking at thermocouples T20 (Crib at a height of 2.59 m) and T1 (Rake #1 at a height of 2.59 m) These two thermocouples were located approximately 30 cm from both the front and right wall of the EFDS and centered above the crib. The development of the intermittent flame zone is taken to be characterized by a temperature of 320°C, while steady flame is marked by a temperature of 550°C [36]. Table 17 shows the time for each thermocouple to reach these benchmark temperatures for extreme and typical burns, while Figures 68 and 69 show the more detailed time-dependent temperature profiles for T20 and T1, respectively. These data demonstrate the wide range in fire development that is observed. This method to assess fire

development will be employed in Sections 4.4.1 and 4.6 to look at how different crib designs and ambient conditions affect early fire development, respectively.

**Table 17: Typical and extreme plume development**

| Date | T20: Crib - 2.59 m | | T1: Rake #1 - 2.59 m | |
|------|--------|--------|--------|--------|
| | 320°C | 550°C | 320°C | 550°C |
| 11-Jul-17 | 01:48 | 02:23 | 08:40 | 09:22 |
| 31-May-17 | 04:20 | 04:57 | 07:55 | 00:00 |
| 21-Oct-16 | 09:29 | - | 00:00 | 00:00 |
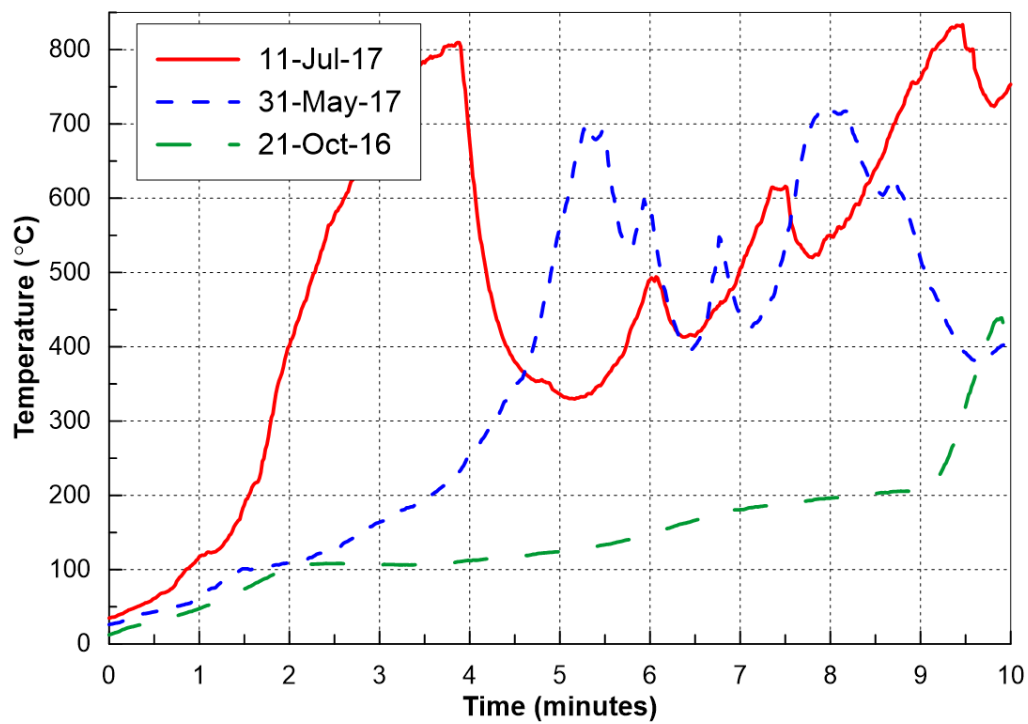


**Figure 68: Typical and extreme plume development – T20: Crib 2.59 m**
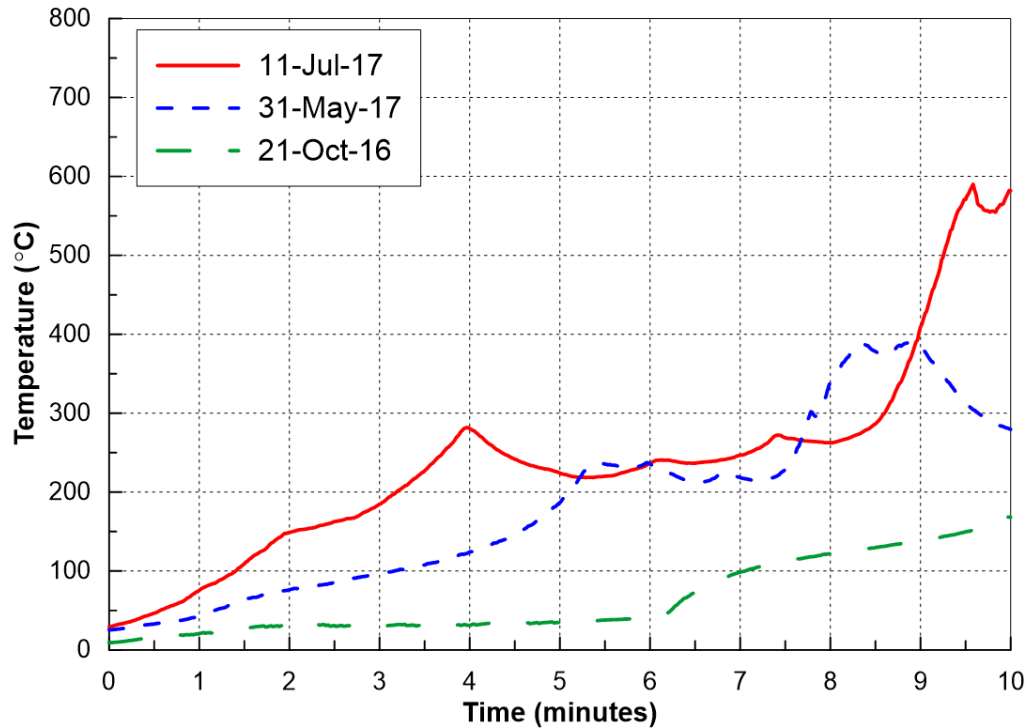
**Figure 69: Typical and extreme plume development – T1: Rake #1 2.59 m**

## 4.1.2 Upper Layer Temperatures

Despite the variation of the interface height during test burns, the interface in the fire compartment was generally considered to be located in the region above the thermocouples situated at 0.76 m above the floor and below the ones situated at 1.37 m off the floor. The interface height will not exist prior to the establishment of an upper layer of hot fire gases, so it will be considerably higher than 1.37 m above the floor early in the burn. During training evolutions, therefore, the ventilation is controlled and limited early in the burn to help build up the hot upper layer of combustion gases and to allow the interface height to lower. This is done both to allow participants to view the build-up of the upper layer, as well as to speed the heating of the upper layer and the ceiling regions of the EFDS to shorten the time before other learning objectives can be taught. While instructors might periodically lower the interface layer to heights very close to the floor, this would only be done either to demonstrate the effects of ventilation, or to reinforce the role of conductive and convective heat transfer relative to that by radiation. Generally, the interface height is kept above the heads of participants, which usually is approximately 1 m above the floor. Figure 70 shows thermocouple data for the nine thermocouples (shown schematically in Figure 71) in the upper layer from the test burn conducted on June 13th, 2017.

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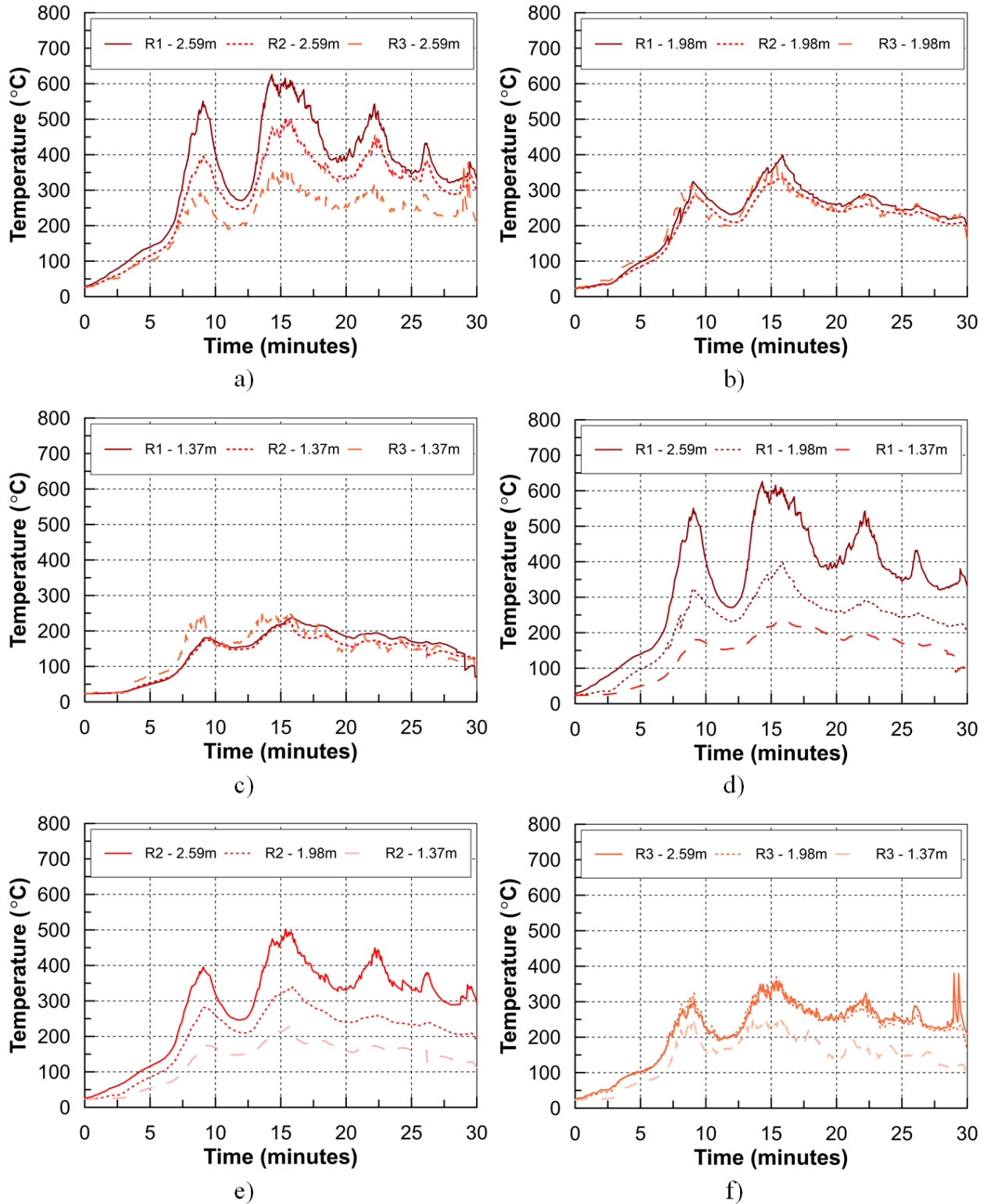
**Figure 70: Upper layer temperatures from June 13th, 2017 for: a) 2.59 m; b) 1.98 m; c) 1.37 m; d) Rake #1; e) Rake #2; and, f) Rake #3**
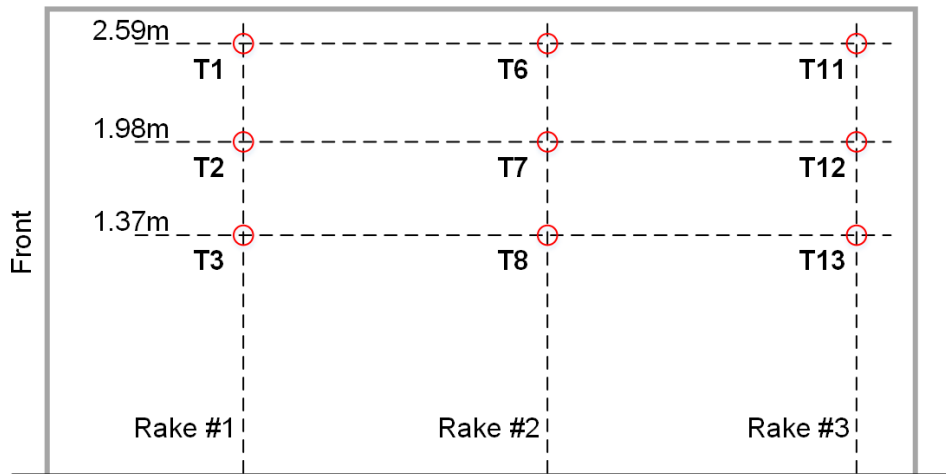
**Figure 71: Schematic of upper layer thermocouple distribution**

This test was chosen as it does not exhibit extreme peak temperatures. These are presented grouped both horizontally as well as vertically to show the temperature distribution throughout the upper layer. Figure 70a through c show horizontal distributions of temperature for three heights in the upper layer. Each set of plots contains a comparison of time-varying temperatures measured by thermocouples at the same height but different downstream locations from the fire. These indicate that while there is significant variation in temperature with distance from the fire very close to the ceiling, the temperature uniformity increases moving lower in the upper layer. Figures Figure 70d through f show the same temperatures plotted to highlight the vertical variation in temperature through the hot layer for Rakes #1 through #3. Similarly, the vertical temperature uniformity increases with distance from the fire, being cooler but more uniform in temperature closer to the bulkhead of the EFDS. Both of these observations are consistent with the presence of a relatively localized flame close to the front of EFDS with an ensuing ceiling jet of hot gases. Clearly the two-zone model of a uniform upper layer is inexact, a subject of further review and discussion in Section 4.1.2.

### 4.1.3 Temperatures Experienced by Firefighters

Given an approximate interface height between 0.76 m and 1.37 m, this leaves the lower two thermocouples in each rake, positioned at 0.76 m and 0.15 m above the floor, as representative of the lower layer in which participants are located. Given Rake #1 is placed far forward of where

firefighters are located, only Rakes #2 and #3 are presented in Figure 72 which shows data from test burns with extreme and typical temperatures in these areas.
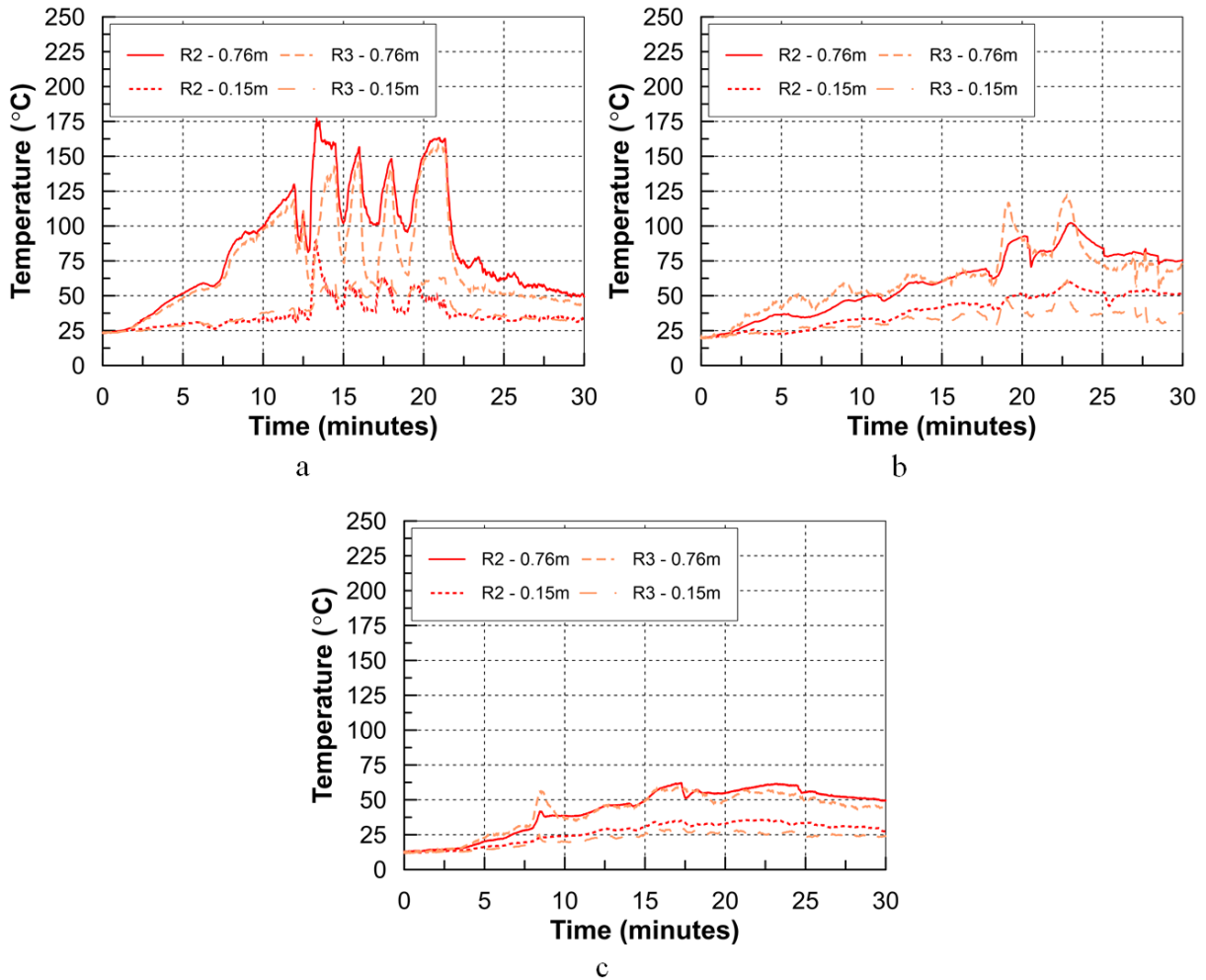


**Figure 72: Typical and extreme lower layer temperatures: a) Maximum – August 6th, 2015; b) Average – Jun 15th, 2017; and, c) Minimum – Jun 6th, 2017**

It can be seen that the highest temperatures occur at a height of 0.76 m above the floor as expected, and there is reasonable horizontal uniformity at both heights over all three tests. It should also be noted that the maximum temperatures occurred during the first test (August 6th, 2015), and that the temperatures were significantly lower in the other two examples from 2017. This might well be due to better control of the fire development owing to increased experience and expertise on the part of the firefighters involved. Given that temperature is one of the metrics that has been used to estimate the severity of the thermal environment experienced by firefighters [59] [63], as discussed in Section 2.3.3, these four thermocouples are of importance in characterizing the thermal

environment in the EFDS. Given the higher temperatures for both thermocouples at a height of 0.76 m (T9 and T14), only these thermocouples will be examined in the subsequent analysis presented in Section 4.5.2.

## 4.2 Heat Flux Measurements

Heat flux data were collected in four locations that were chosen in an attempt to best characterize the thermal environment of participants in live fire evolutions conducted in the EFDS or similar training simulators. H1 and H2 are mounted in the floor so as to provide a benchmark against the common definition for flashover of 20 kW/m$^2$ at the floor [36]. H3 was located at the safety door and directed at the right, top, front corner of the EFDS as an estimate of the view factor of a firefighter exiting using the Safety Door under emergency conditions from the main body of fire within the EFDS. H4 is directed at the middle of the front wall, and located at the approximate height of a firefighter against the bulkhead wall of the EFDS. This represents the heat flux experienced by a firefighter upon entering or exiting the EFDS using the bulkhead door.

The heat flux data had a considerable amount of noise in it, as well as at times suggesting negative heat flux values. These issues were addressed by using a 10 second rolling average for the heat flux, and setting any remaining negative measurements to zero. The typical and extreme measurements for both peak heat flux, as well as total heat transfer are presented in Table 18. Total heat transfer is calculated simply by summing the average heat flux measurements (as the measurement frequency is once per second) to convert from Watts to Joules. H1 and H2 have higher maximum, average, and minimum peak heat flux and heat transfer values, with H3 having the lowest values across the board. Interestingly, H4 has higher values than H3 despite being further from the seat of the fire, and this will be discussed in the subsequent Sections. Figure 73 shows the time-dependent heat flux data from test burns with typical and extreme peak heat flux, while Figure 74 shows time-dependent heat flux data from burns with typical and extreme total heat transfer, for each of the four heat flux gauges. It should be noted that, once again, many of the maximum thermal exposures occurred earlier in the research project, both when fiberboard was used as a fuel, and the participants were less experienced in setting thermal conditions, with the exception of the peak heat flux for H3 on the last test burn, conducted on July 11th, 2017. Further, as will be discussed in Section 4.5.2, it is important to note that the peak heat flux never approaches the limits of either Thermal Class III or Ordinary Operating Conditions as presented in

Section 2.3.3 [59] [63]. The following Sections will examine the heat transfer models, both radiative and convective as it applies to the four heat flux gauges.

**Table 18: Typical and extreme heat flux and heat transfer measurements**

| Heat Flux Gauge | | Peak Heat Flux (kW/m$^2$) | | | Heat Transfer (MJ/m$^2$) | | |
|---|---|---|---|---|---|---|---|
| # | Description | Max. | Avg. | Min. | Max. | Avg. | Min. |
| H1 | Floor - Forward | 5.6 | 3.51 | 2.41 | 4.67 | 2.76 | 1.36 |
| H2 | Floor - Middle | 3.41 | 2.29 | 1.37 | 2.98 | 1.82 | 0.96 |
| H3 | Safety Door | 7.29 | 5.27 | 2.73 | 5.52 | 3.81 | 1.83 |
| H4 | Bulkhead | 4.9 | 3.33 | 1.54 | 4.17 | 2.18 | 0.82 |
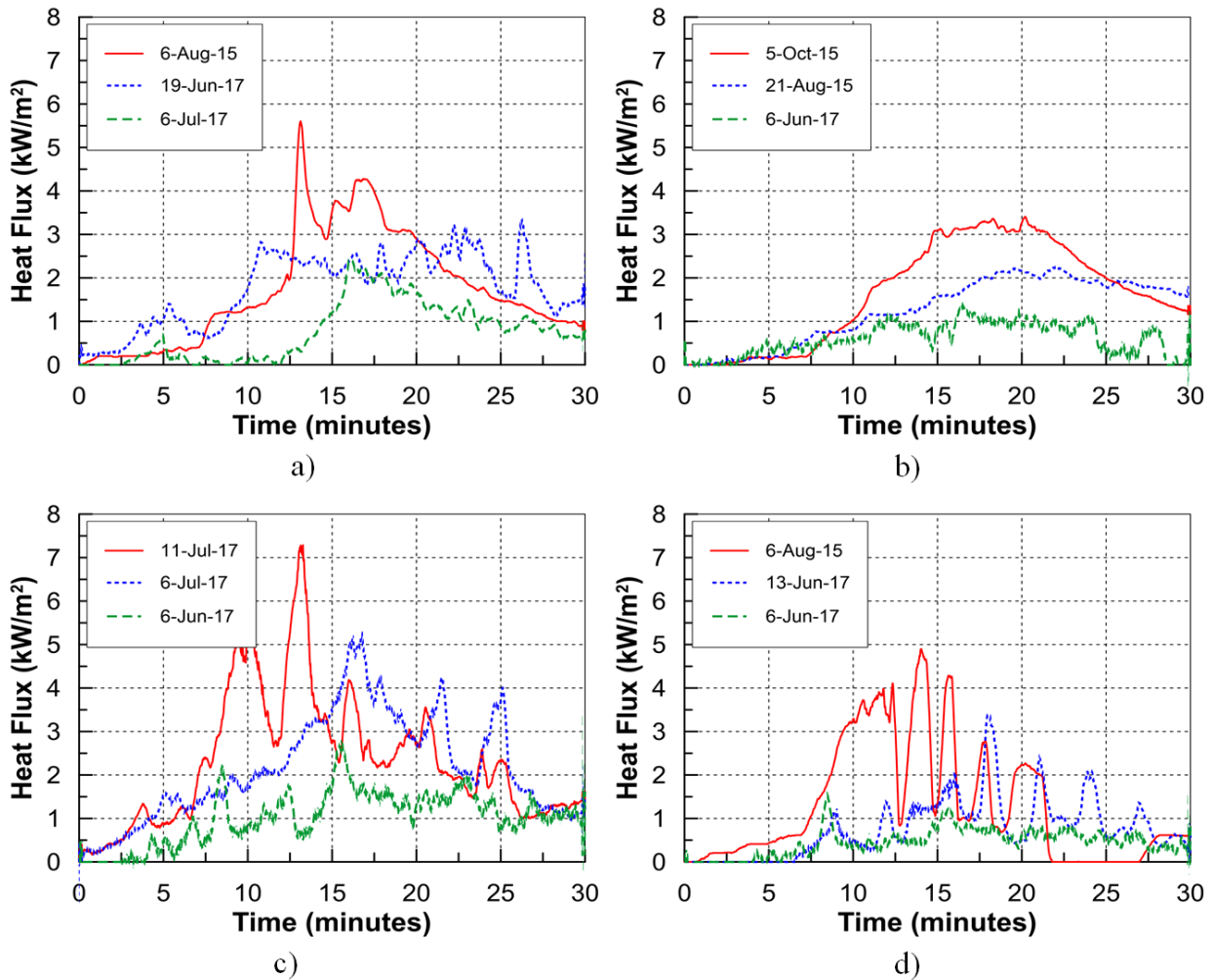


**Figure 73: Typical and extreme heat flux experiments for: a) H1 - Floor Forward; b) H2 - Floor Middle; c) H3 - Safety Door; and, d) H4 – Bulkhead**
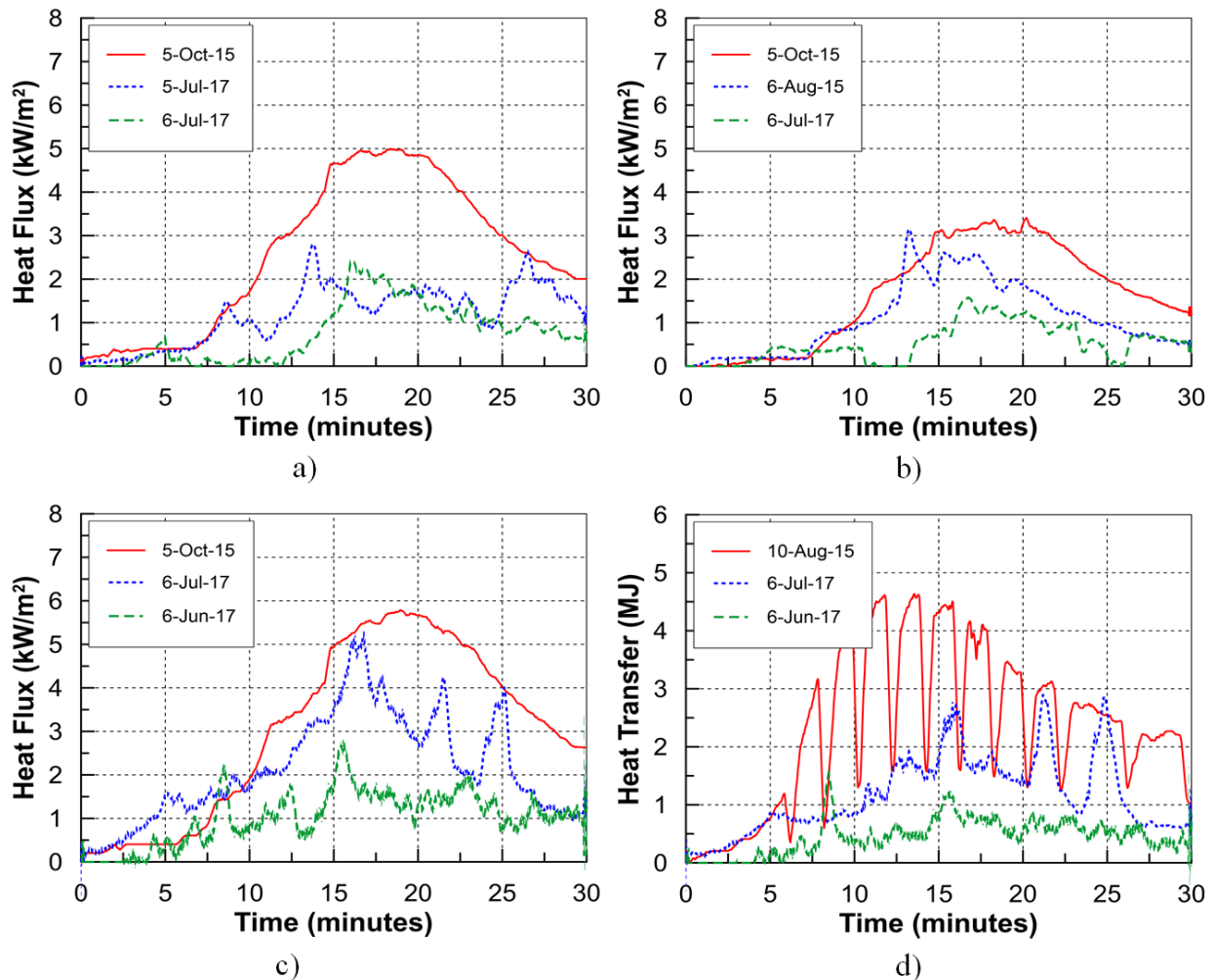
**Figure 74: Typical and extreme heat transfer experiments for: a) H1 - Floor Forward; b) H2 - Floor Middle; c) H3 - Safety Door; and, d) Bulkhead**

## 4.3 Video Images of Interior Fire Conditions

The goal of a competent instructor is to set interior fire conditions that will facilitate the teaching of the learning objectives set forth for a particular training evolution. The goal of the instructor cadre during this research project was to set conditions comparable to two of the more basic training evolutions that were developed as part of the FKTP Project [29].

The Fire Behaviour Burn [73] is intended to familiarize new fire recruits with live fire conditions and build their confidence in their PPE, while allowing the students to focus on fire phenomena without having to perform any tasks or practice any techniques. The Demonstration Burn [72] builds on this training evolution while demonstrating the effectiveness of the smoke cooling tactic,

and allowing students to practice this technique within a live fire environment. During both of these training evolutions, it is desirable that visibility be maintained for a large portion of the evolution by maintaining the interface height just above the height of a kneeling firefighter. This also limits convective heat transfer to participants from the upper layer. At some points during the evolution, the interface layer can be lowered to demonstrate the effects of ventilation control, as well as the increased heat transfer from the upper layer.

Given the role of ambient conditions on fire development that will be discussed in Section 4.6, even competent instructors cannot control the fire development or set interior conditions through a prescribed set of actions. Rather, extensive experience is required to recognize how the fire is developing and anticipate control actions using water application or ventilation (as described in Sections 3.4.1and 3.4.2 respectively) that will create the training environment that is desired.

Without the benefit of real-time instrumentation of the interior fire environment, instructors rely instead on their subjective observations of the fire conditions including heat, the amount and location of flame, and the optical density of the upper layer. To relate the participants' perspective of the interior fire conditions to the temperatures recorded by the instrumentation, time-dependent temperature graphs are shown in Figure 75 while still images from video cameras 1 and 2 are shown in Figures 76 through 84 from the burn conducted on November 3rd, 2015.
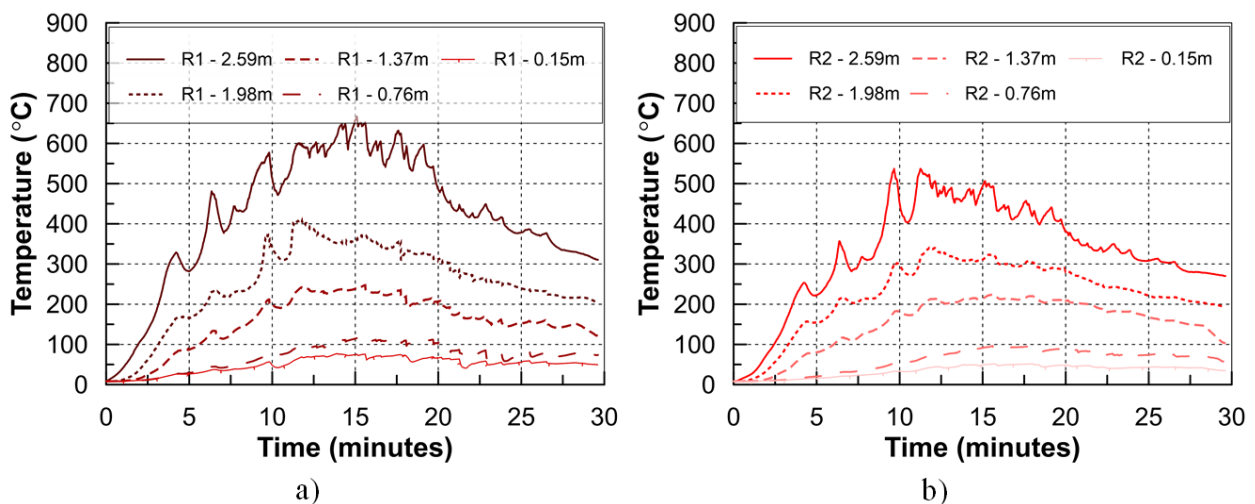


**Figure 75: Sample thermocouple measurements from November 3rd, 2015 for:**

**a) Rake #1; and, b) Rake #2**

This burn was chosen as the peak temperatures recorded were close to the average values of the 22 different test burns and video was available (the video from later burns during 2017 was never received from the NRC). As described at the beginning of this Chapter, video is synched with temperature and heat flux data by using a stopwatch that is started at the same time as the data acquisition. The times shown in Figures 76 through 84 are synched with the data in Figure 75 based on this method.

Figure 76 shows the ignition of the elevated pine crib using a burner. This ignition happens eight seconds prior to the ignition time used in Figure 75 which is defined by a 5°C rise in temperature from the thermocouple 1.83m above the crib (T21). The delay between the actual ignition of the burner and a temperature rise measured by T21 is likely a result both of the thermal delay inherent in shielded thermocouples as well as the time for a fire plume to develop sufficiently to raise the temperature at a 1.83m height. The housing for Camera 2 can be seen to the right of Figure 75a, mounted to the interior wall of the EFDS. Thermocouple Rake #1 is blocked by Rake #2 in Figure 75a while both can be seen in Figure 75b. The author can be seen igniting the propane burner in both Figure 75a and b. Light from holes that were drilled into the EFDS for instrumentation can be seen to the right of Figure 75b. In addition, the different viewing angle between camera 1 and 2 should be noted, with camera 2 having a much wider angle, which results in noticeable distortion. Further, Figure 75b shows the effect of some condensation in from of the camera lens as the ambient temperature at the time of ignition was measured to be 8.3°C.



a)                                                          b)

**Figure 76: Video still images at time of ignition (t = -00:08s) for:**

**a) Camera 1; and 2) Camera 2**

Figure 77 shows the views from both cameras at t = 00:00s as recorded in the graphs shown in Figure 75, while Figure 78 shows the views from both cameras at t = 05:00s. Tests burns were conducted with three instructors from the OFS Instructor cadre.

- The first instructor is located to the left of EFDS close to the safety door as can be seen to the left in Figure 77a. This first instructor will control the burn through water application, as well as operating the lever for the side vent that is located just behind the safety door.

- A second instructor is located in the vestibule area and is responsible for adjusting the opening and closing of one of the vestibule doors to control the ventilation during the burn.

- A third instructor is located to the right of the EFDS across from the safety door as can be seen to the right in Figure 78a. This position was typically occupied by the author, who directed the actions of the first two instructors.



a)                                                                 b)

**Figure 77: Video still images at time t = 00:00s for: a) Camera 1; and 2) Camera 2**

In Figure 78 the development of an interface layer and a hot upper layer can be seen from pyrolysis of the sheet material on the walls and ceiling of the EFDS. The development of a well-demarcated interface layer facilitates the teaching of the two zone model as described in Section 2.2.3, while the pyrolysis and growth of the fire reinforces curriculum topics such as; the stages of fire development, as well as different heat transfer mechanisms as described in Sections 2.2.1 and 2.2.2 respectively.

Figure 79 shows the views from both cameras at t = 10:00s. In Figure 79a, the fire is barely visible, while the crib can still be seen in Figure 79b. These two views reinforce both the difficulty in

seeing within a fire compartment, the importance of staying below the interface layer to increase visibility. The disparity between these two views also demonstrates the importance of rotating students during the training evolution as the local conditions within the EFDS vary considerably.



a)                                                          b)

**Figure 78: Video still images at time t = 05:00s for: a) Camera 1; and 2) Camera 2**



a)                                                          b)
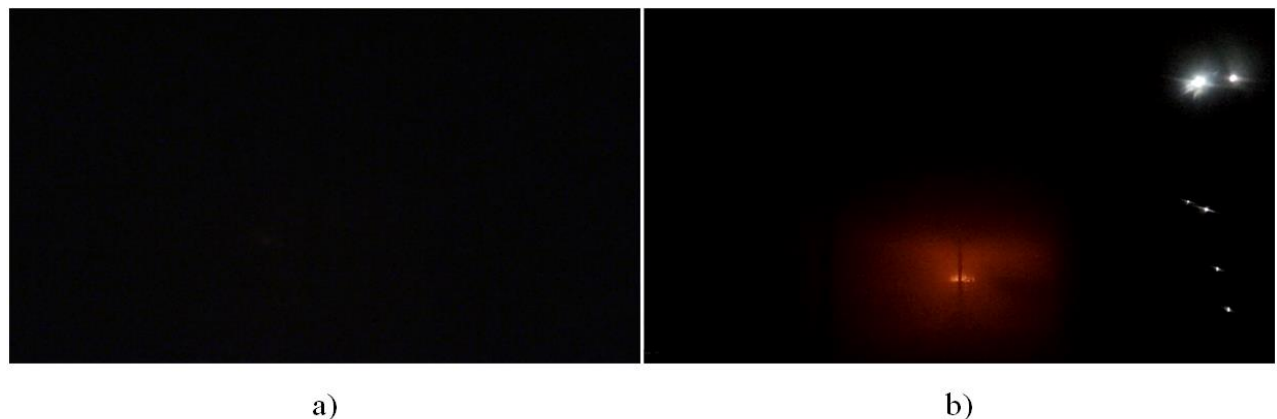
**Figure 79: Video still images at time t = 10:00s for: a) Camera 1; and 2) Camera 2**

Figures 80 through 82 – between t = 15:00s and t = 23:28s – continue to show a well demarcated interface layer at a height of approximately 1m, which would be above the height of most kneeling firefighters. Figure 82 is taken at t = 23:28s as this represents the end of video capture from camera #2. During testing, the cameras sometimes stopped recording once they had heated up too much, which might be the cause of the premature end to video capture from this camera. The similarity of the interior fire conditions shown in these three Figures corresponds to relatively stable temperatures at Rakes #1 and #2 respectively at these times as shown in Figure 75a and b respectively, particularly at the heights of 1.37m and 0.76m, the thermocouples just above and just

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below the interface. While interior fire conditions in actual fires are seldom stable, it is desirable to achieve a certain degree of stability during training evolutions.



a)                                                    b)

**Figure 80: Video still images at time t = 15:00s for: a) Camera 1; and 2) Camera 2**



a)                                                    b)

**Figure 81: Video still images at time t = 20:00s for: a) Camera 1; and 2) Camera 2**



a)                                                    b)

**Figure 82: Video still images at time t = 23:28s for: a) Camera 1; and 2) Camera 2**

Having a period with consistent conditions allows time for the instructor to demonstrate fire phenomena as well as time for students to practice techniques under similar conditions. In this way, the fidelity of the interior fire environment is quite low, but the safety and logistics are improved (a trade-off as discussed in Section 2.1.3).

The amount of fire has decreased considerably by t = 25:00s as shown in Figure 83, and the instructors can be seen ending the evolution and exiting through the safety door at t = 28:30s in Figure 84. The interface layer height is very high in this last Figure, due to the limited amount of remaining fuel.



**Figure 83: Video still image at time = 25:00s for Camera 1**



**Figure 84: Video still image at time = 28:30s for Camera 1**

**4.4 Effect of Fuel Load Changes on the Fire Environment**

Three elements of the total fuel load were varied during testing: crib design, fuel type and fuel configuration. These will be examined in the subsequent Sections. There were two types of particleboard that were used during the experiments: a typical one; and, a zero emission one denoted as "0E" in Table 13. This particleboard was marketed as having zero emissions of formaldehyde, and it was hoped that it would thus reduce participants' exposure to toxic by-products of combustion. Unfortunately, this product ceased to be offered during the course of testing. Building materials are not specified by their material composition, and instead are specified by their mechanical properties. As they are not designed to be burned, their products of combustion are not a part of their specifications [115]. As such, there is no guarantee that a given batch of particleboard will have the same properties – including heat of combustion, smoke production, or smoke composition – as a previous batch. Only two burns, on October 18th and November 4th, were conducted using this material making any analysis difficult. Further complicating this situation is that dependable heat flux measurements were not collected for either of these tests. As such, no analysis based on the 0E particleboard will be conducted here.

**4.4.1 Crib Design**

The initial experiments used a crib built of pine that was ignited using a propane burner. This crib design was chosen so that the contribution of the propane ignition could be subtracted from the analysis of the fire development. While this is a sound methodology, it is geared towards testing that would involve far fewer test variables and be more focused on developing a full quantitative characterization of fire development and conditions. This crib design, particularly the ignition technique, is not representative of those used in training evolutions. For this reason, testing moved to cribs that were ignited using a propane torch. Feedback from several SMEs during a training symposium [108] indicated that using a crib that was constructed of particleboard might achieve better fire development. Based on these recommendations, this crib design was used during the training symposium, and it was decided that the research project should incorporate it as well. However, this crib design requires significant labour to produce as particleboard sheets need to be cut into 2" (50.8 mm) wide strips and then cut down to approximately 30 cm lengths. The original crib design also involved significant labour, requiring all 36 individual pieces of 2"x2" lumber to

be nailed together. A solution was achieved whereby a steel jig was constructed that allowed for minimal labour in preparation of the crib. All three crib designs are described in Section 3.3.2.1.

Six tests were conducted from which the results can be directly compared. These include three tests using the CFBT fuel configuration [24], and three with the DNVFRS [69] fuel configuration. All of the experiments used particleboard for the main fuel load with cribs made of pine, particleboard or pine in the jig as were shown in Figure 53. Fire plume development, as measured by T20, above the crib at a height of 2.59 m, is summarized in Table 19, and time-dependent temperature profiles in the first 10 minutes of the experiments are shown graphically in Figure 85.

Table 20 summarized the times for thermocouple T20 to reach 320°C and 550°C, as well as the time during which temperatures at the thermocouple were above these thresholds (as previously discussed in Section 4.1.1). Time-dependent temperature profiles in the first 10 minutes of the experiments presented in Table 20 are shown in Figure 86.

**Table 19: Temperature thresholds for various crib designs (T20: Crib - 2.59 m)**

| Date | Crib Type | Fuel Load Type | Time to Reach Temp. | | Time Above Temp. | |
|---|---|---|---|---|---|---|
| | | | 320°C | 550°C | 320°C | 550°C |
| 31-May-17 | Pine | CFBT | 04:22 | 04:59 | 20:31 | 04:42 |
| 06-Jun-17 | PB | | 03:35 | 04:09 | 20:21 | 02:36 |
| 13-Jun-17 | Jig | | 05:57 | 06:49 | 21:54 | 06:43 |
| 15-Jun-17 | Pine | DNVFRS | 02:57 | 05:10 | 18:53 | 00:44 |
| 19-Jun-17 | Particleboard | | 02:17 | 02:57 | 25:01 | 18:48 |
| 05-Jul-17 | Jig | | 06:39 | 07:56 | 23:22 | 06:46 |

In both test subsets, those with the CFBT [24] and those with the DNVFRS [69] fuel configurations, test burns with particleboard cribs show quicker plume development, exactly the intended goal of the SMEs when suggesting use of this material [108]. However, when looking at the time spent above both temperature thresholds, the crib design is less prescriptive. Feedback from OFS instructors [121] indicates that the crib jig requires more time to develop which is supported by the data below. Following this initial development, the data from this research project

do not indicate a persistent quantitative effect of use of the pine jig on the overall fire conditions or longevity of the fire during the experiments. As such, the guidance provided to OFS has been to continue to use the crib jig to reduce the labour requirements associated with crib production during training.



a)                                                                        b)
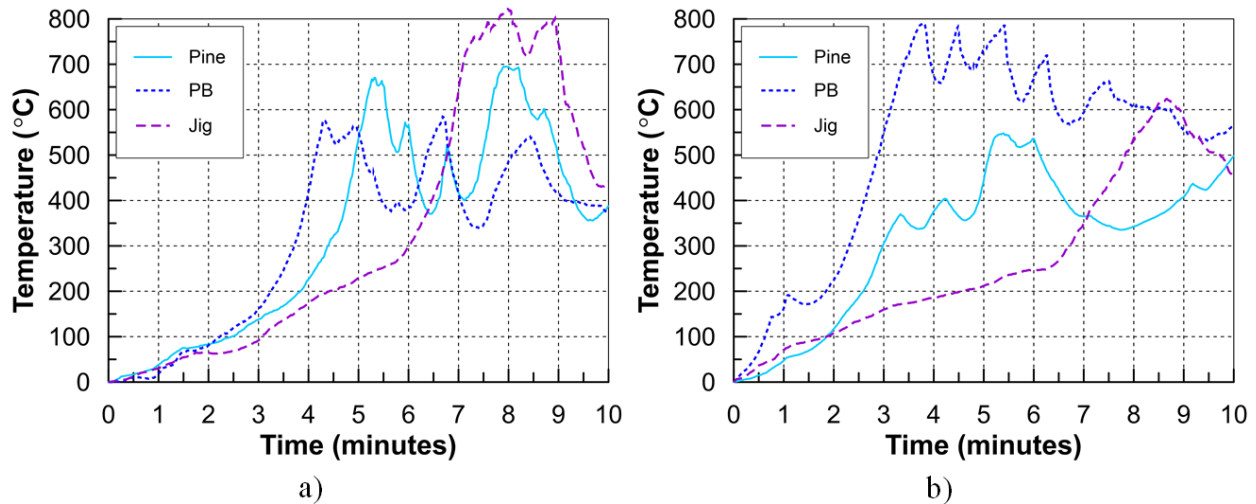
**Figure 85: Temperature rise for various crib designs (pine crib, particleboard crib, and pine crib with a steel jig) – T20: Crib 2.59 m with: a) CFBT fuel load; and, b) DNVRFS fuel load**

**Table 20: Temperature thresholds for various crib designs (T1: Rake #1 - 2.59 m)**

| Date | Crib Type | Fuel Load Type | Time to Reach Temp. | | Time Above Temp. | |
|---|---|---|---|---|---|---|
| | | | 320°C | 550°C | 320°C | 550°C |
| 31-May-17 | Pine | CFBT | 07:57 | 12:55 | 19:17 | 06:02 |
| 06-Jun-17 | Particleboard | | 06:35 | 12:16 | 16:54 | 02:05 |
| 13-Jun-17 | Jig | | 07:31 | 09:03 | 20:21 | 03:02 |
| 15-Jun-17 | Pine | DNVFRS | 05:48 | 12:52 | 19:35 | 02:02 |
| 19-Jun-17 | Particleboard | | 04:20 | 10:15 | 22:10 | 05:23 |
| 05-Jul-17 | Jig | | 08:35 | 13:31 | 15:06 | 03:22 |
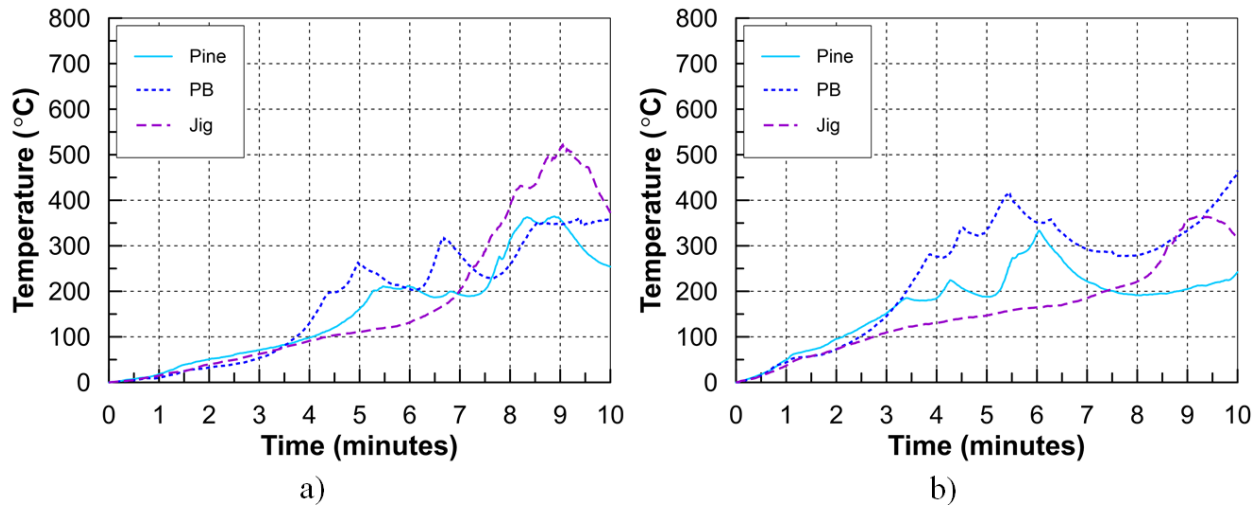
**Figure 86: Temperature rise for various crib designs (pine crib, particleboard crib, and pine crib with a steel jig) – T1: Rake #1 2.59 m with: a) CFBT fuel load; and, b) DNVRFS fuel load**

### 4.4.2 Fuel Type

Only three tests allow for a direct comparison of the fuel type, those conducted on: October 5th, 2015, October 6th, 2015, and November 4th 2016. The details of these experiments are listed in Table 21. All three tests involved a pine crib that was ignited using a burner. Both tests from October, 2015 use fibreboard (FB) as a fuel, while the test on November 4th, 2016 uses particleboard (PB). While the ambient conditions for both fibreboard tests are similar, they are significantly different from the ambient conditions for the test where particleboard was used for the fuel load.

**Table 21: Fuel type comparison details**

| Date | Fuel Type | Configuration | Crib | Ignition | Ambient Conditions | |
|------|-----------|---------------|------|----------|--------------------|----------------|
| | | | | | Temp (°C) | Humidity (%) |
| 05-Oct-15 | Fibreboard | | | | 15.2 | 59 |
| 06-Oct-15 | Fibreboard | DNVFRS | Pine (Elevated) | Torch | 14.0 | 67 |
| 04-Nov-16 | Particleboard | | | | 1.7 | 72 |

Given the small number of comparable tests, as well as the role that ambient conditions might have played, no further analysis of the role of fuel type will be conducted here. Rather, an examination

of results presented with respect to the thermal environment and outlined in Section 4.5.2 are separated by fuel type and the role of ambient conditions is further discussed in Section 4.6, so that general trends might be observed.

### 4.4.3 Fuel Configuration

There were insufficient tests to allow for a comparison of the different fuel configurations given the number of other variables. However, the lack of a clear quantitative difference between the configurations indicates that either the CFBT [24] or DNVFRS [69] configuration could likely be used without concerns over safety or the ability to achieve conditions that enable teaching of the desired learning objectives. Currently the OFS is using the CFBT fuel configuration [23, 24], largely due to familiarity with that fuel loading, as well as a lack of a quantitative motivation to move to the DNVFRS [69] fuel configuration.

### 4.5 Thermal Environment Experienced by Firefighters

Given the number of uncontrolled variables during testing, definitive correlations between specific variables and fire development are hard to establish, and this wasn't the primary goal of the research project. Rather, the goal was broadly to characterize the EFDS in terms of the safety of the live fire training environment, as well as to provide guidance to other users with respect to fuel load and design refinements of the simulator design. More definitive correlations might be achievable with more focussed testing with fewer variables, or by building a model and validating it with data that was gathered for this research project.

This Section will review different ways to characterize the interior environment of the EFDS during live fire experiments. Section 4.5.1 will examine the characterization of the upper layer as this can be used generally to offer feedback to instructors and students about their burn. Section 4.5.2 will review the thermal exposure of participants within the EFDS according to measurements from the four heat flux gauges as well as the local temperatures in the lower layer. Finally, the association model between heat flux and temperature measurements, laid out in Section 4.2, will be explored in Section 4.5.3.

### 4.5.1 Upper Layer Temperature Approximation

Measurement of upper layer temperatures provides useful feedback as to the experience of firefighters during live fire training evolutions. Higher upper layer temperatures will mean that smoke in this layer is more likely to be above the auto-ignition temperatures, and so more flame, particularly flame that is separated from the main fire plume will be present. Also, given the contribution of the ceiling and upper layer to the modelled radiative heat flux as modelled as effective emissivities in Section 3.2.3.1, upper layer temperatures will have an effect on the heat transferred to participants, and therefore the safety of the interior fire environment. Given that participants are applying water and interacting with the upper layer, there is expected to be some variation between the nine thermocouples in the upper layer (as shown in Figure 71). Temperature uniformity, both horizontally and vertically, was examined briefly in Section 4.1.2, showing that this uniformity increases lower in the upper layer and further away from the seat of the fire.

In the interest of providing guidance for future users of the EFDS (or similar live fire simulators), the question becomes whether a limited number of thermocouples can provide a reasonable approximation of overall upper layer temperatures. Average temperatures for each test were examined along the three horizontal groupings of three thermocouples each at heights 2.59 m, 1.98 m, and 1.37 m above the floor. These were compared to the average temperature of all nine thermocouples. It was determined that the average temperatures determined using the mid-height grouping at 1.98 m above the floor provided the best fit to the nine-thermocouple average, and further that a single measurement from Rake #2 (T7) was able to provide a reasonable approximation of the overall upper layer temperature. The maximum positive and negative deviations as well as the average difference between the upper layer average temperature and the single temperature measured at T7 are presented in Table 22 and shown graphically in Figure 87.

There are two ways in which the accuracy in use of T7 as an environmental indicator can be described. The first is by the maximum range of individual deviations between the nine-point average of all the thermocouples in the upper layer and T7 temperature; the second is by the average error over the duration of each test.

**Table 22: Upper layer temperature approximation**

| Date | Upper Layer Approximation Error (°C) | | |
| --- | --- | --- | --- |
| | Error (-) | Avg. | Error (+) |
| 6-Aug-15 | -73.3 | -8.0 | 23.2 |
| 10-Aug-15 | -45.9 | -13.4 | 12.5 |
| 21-Aug-15 | -33.0 | -16.5 | 0.9 |
| 5-Oct-15 | -43.1 | -10.8 | 2.5 |
| 6-Oct-15 | -26.8 | 1.8 | 28.9 |
| 12-Oct-16 | -37.7 | -8.1 | 15.1 |
| 20-Oct-16 | -51.3 | -7.7 | 16.5 |
| 21-Oct-16 | -37.4 | -7.4 | 8.6 |
| 3-Nov-16 | -50.6 | -15.2 | 6.6 |
| 4-Nov-16 | -39.4 | -8.7 | 4.9 |
| 7-Nov-16 | -35.1 | 2.6 | 21.4 |
| 9-Nov-16 | -55.2 | -8.7 | 15.7 |
| 31-May-17 | -40.3 | -10.8 | 9.7 |
| 6-Jun-17 | -53.8 | -12.8 | 4.1 |
| 13-Jun-17 | -41.6 | -9.4 | 18.5 |
| 15-Jun-17 | -63.5 | -12.5 | 13.0 |
| 19-Jun-17 | -53.0 | -14.1 | 14.0 |
| 5-Jul-17 | -47.4 | -10.0 | 10.2 |
| 6-Jul-17 | -61.5 | -7.2 | 8.8 |
| 11-Jul-17 | 26.1 | 26.3 | 25.5 |

Worst and best-case approximation scenarios are presented in Figures 88 through 90, along with the associated thermocouple measurement error of ±7.7°C that was determined in Section 3.2.1. The worst-case scenario for the maximum deviation was seen in data from the test burn conducted on August 6th, 2015 and is shown in Figure 88. The largest deviations seem to occur during quick temperature transitions, which is not surprising as a greater spatial variation in upper layer temperatures would be expected under transient conditions. These transient temperatures are

caused either by a rapid increase in combustion within the upper layer, by the addition of water by participants, or by a change in ventilation conditions. All three of these phenomena would be at least somewhat localized and so using a single temperature measurement to define the fire compartment environment would be expected to be less accurate.
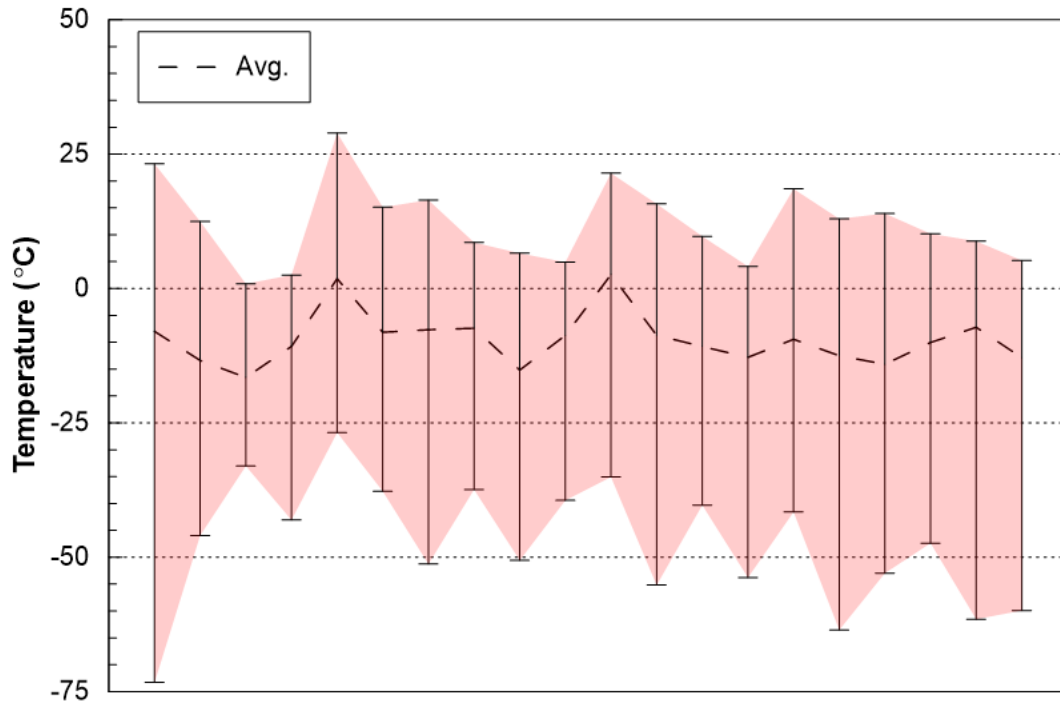


**Figure 87: Error range for UL temperature approximation**

The largest average deviation, from the test burn conducted on August 21$^{st}$, 2015 is shown in Figure 89, during which the approximation based on T7 seems to be consistently below the average temperature of the upper layer. The best-case scenario, where the average offset between the average temperature and that measured at T7 is shown in Figure 90, can be seen in data from the test on October 6$^{th}$, 2015. The upper layer temperature approximation often lies within the measurement uncertainty, and the deviations once again occur during more rapid temperature changes, as was also evident in Figure 88.
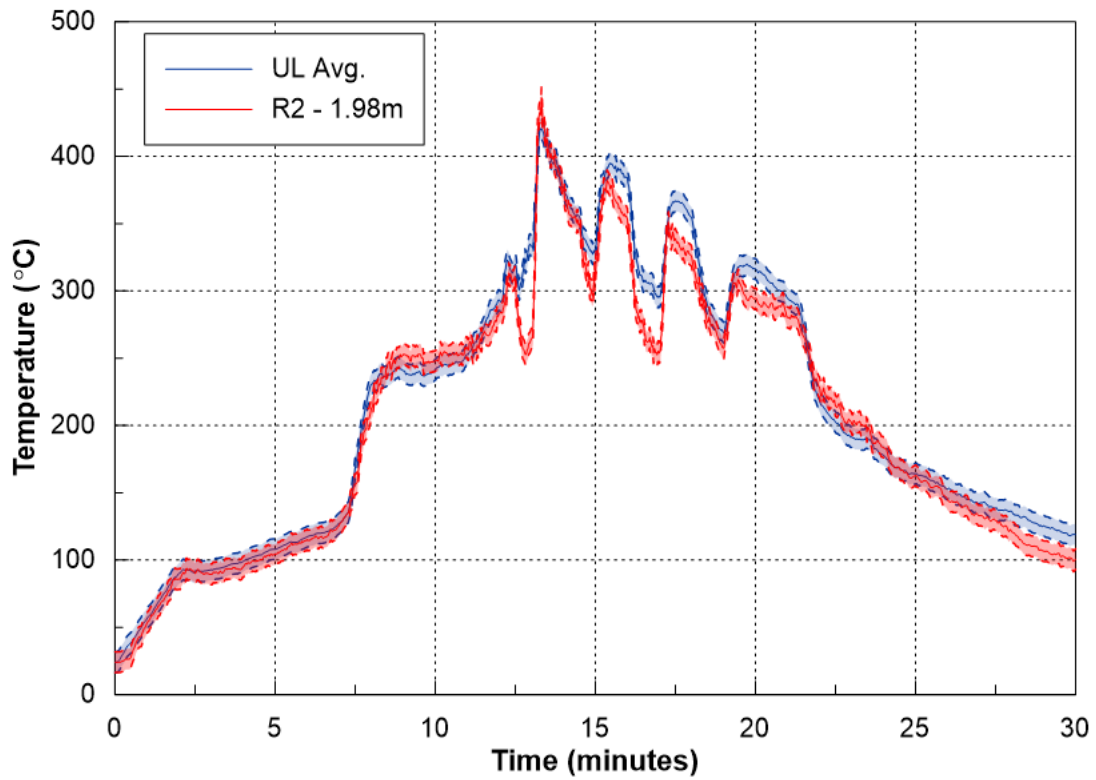
**Figure 88: UL temperature approximation – max. deviation worst case August 6th, 2015**
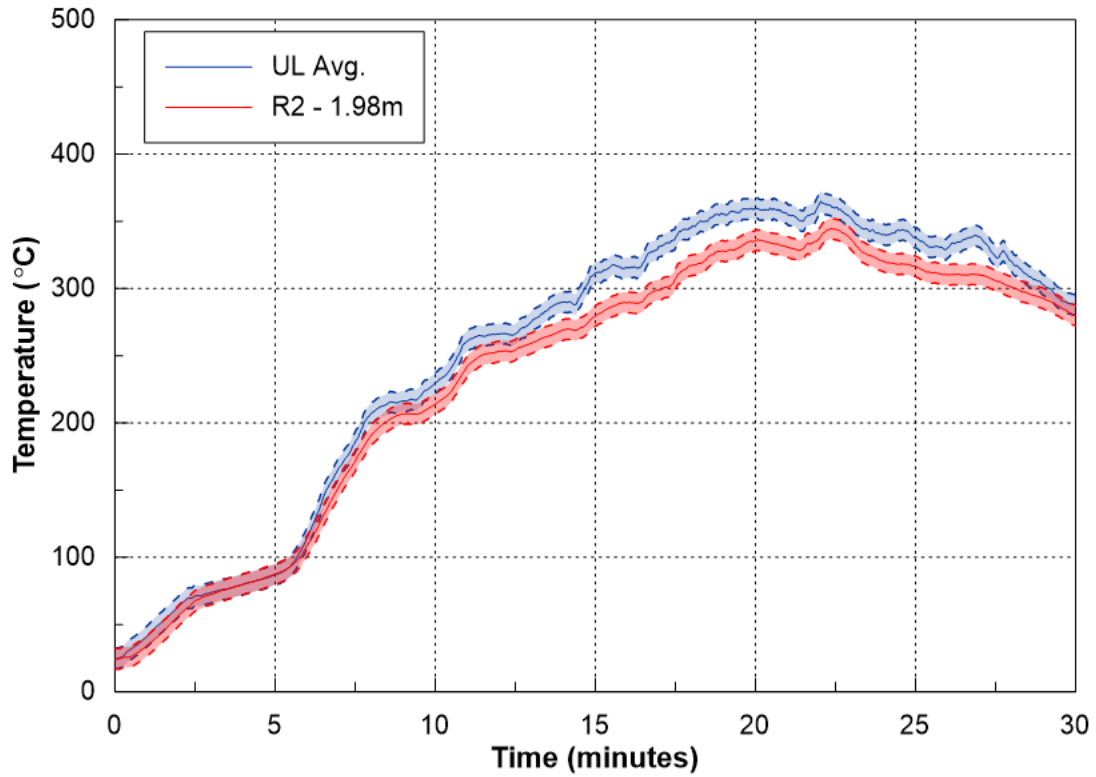


**Figure 89: UL temperature approximation – avg. deviation worst case August 21st, 2015**

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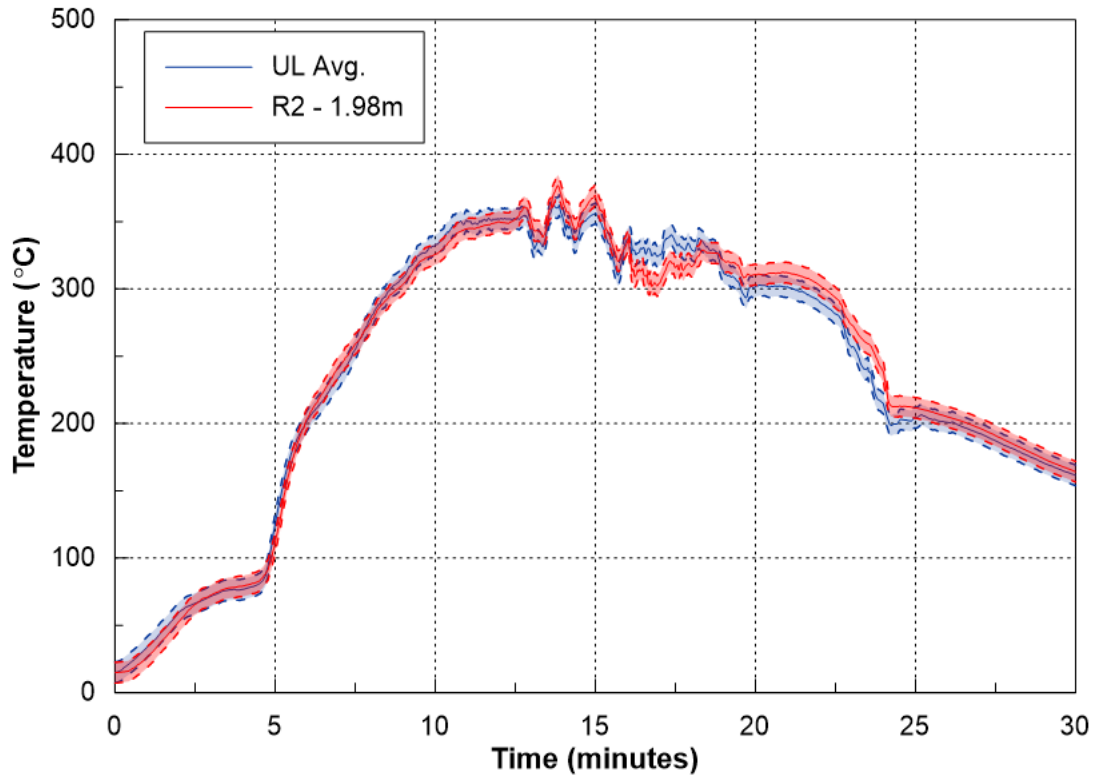
**Figure 90: UL temperature approximation - best case October 6th, 2015**

Table 23 summarizes the maximum, average, and minimum observed positive, average and negative approximation errors in upper layer temperatures as monitored using T7.

**Table 23: Upper layer temperature approximation summary**

| (°C) | Error (-) | Avg. | Error (+) |
|---------|-----------|-------|-----------|
| Maximum | -26.8 | 2.6 | 28.9 |
| Average | -47.7 | -9.5 | 11.8 |
| Minimum | -73.3 | -16.5 | 0.9 |

Results in Table 23 indicate that while the approximation can be relatively inaccurate for instantaneous temperature measurements, on average there is only a -9.5°C error in using this method, with the approximated average temperature falling in the range of -16.5°C to 2.6°C across all tests. This range is less than the ±7.7°C measurement uncertainty bounds of the thermocouple measurements. Further, even though this accuracy does not strictly apply to estimation of temperatures in the upper layer at any instant in time, plotting the approximated upper layer temperature values obtained during a test still presents a good qualitative representation of upper

layer conditions throughout any given burn. While this error range might be too large for research purposes, the goal of quantifying this approximation is to provide a simplified instrumentation scheme that could be used in fire simulators in other jurisdictions.

## 4.5.2 Temperature and Heat Flux Exposures

The most important goal of this research project was to assess the compartment environment in the EFDS under a variety of operating conditions in order to gain more in-depth understanding of the safety of the EFDS as a live fire training simulator. While the large number of variables during testing does not allow for association of fire conditions with single variables, the large number of tests were conducted over a wide range of ambient conditions, different crib designs, and fuel configurations and types. Critically, they represented training conditions when the EFDS was operated by the same cadre of instructors as they gained experience in controlling the interior conditions. As such, the range of conditions can be seen as representative of conditions that might be experienced during live fire training within Ottawa Fire Services, or in other jurisdictions that might adopt the FKTP curriculum, designs, and guidance associated with the EFDS. Therefore, the characterization of the thermal conditions during training do provide applicable guidance on the safety of the EFDS, or a similar training simulator, if it is being controlled by a relatively experienced instructor using a similar fuel load.

As was discussed in Section 2.3.3, determining how to define a safe environment for training is not straightforward. The NFPA standards for PPE typically focus on failure limits for those pieces of PPE rather than on how much heat is transferred to the firefighter [55, 56, 57]. While these standards include requirements for thermal protective insulation levels for firefighting gear, both when it is compressed and not, they do not specify safe operating environments for firefighters. Due to the nature of training activities, a compelling case can be made for a time-dose approach as proposed by UL FSRI [41], or for characterization of the amount of time that training participants spend within each of the thermal classes proposed in NIST Technical Note 1474 [59]. Both of these approaches recognize the importance of characterizing the thermal environment in the training compartment not simply by temperature, but also by heat flux. Averaging this exposure over time demonstrates the importance not only of heat flux extremes, but also of the total amount of heat transfer to participants through conduction, convection, and radiation. The UL FSRI study involved instrumenting firefighters moving within a larger, more compartmentalized training

environment and so instrumentation was attached to firefighters [41]. The use of stationary measurement in this research project is appropriate given the smaller and single compartmental interior volume. In addition, the four heat flux gauges were positioned in a way that heat flux was measured throughout much of this interior volume, as well as in positions and orientations that were anticipated to provide worst-case heat transfer to training participants. The UL FSRI study also made mention of the fact that thermal exposure seemed more severe when considering heat flux than local temperatures, likely due to firefighters' efforts to stay beneath the interface layer [41]. This would apply even more so with training in the EFDS as longer exposures occur during training evolutions where the interface layer is maintained above the participants for the majority of the evolution.

Two standards have been referenced in recent literature that attempt to classify different operating zones based on temperature and heat flux, and suggest limits for times that firefighters can expect to operate safety in these thermal conditions. The applicability of these to thermal stress and injury of firefighters is unclear. The Operational Zones proposed by Utech [63] date back over 30 years, during which firefighting PPE has changed dramatically, while the Thermal Classes proposed by NIST [59] were proposed for electronic equipment. Both of these would seem to be conservative values, at least when it comes to thermal injury, so it is also important to consider the experience gained during this research project.

The EFDS was instrumented with four heat flux gauges as well as 27 thermocouples, allowing for a relatively detailed characterization of the environment within the fire compartment. Given all of these considerations, the thermal environment was characterized through examination of local temperatures measured at positions close to the height of a firefighter in a kneeling position in the area where these firefighters are operating. Such conditions are represented by the data from Thermocouples T9 and T14, both of which are located at a height of 0.76 m above the floor in Rakes #2 and #3, respectively, and shown in Figure 41. Examining the temperatures at each of these two locations allows for a worst-case analysis of temperature in the areas where participants are located. Similarly, the heat flux as measured at each of the four HFGs is also examined.

Ten experiments were reviewed during the analysis of firefighter exposure to the live fire environment: four tests in 2015, all using fibreboard as a fuel, and six in 2017, all with

particleboard as a fuel. Only these 10 tests were analyzed as the rest had data acquisition issues that were reviewed at the start of Chapter 4.

Typical and extreme time-dependent temperature measurements for the lower layer were plotted in Section 4.1.3, while typical and extreme time-dependent measurements for each of the four heat flux gauges were plotted in Section 4.2. Converting from these time-dependent plots, to an evaluation of the test burns based on the above-noted standards, involved looking at the amount of time that the thermal conditions fell within each of the defined operating ranges. The data are therefore replotted to directly indicate the time spent within the different operating classes in Figures 91 and 92 for temperature and heat flux, respectively.
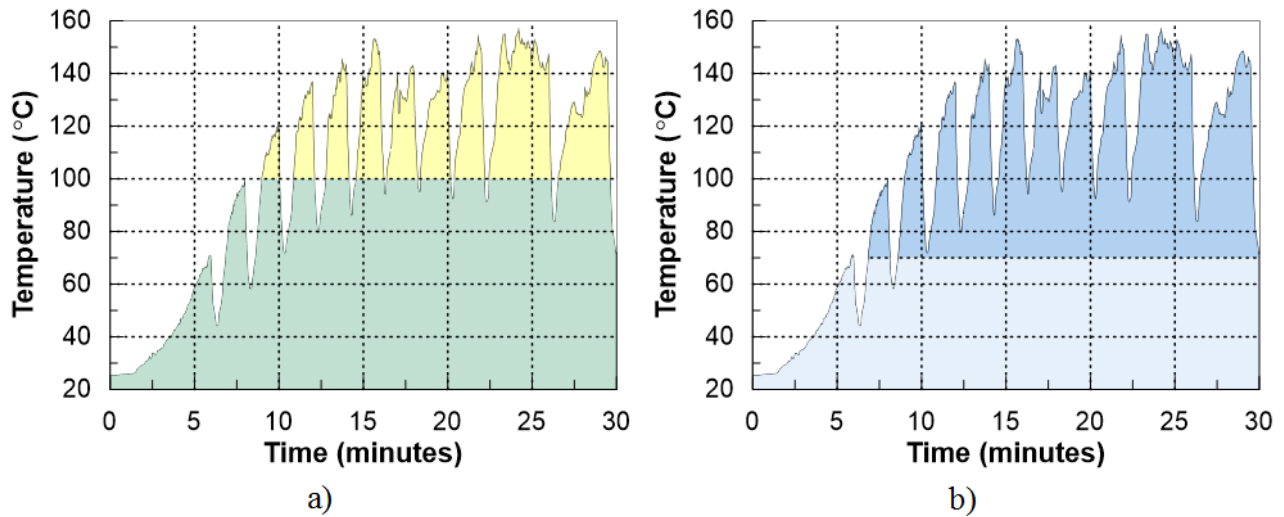


**Figure 91: T14 temperature for August 10th, 2015 related to: a) Thermal Classes I & II; and, b) Routine & Ordinary Operating Conditions [59] [63]**

Data from the test burn conducted on August 10th, 2015 (an early test that used fibreboard as the main fuel load) was chosen as it presented extreme conditions with respect to the operating classes for both temperature and heat flux. Figure 91a shows the time over which thermocouple T14 registered temperatures in Thermal Classes I and II (illustrated as green and yellow shading, respectively), while Figure 91b shows the same data as they relate to the time spent in both Routine and Ordinary Operating Conditions (illustrated as light and dark blue, respectively). Figure 92a shows time-dependent data for heat flux gauge H3 as it relates to Thermal Classes I, II, and III (illustrated as green, yellow, and orange, respectively), while Figure 92b shows these data

as they relate to both Routine and Ordinary Operating Conditions (shown as light and dark blue, respectively).
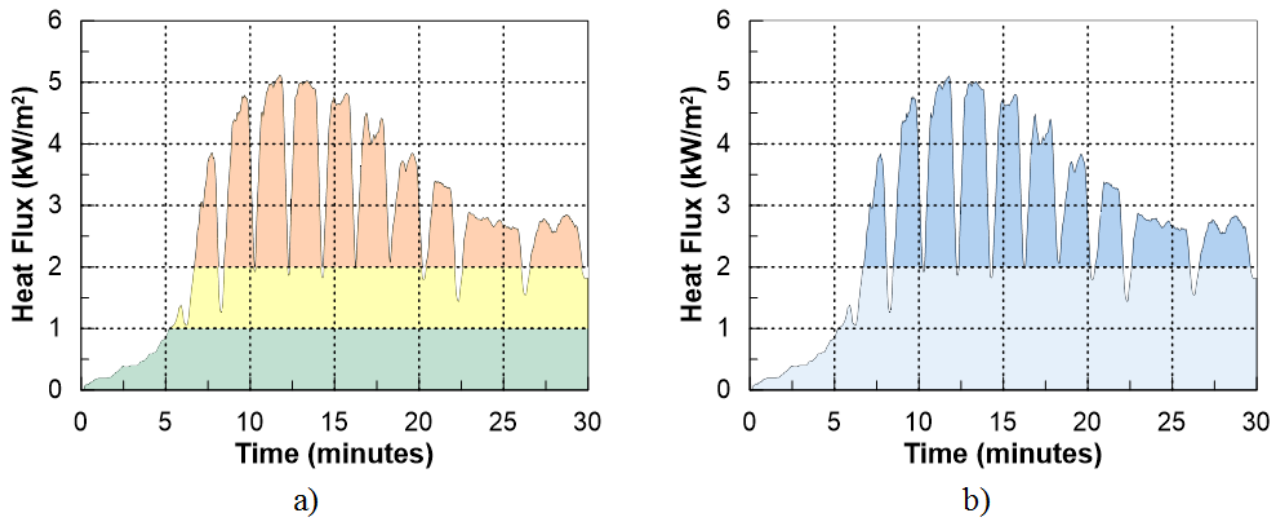


**Figure 92: H3 heat flux for August 10th, 2015 related to: a) Thermal Classes I, II & III; and, b) Routine & Ordinary Operating Conditions [59] [63]**

The standards for firefighter safety proposed here involve the times spent within a range of either temperature or heat flux; therefore, the number of data points within the applicable zones for each set of data is used to determine the operating times. These are represented as blue for fibreboard tests and red for particleboard tests in this Section. The times spent in Thermal Classes I (below 100°C and 1 kw/m$^2$), II (between 100 and 160°C and between 1 and 2 kW/m$^2$) and III (between 160 and 260°C and between 2 and 10 kW/m$^2$) [59] for 10 of the test burns is shown in Figures 93 through 95, respectively.

The times spent in Routine (between 20 and 70°C and between 1 and 2 kW/m$^2$) and Ordinary Conditions (between 70 and 200°C and between 2 and 12 kW/m$^2$) [63] are shown in Figures 96 and 97, respectively along with the time limits defined for each. The times presented in these Figures were assessed based on the respective criteria for the six measurements, two local temperatures and four heat flux measurements, as detailed above.

While many of the particleboard (PB) tests showed excessive time in Thermal Class I based on time spent in environment temperatures below 100°C as shown in Figure 93, this is largely due to so little of the time being spent in more extreme temperature conditions.

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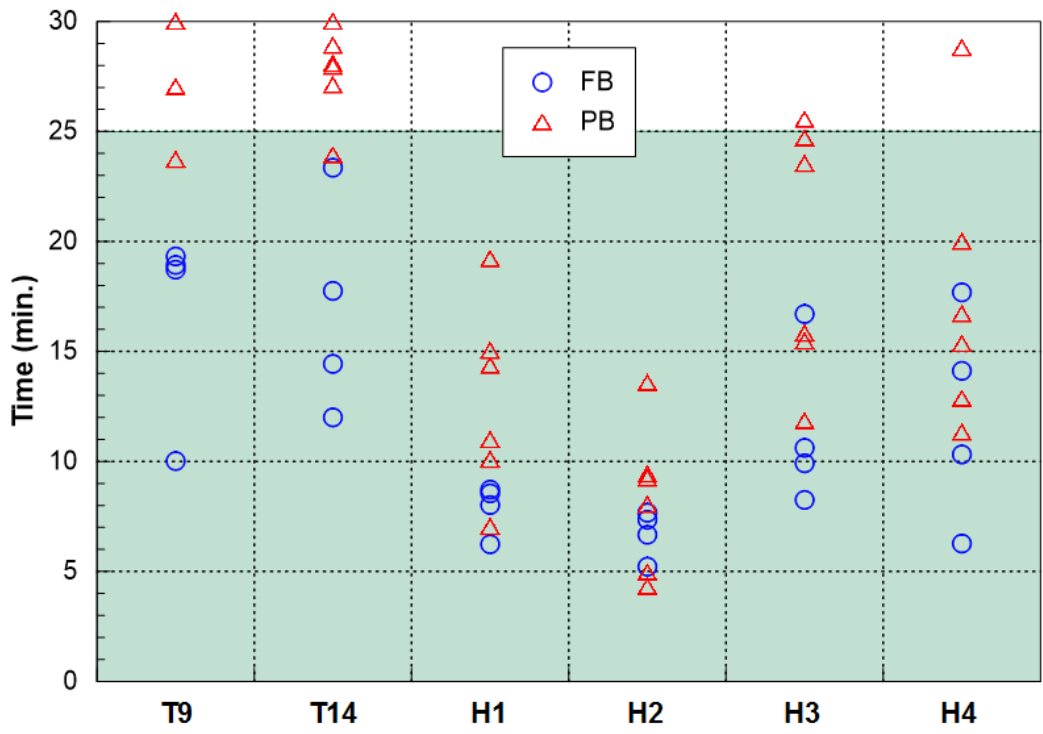
**Figure 93: Time spent in Thermal Class I**
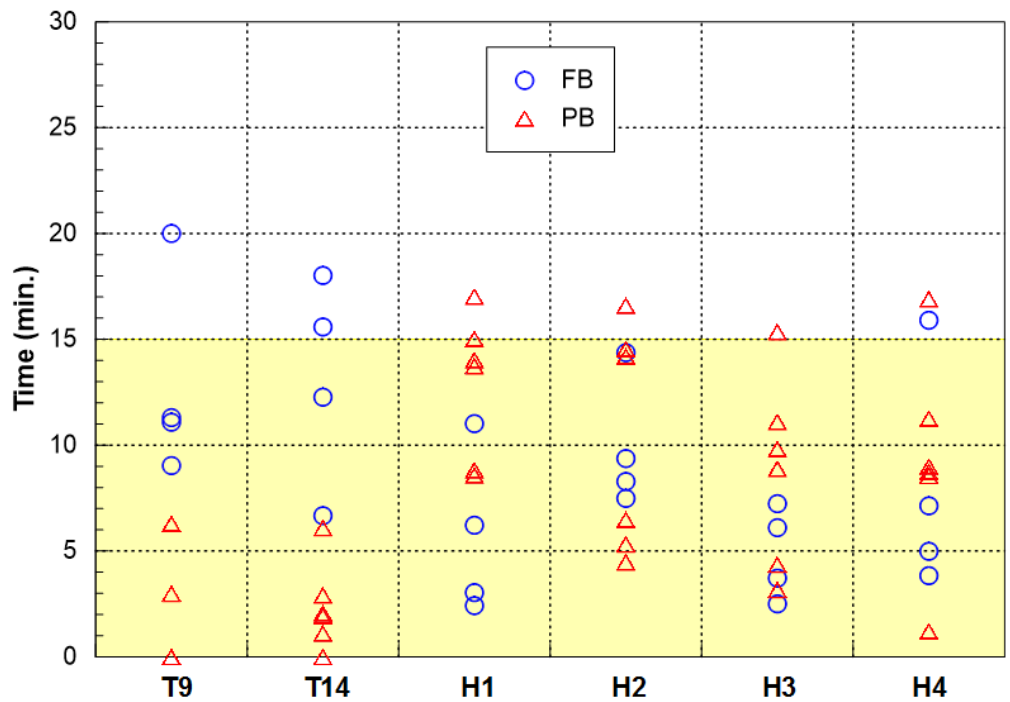


**Figure 94: Time spent in Thermal Class II**
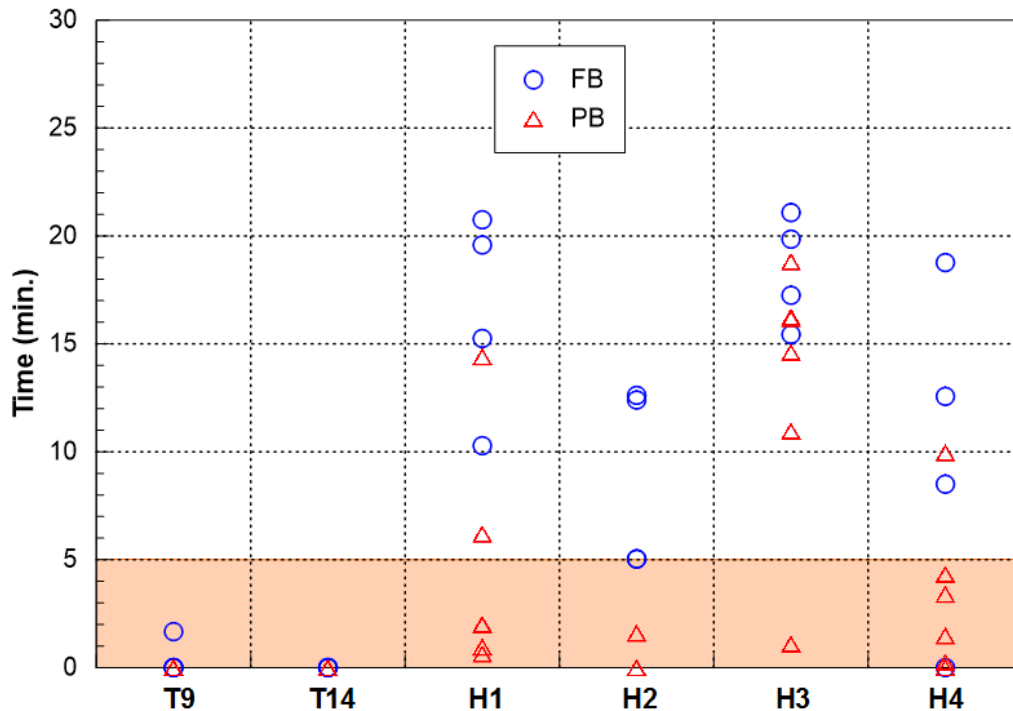
**Figure 95: Time spent in Thermal Class III**

The time spent in Thermal Class II, as shown in Figure 94, exceeds the limit of 15 minutes for several tests under each of the six metrics, although it should be noted that the only tests that exceed this limit based on temperature are those that used fibreboard. Therefore, these would also be some of the earliest tests conducted when the instructors had the least amount of experience in terms of controlling the compartment fire environment. None of the tests exceeded the time limit of five minutes for Thermal Class III based on temperature, as shown in Figure 95, while many of the tests, including all of the ones using fibreboard as the fuel type exceeded the time limit for Thermal Class III based on a threshold heat flux between 2 and 10 kW/m$^2$ for all four HFGs.

The second relevant standard, developed by Utech [63] provides no time limit for operating under the Routine Operating Conditions that are shown in Figure 96. This work expands the Ordinary classification, shown in Figure 97, to include a wider heat flux range while lowering the upper temperature with the allowable time staying the same at 20 minutes when compared to Thermal Class III. The upper heat flux limit goes from 10 kW/m$^2$ to 12 kW/m$^2$, the temperature range expands from 100°C to 130°C while the upper limit is lowered significantly from 260°C to 200°C. The six temperature or heat flux parameters against which the time in this zone exceeds the 20-

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minute limit arise from three tests, and four of those instances arise from a single test. Five of these six instances occurred during tests when fibreboard was used as the fuel.
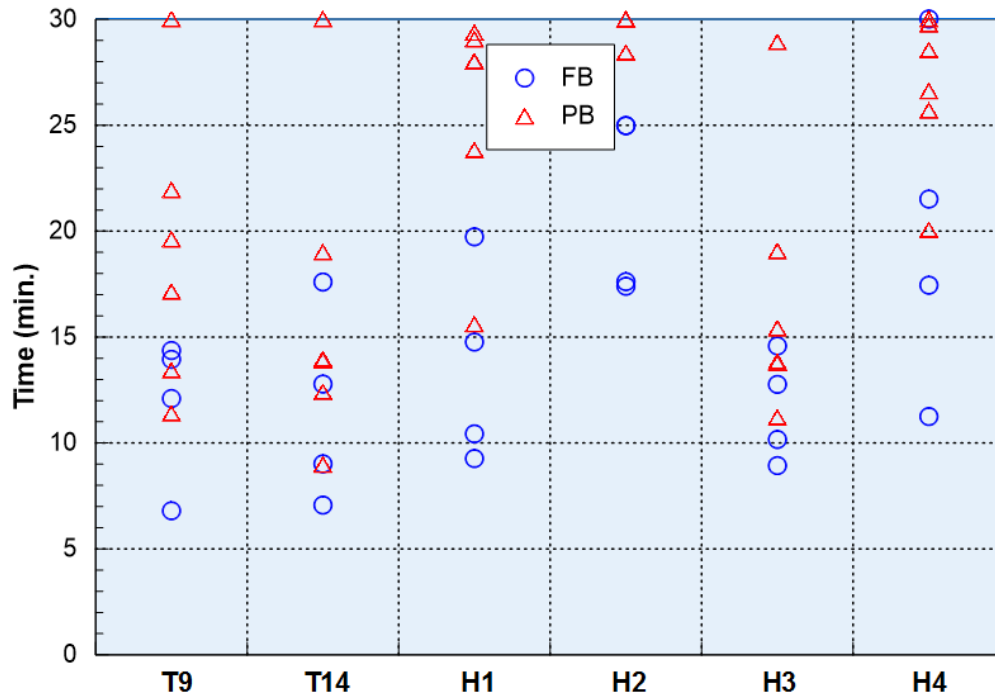


**Figure 96: Time spent in Routine Operating Conditions**
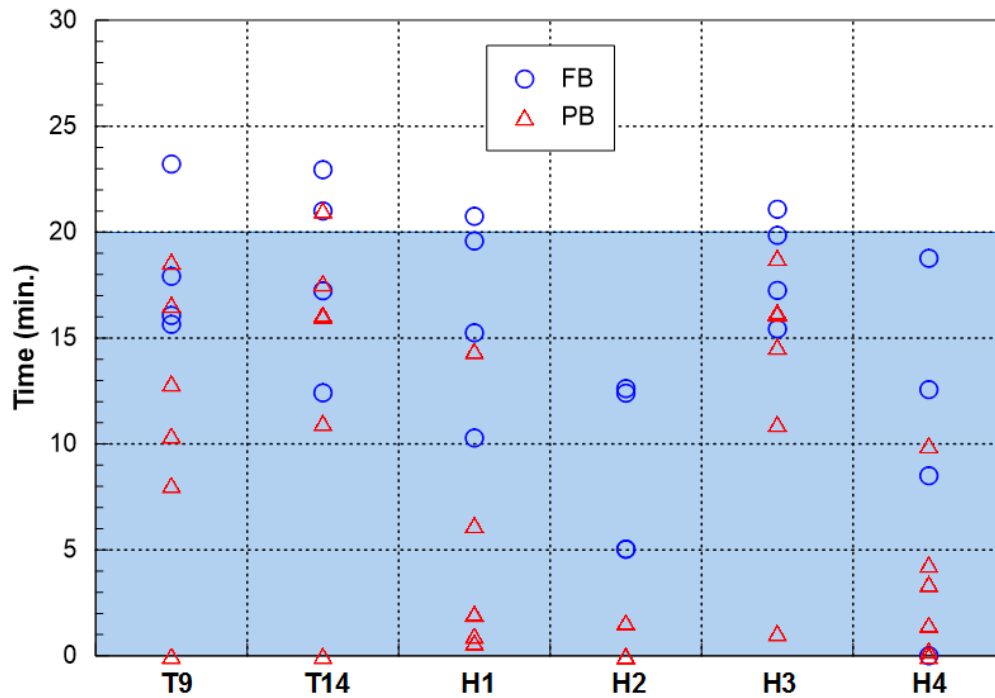


**Figure 97: Time spent in Ordinary Operating Conditions**

A further consideration is that while the exposures for T14 and H3 from the test burn on August 10th, 2015 were used in Figures 91 and 92 as extremes with respect to the operating classes, this burn was neither an extreme example for thermal exposure when considering lower layer temperatures in Section 4.1.3, nor when considering either peak heat flux or total heat transfer for H3 in Section 4.2. The fact that conditions can be considered as extreme based on so many different criteria is an indication that despite the guidance provided by both NIST [58] and Utech [63], there is no single, definitive, set of quantitative criteria for determining safe operating conditions for firefighters.

Given the relatively low maximum and average peak heat flux values recorded by the HFGs, as reviewed in Section 4.2, when compared to the upper end of the range, it is unclear whether the excess time spent in Thermal Class III or Ordinary Operating Conditions presents as severe an exposure as might be suggested; therefore, it becomes important to determine how the time spent in these exposure classes is distributed. Despite the various instances where the times exceeded the limits set by either of the proposed standards [58, 63], no PPE failures or degradation was observed as a result of the actual exposures. More importantly, while firefighters certainly experienced thermal stress during and following these experiments, no firefighters reported even mild first-degree burns following any of the experiments. Qualitatively then, despite these apparently 'excessive' exposures, the operating environment appears to have been safe for participants. Figure 98 shows the average distribution of time spent under exposure to different heat flux values for each of the four HFGs, broken down by type of fuel. Two main conclusions can be drawn from these graphs:

1) The time spent within any thermal classes is almost exclusively spent in the lower 40% of the heat flux range; and,

2) The thermal exposure is higher for the fibreboard test burns than for the particleboard burns.

This distribution towards the lower end of heat flux exposures can also be seen in Figure 92 where, despite considerable time being spent in the operating classes defined by both Thermal Class III and Ordinary Operating Conditions, the peak heat flux is still relatively low. Thermal Class III and Ordinary Operating Conditions are extremely broad as they extend from 2 kW/m$^2$ (only double

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that experienced on a sunny day [64]) up to 10 kW/m$^2$ (an exposure that results in pain to exposed skin in only three seconds [36]) and 12 kW/m$^2$, respectively.
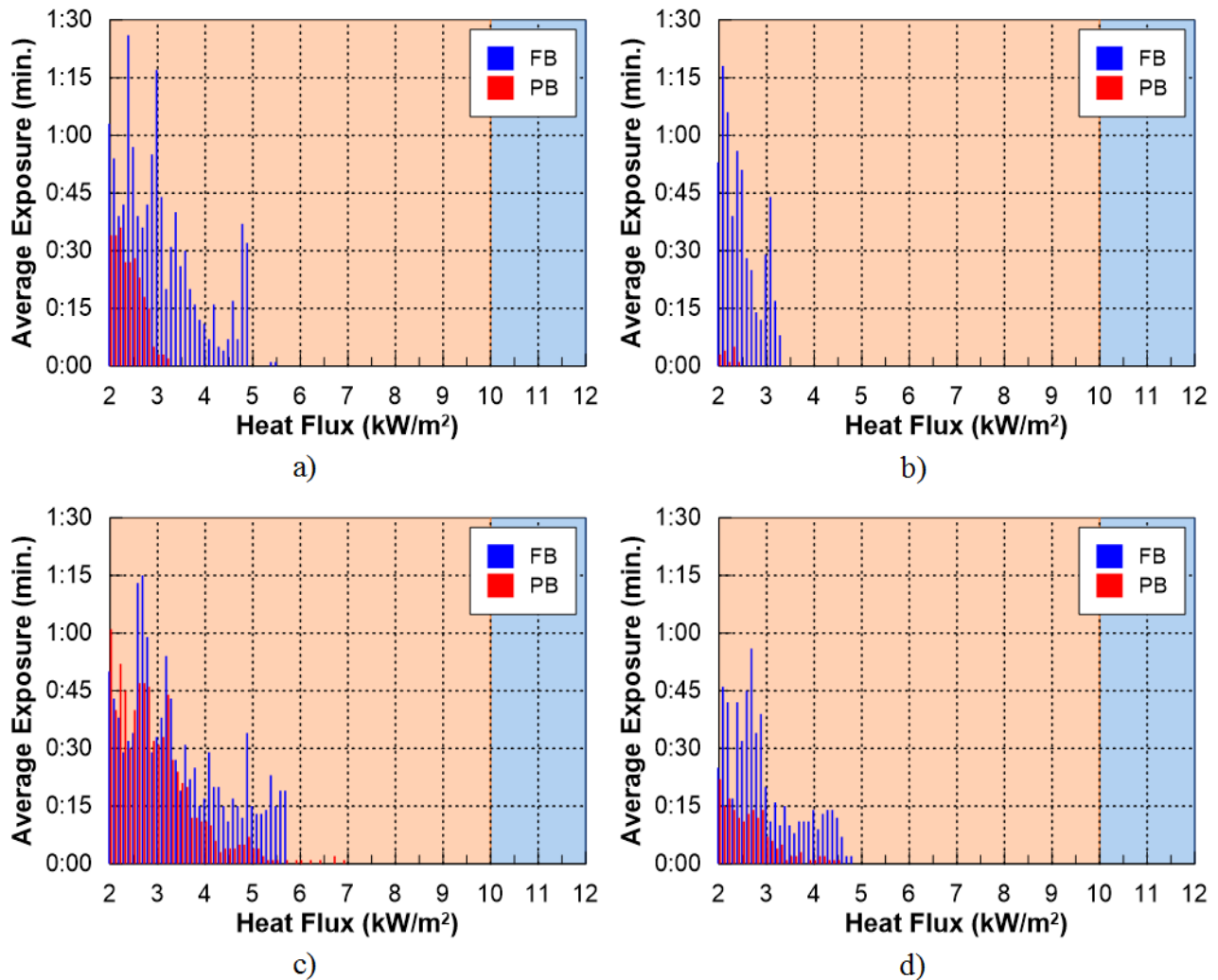


**Figure 98: Average exposure time at different heat fluxes for:**

**a) H1; b) H2; c) H3; and, d) H4**

In terms of heat transfer, 20 minutes spent at the lower limit of these zones would represent a total heat transfer of only 2.4 MJ/m$^2$ compared to 12 MJ/m$^2$ and 14.4 MJ/m$^2$ at their upper limits, respectively. It makes little sense then to consider exposures at these limits to be comparable, and it should also be noted that both of these upper limits are far below the radiant heat flux testing level of 84 kW/m$^2$ for TPP established in NFPA 1971 [55]. Considering that heat flux or temperature in any real fire situation will always fluctuate dynamically with time, a better way to characterize the safety for firefighters might be to reformulate the threshold exposure zones using

an integrated measure of total heat transfer. A time-dose relationship was proposed in the UL study on concrete training structures instead of single values for upper and lower setpoints that might better reflect the transient thermal conditions typical of training simulators [41].

It should be noted at this point that the heat flux and total heat transfer considered here are the values as measured by the instrumented heat flux gauges and do not arise from a model of the heat that might be transferred to a student or instructor situated at an arbitrary location within the EFDS. To consider the latter, a model of the view factors of firefighters in different locations and positions would need to be considered, not only in terms of the EFDS as was developed in Section 3.2.3.1, but considering the firefighters' geometry as well instead of just infinitesimal receptors. An analysis such as this was considered beyond the scope of this research project. Instead, the measurements from the four HFGs are considered as representative of the heat flux during live fire training evolutions for the purpose of discussing how the peak measurements and total heat transfer vary at different locations. Further, a worst-case analysis of any of the four HFGs could be used as a benchmark in the absence of any more involved radiant heat transfer model.

These standards look at how likely temperature and heat flux exposures are to result in injuries such as burns. However, heat stress is also an issue, regardless of the thermal environment [65]; therefore, participants should be monitored closely to ensure they are not exhibiting signs of heat stress following any training, not just live fire training.

### 4.5.3 Temperature and Heat Flux Association

Due to the expense and difficulty in operating HFGs, they are not a viable option for instrumenting live fire training simulators to be used in different jurisdictions. However, as discussed in Sections 2.3.3 and 4.2, heat flux and heat transfer are key metrics in determining the thermal stress experienced by firefighters during training evolutions. Further, instrumentation of live fire simulators is recommended to increase the safety of participants [21, 41]. The question then becomes whether heat flux can be approximated through temperature measurements taken using thermocouples, which are much cheaper, easier to install and operate, and whose data acquisition and analysis are straightforward.

Very little background in this area of research was found in literature, with only one study of tunnel fires by the SP Technical Research Institute of Sweden in 2011 mentioning this explicitly

[122]. How applicable this previous work is to this research project is questionable as the view factor to the sensor at the floor was considered to be 1, given the ceiling of the tunnel was enclosed with flame during these tests.

An attempt to correlate heat flux measurements from each of the four HFGs was undertaken using data from the 10 experiments used for the analysis of the thermal environment in Section 3.2.3. To perform this association a radiant heat transfer model was considered using the equation for radiant heat transfer from one element to another as presented in Section 3.2.3.1:

$$E_{d1-2} = F_{d1-2}\varepsilon\sigma T^4$$
$$\qquad\qquad 4.1\ [33]$$

where $F_{d1-2}$ is the radiation view factor between the two elements, $\varepsilon$ (a dimensionless unit) is the emissivity of surface 2, $\sigma$ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m$^2$K$^4$), and $T$ is the temperature of surface 2 in degrees Kelvin. This Section also showed the consideration of what the view factors would be for each of the four HFGs positioned within the EFDS. Equation 4.1 can be simplified to combine the radiation view factor with the emissivity of the emitting surface as well as be expanded to consider radiative heat transfer from multiple surfaces:

$$E = \sum_j \varepsilon_j \sigma T_j^4$$
$$\qquad\qquad 4.2$$

where $\varepsilon_j$ is a dimensionless value combining the view factor and emissivity of the emitting surface, and $T_j$ is the temperature of that surface. Convective heat transfer was also considered using the equation as presented in Section 3.2.3.2:

$$\dot{q}'' = h\Delta T$$
$$\qquad\qquad 4.3\ [36]$$

where $h$ is the convective heat transfer coefficient, and $\Delta T$ is the temperature difference between the sensor and the convective medium in either K or °C.

The Solver tool in Microsoft® Excel™ was used to perform a least squares optimization between the heat flux measurements from each of the four HFGs and a radiant heat flux model using measurements from up to two of the thermocouples instrumented for the testing. A series of different thermocouple combinations were chosen manually and subsequently fit to the heat flux

data to determine which provided the best fit for each of the HFGs using the effective emmissivities presented in Section 3.2.3.1 to guide which thermocouples might provide the best results. The use of a purely radiant heat flux model seemed appropriate for both H1 and H2, given their location on the floor of the EFDS. However, the question of whether a better fit could be obtained considering a combination of radiant and convective heat flux was examined for H3 and H4. Ultimately, a purely radiant heat flux model was found to provide the best fits for H1, H2, and H3, while a purely convective heat flux model provided the best fit for H4. While the heat flux to H4 will certainly depend on both radiative and conductive contributions, the best fit was found using a purely convective heat flux model based on an effective heat transfer coefficient and a single thermocouple measurement. Fitting H4 with a convective heat flux model is supported by the higher peak heat flux and total heat transfer values measured by H4 when compared to H2, despite the closer proximity of H2 to the seat of the fire and therefore its higher radiation view factors for the ceiling, upper layer and front wall of the EFDS as shown in Table 8. H4 is positioned in close proximity to the rear bulkhead door, where the neutral plane can be lower than the interface height, and where the velocity of hot smoke exiting the EFDS is higher. While the HFG is directed at the front wall of the EFDS, if it is indeed above the neutral plane of the bulkhead door, the effects of convective heat transfer will be increased while the smoke of the upper layer will also impede the HFG from registering heat flux due to radiation from the seat of the fire. Feedback from OFS instructors reinforces the higher heat flux values for H4 in Section 4.2 as consistent with their experiences of experiencing higher heat transfer while situated in this location [123].

After checking many different thermocouples and performing least squares fits on different combinations, five thermocouples were identified that provided the best fits to the heat flux measurements. Heat flux gauge H1 was fit to T6 and T16, H2 was fit to T16 and T17, H3 was fit to T8 and T16, and H4 was fit to T14.

- T6: Rake # 2 at a height of 2.59 m. This thermocouple might represent an approximation of the upper layer temperature, or, might also represent a measurement of the flaming combustion that is present in the vicinity of T6. T6 is located near the center of the viewing angle for H1, so it might also simply provide a good approximation of the average temperature of the gasses near the ceiling across the viewing angle of H1.

- T8: Rake #2 at a height of 1.37 m, which is used with H3. Given the proximity of this thermocouple to H3, and the strong reliance of the output of the simplified radiant heat flux model to this measurement, it appears that H3 is largely affected by the upper layer temperature close to its location. A further extension of this might indicate that heat transfer near or above the interface layer height might well be modelled by a radiant heat transfer model using a temperature measurement at the same location.

- T14: Rake #3 at a height of 0.76 m, which is used to model the heat flux at H4. The close proximity of thermocouple T14 to H4 is supportive of it being a good input into the convective heat transfer model used for this HFG. However, the convection coefficient is quite low when compared to the range of values presented in Section 3.2.3.2, indicating that the association might not be representative of a realistic physical model of heat transfer in this location. Further, the strong reliance of the modelled heat flux for H3 on thermocouple T8 using a radiative heat flux model would provide further evidence against simply considering convection as the sole or necessarily dominant mode of heat transfer for the HFGs located above the interface layer.

- T16: Exterior on the roof of the EFDS above Rake #1, which is used in the modelled heat flux for H1, H2, and H3. The fact that this thermocouple measurement is used in three different heat flux models is interesting. While this might indicate an importance of the EFDS ceiling temperature on the overall heat flux to participants within the EFDS, this isn't a definitive conclusion that the EFDS exterior shell temperature plays a dominant role in the overall radiation to participants.

- T17: Exterior on the roof of the EFDS above Rake #2, which is used to model the heat flux at H3. Once again, any extension of this modelling to the importance of the EFDS ceiling temperature to the heat flux to participants is inconclusive at this point.

The effective emissivities ($\varepsilon$) for each of the thermocouples for H1, H2, and H3 as well as the convective heat coefficient ($h$) and temperature ($T_0$) for H4 as they relate to equations 4.2 and 4.3 are presented for the fibreboard experiments in Table 24 and for the particleboard experiments in Table 25. The results are presented separately for the fibreboard and particleboard tests based on the substantially different average values for each subset of data. The cause of these differences is proposed to be the different smoke characteristics between the two fuels [108], leading to a different emissivity that would affect the contribution to the total radiation view factors of all

internal surfaces. Beyond determining the best heat flux coefficients for each individual test, least squares fits were performed with general coefficients. Development of these general coefficients, if they provide sufficiently good fits, would allow for the prediction of heat flux to live fire training participants in the EFDS without the substantial logistic and cost issues associated with instrumenting training simulators with Gardon gauges.

**Table 24: Heat flux coefficients for fibreboard experiments**

| Date | H1 | | H2 | | H3 | | H4 | |
|---|---|---|---|---|---|---|---|---|
| | $\varepsilon_{16}$ | $\varepsilon_6$ | $\varepsilon_{17}$ | $\varepsilon_{16}$ | $\varepsilon_8$ | $\varepsilon_{16}$ | $h_{14}$ (kW/m$^2$·K) | $T_0$ (°C) |
| 6-Aug-15 | 0.382 | 0.067 | 0.490 | 0.048 | 0.995 | 0.030 | 0.031 | 33.36 |
| 10-Aug-15 | 0.479 | 0.029 | 0.588 | 0.033 | 0.843 | 0.000 | 0.026 | 15.87 |
| 21-Aug-15 | 0.289 | 0.033 | 0.358 | 0.037 | 0.376 | 0.074 | 0.010 | 0.00 |
| 5-Oct-15 | 0.517 | 0.009 | 0.527 | 0.041 | 0.968 | 0.026 | 0.025 | 13.76 |
| Average | 0.417 | 0.034 | 0.491 | 0.040 | 0.795 | 0.032 | 0.023 | 15.75 |

This analysis was only performed for the subset of tests that used particleboard as the fuel based on the different average effective emissivity values and smoke characteristics of the two fuels, as well as the decision within OFS to use particleboard as a fuel for training evolutions going forward. This decision has subsequently been reinforced by the findings of higher heat flux and increased thermal exposure when fibreboard was used as fuel as shown in Sections 4.2 and 4.5.2, respectively; however, the question about whether, or to what extent, these findings are related to the experience level of instructors still remains. General coefficients were determined in two ways:

- By simply taking the average values of the individual coefficients determined across the set of six tests; and,
- By performing a second least squares fit of data for a given HFG across all six experiments.

The coefficients that were determined using both methods are shown in the bottom two rows of Table 25. The errors between the heat flux measurements and the fits using each of these sets of coefficients and the thermocouple temperature data identified above are presented in Table 25 based on the total heat transfer during a given experiment. Performing a least-squares fit of all the experiments, instead of using the average values, had a modest effect on the error in modelled vs.

measured results, and the values determined using this method will be used subsequently for further analysis.

**Table 25: Heat flux coefficients for particleboard experiments**

| Date | H1 | | H2 | | H3 | | H4 | |
|---|---|---|---|---|---|---|---|---|
| | $\varepsilon_{16}$ | $\varepsilon_6$ | $\varepsilon_{17}$ | $\varepsilon_{16}$ | $\varepsilon_8$ | $\varepsilon_{16}$ | $h_{14}$ (kW/m$^2$·K) | $T_0$ (°C) |
| 6-Jun-17 | 0.109 | 0.158 | 0.122 | 0.081 | 0.337 | 0.141 | 0.019 | 18.4 |
| 13-Jun-17 | 0.182 | 0.107 | 0.134 | 0.097 | 0.441 | 0.125 | 0.029 | 46.1 |
| 19-Jun-17 | 0.117 | 0.149 | 0.113 | 0.079 | 0.461 | 0.136 | 0.021 | 24.3 |
| 5-Jul-17 | 0.205 | 0.103 | 0.252 | 0.059 | 0.791 | 0.137 | 0.035 | 36.1 |
| 6-Jul-17 | 0.104 | 0.109 | 0.096 | 0.071 | 1.039 | 0.115 | 0.035 | 36.0 |
| 11-Jul-17 | 0.122 | 0.095 | 0.227 | 0.042 | 0.535 | 0.254 | 0.053 | 52.4 |
| Average | 0.140 | 0.120 | 0.157 | 0.071 | 0.601 | 0.151 | 0.032 | 35.6 |
| LSF | 0.123 | 0.124 | 0.139 | 0.071 | 0.855 | 0.092 | 0.029 | 32.2 |

As previously discussed in Section 4.5.1, the accuracy of a fit can be affected both by instantaneous differences between measured and modelled heat flux, as well as an overall bias error. The overall bias error is represented as the minimum and maximum values of association error in the last two rows of Table 26. However, measurement of both heat flux and temperature are subject to measurement uncertainty; therefore, looking at the error in measurement for the total heat flux might not be representative of the quality of this model. Another method to assess the quality of the fit between the measured and modelled heat flux is to review the difference between the modelled versus measured values for each heat flux gauge. This method considers the combined measurement uncertainty in both temperature as used in the model, and heat flux, as the comparative value. To investigate this further, a count of the amount of time that the measured values of heat flux and the modelled values of heat flux lay within the envelope of values determined using the respective uncertainties was also determined. This was then represented as a percentage of the total burn time of 30 minutes with the values as shown in Table 27. The uncertainty of the measured heat flux was simply taken as the ±8.6% identified in Section 3.2.2 while the measurement uncertainty for the modelled heat flux was determined by calculating the modelled heat flux using temperatures ±7.7°C from the measured values. It can be seen that when

measurement uncertainties are accounted for, the modelled heat flux values and the heat flux measured are within the envelope of their respective uncertainties.

**Table 26: Percentage error in association of total heat flux to each gauge using different optimization techniques**

| Date | Heat Transfer (MJ/m$^2$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | H1 Error (%) | | H2 Error (%) | | H3 Error (%) | | H4 Error (%) | |
| | Avg. | LSF | Avg. | LSF | Avg. | LSF | Avg. | LSF |
| 6-Jun-17 | 83% | 81% | 99% | 94% | 132% | 128% | 70% | 79% |
| 13-Jun-17 | 92% | 90% | 81% | 77% | 132% | 132% | 145% | 141% |
| 19-Jun-17 | 90% | 87% | 104% | 99% | 124% | 122% | 119% | 116% |
| 5-Jul-17 | 91% | 89% | 84% | 80% | 92% | 97% | 92% | 88% |
| 6-Jul-17 | 130% | 126% | 126% | 119% | 80% | 83% | 84% | 83% |
| 11-Jul-17 | 118% | 115% | 103% | 98% | 79% | 82% | 97% | 95% |
| Min. | 83% | 81% | 81% | 77% | 79% | 82% | 70% | 79% |
| Max. | 130% | 126% | 126% | 119% | 132% | 132% | 145% | 141% |

**Table 27: Association accuracy including measurement errors**

| Date | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| 6-Jun-17 | 28% | 18% | 31% | 79% |
| 13-Jun-17 | 24% | 4% | 20% | 50% |
| 19-Jun-17 | 41% | 31% | 19% | 69% |
| 5-Jul-17 | 36% | 21% | 17% | 49% |
| 6-Jul-17 | 29% | 47% | 46% | 57% |
| 11-Jul-17 | 25% | 23% | 36% | 50% |

The effective emissivities determined by the modelled heat flux are presented in the top four rows in Table 28 and compared to the effective emissivities that were calculated based on the radiation view factors in Section 3.2.3.1. The equation for determining heat flux to H1 as given by 4.4, with the resulting worst and best fits for H1, based on assessment of the total heat transfer across the full duration of the burn are presented in Figure 99 along with their associated measurement

uncertainties. Similarly, the heat flux for H2 is modelled with T6 and T17, once again correlating well due to the importance of the upper layer and ceiling in the radiation view factors for this heat flux gauge.

**Table 28: Effective emissivities for H1, H2, and H3**

| Surface | Effective Emissivities | | |
|---|---|---|---|
| | H1 | H2 | H3 |
| Upper Layer | 0.192 | 0.197 | 0.131 |
| Ceiling | 0.144 | 0.157 | 0.133 |
| Front Wall | 0.009 | 0.003 | 0.081 |
| Side Walls | 0.453 | 0.410 | 0.381 |
| T6 | 0.124 | 0.071 | 0.092 |
| T8 | - | - | 0.855 |
| T14 | - | - | - |
| T16 | 0.123 | - | - |
| T17 | - | 0.139 | - |

$$HF_1 = 0.124\sigma T^4_{tc6} + 0.123\sigma T^4_{tc16} \qquad\qquad 4.4$$



a)



b)
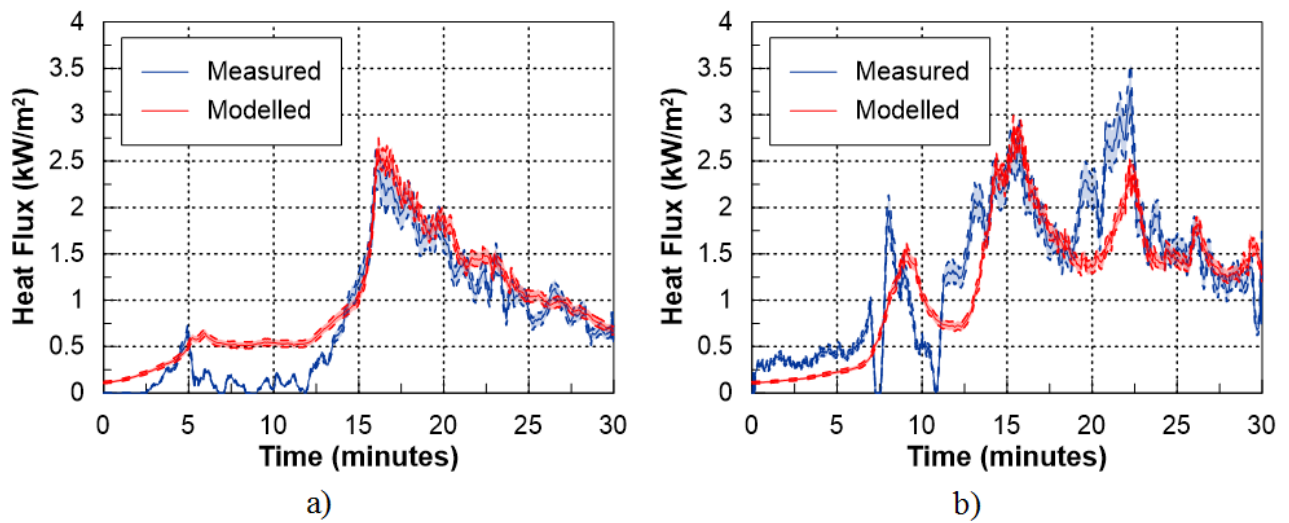
**Figure 99: Heat flux association for H1: a) worst case; and, b) best case**

H2 depends on T17 in lieu of T16, which is understandable given that T17 is in closer proximity to H2. Also, H2 shows less dependence on the temperature data from T6, which is also consistent with the lower view factor it would have of radiation from that position. The equation for determining heat flux to H2 as given by equation 4.5, with the resulting worst and best fits for H1, based on assessment of the total heat transfer across the full duration of the burn are presented in Figure 100 along with their associated measurement uncertainties.

$$HF_2 = 0.071\sigma T_{tc6}^4 + 0.139\sigma T_{tc17}^4 \qquad\qquad 4.5$$
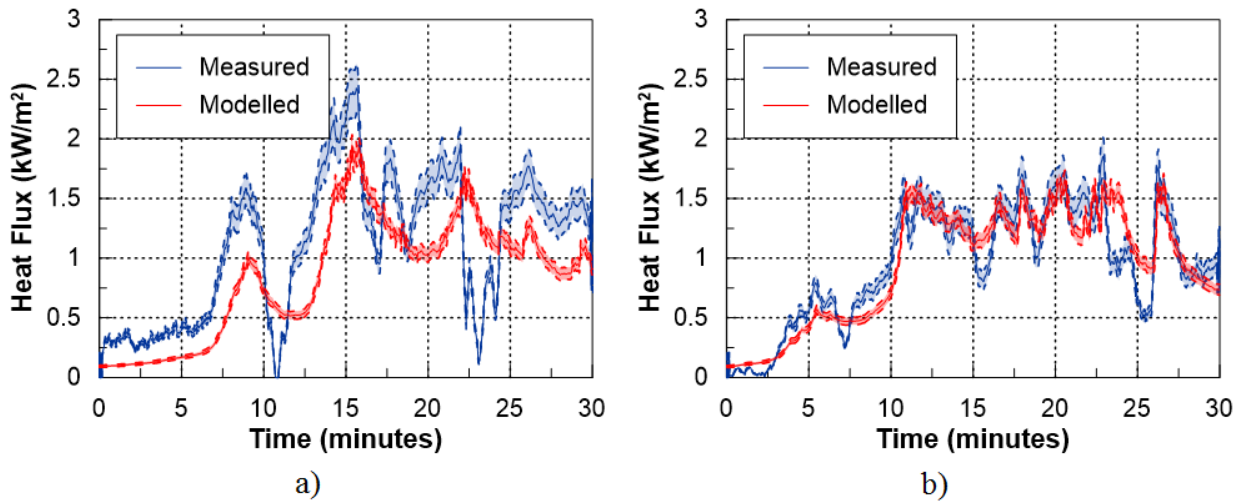


**Figure 100: Heat flux association for H2: a) worst case; and, b) best case**

The heat flux for H3 is very strongly dependent on T8, and once again T6 is a contributor. T8 is the closest thermocouple to H3, and would explain the very high effective emissivity value for this contribution, while T6 once again gives a measurement of the radiation close to the seat of the fire. The equation for determining heat flux to H3 as given by equation 4.6, with the resulting worst and best fits for H1, based on assessment of the total heat transfer across the full duration of the burn are presented in Figure 101 along with their associated measurement uncertainties.

Heat flux to H4 was modelled as convective heat transfer, while the value for the convective coefficient used in this equation, along with those presented in Table 24 and Table 25, are much lower than the range that was discussed in Section 3.2.3.2, the value for the temperature of the receiver is reasonable. The low value for the convective coefficient might indicate that the choice to fit H4 with a convective model works only superficially, while not representing a realistic physical model for the heat transfer to this sensor. The equation for determining heat flux to H3 as

given by equation 4.7, with the resulting worst and best fits for H1, based on assessment of the total heat transfer across the full duration of the burn are presented in Figure 102 along with their associated measurement uncertainties.

$$HF_3 = 0.092\sigma T_{tc6}^4 + 0.855\sigma T_{tc8}^4 \qquad\qquad 4.6$$



a)                                          b)
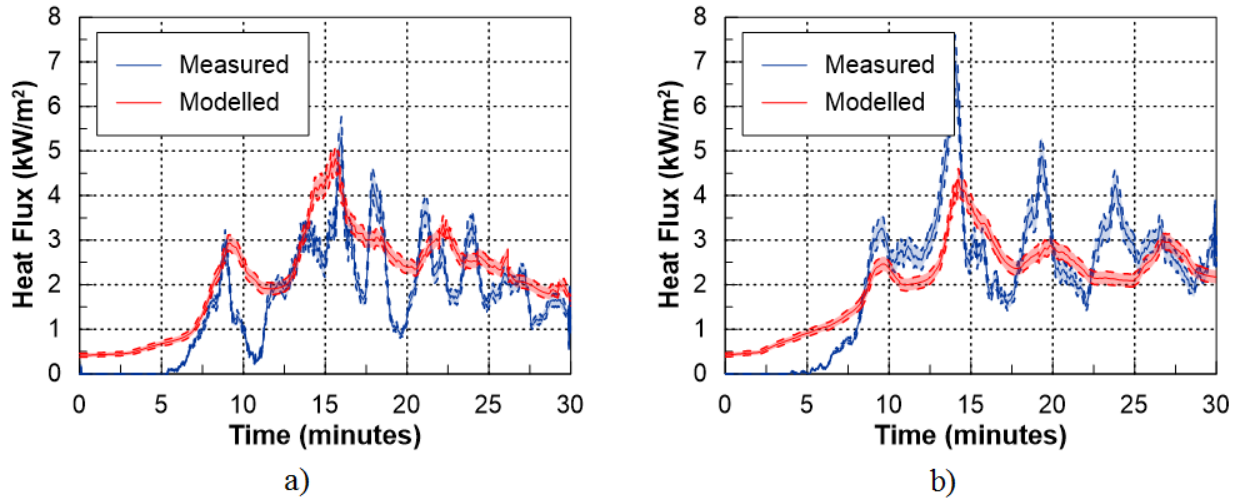
**Figure 101: Heat flux association for H3: a) worst case; and, b) best case**

$$\dot{HF}_4 = 0.029(T_{tc14} - 305.2) \qquad\qquad 4.7$$



a)                                          b)
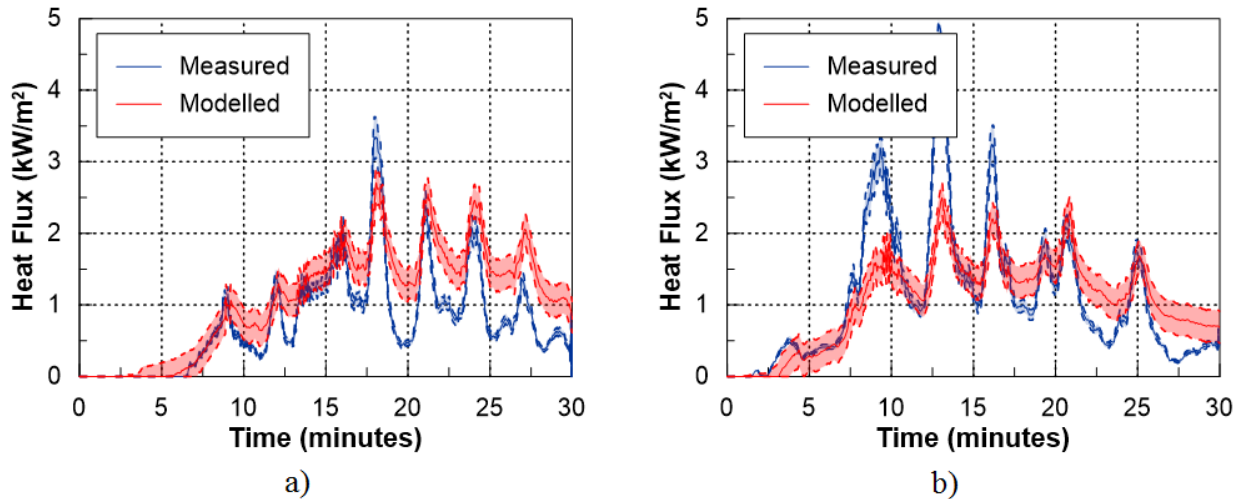
**Figure 102: Heat flux association for H4: a) worst case; and, b) best case**

While the associations presented above use either a solely radiative or convective heat transfer model, in reality heat transfer will be a combination of conduction, convection, and radiation. The correlations are derived based on the estimated total heat transfer that occurs throughout the burns

rather than being tailored to predict peak heat transfer values as can be seen in Figure 99 through Figure 102. The prioritization towards estimates of total heat transfer over peak heat flux is discussed extensively in Section 4.5.2, and supported by the fact that the peak heat flux values are well within the thermal operating classes used in that Section [58, 63], as well as well below the peak values identified in the guidance for PPE identified by various NFPA guidelines [55, 56, 57].

While reasonable fits were obtained between measured heat flux and radiative and convective heat transfer were calculated using a simplified model with limited number of temperature measurements, this should not be interpreted as emphasizing the importance of a temperature measured by a given thermocouple or its associated element as identified in Section 3.2.3. Thermocouples provide a measurement of the temperature only in the immediate vicinity of the sensor, and extending these measurements to represent a large surface is obviously only an approximation, as can be seen by the temperature differences shown in Figure 67. However, these modelled heat fluxes and their respective correlations must be considered in light of one of the primary goals of this research project: to provide guidance that will increase safety for participants using live fire training simulators such as the EFDS. As such, the priority is to develop a simplified instrumentation plan that might be implemented in other jurisdictions at minimal cost and that requires minimal data acquisition expertise. This goal has been met through the development of the generalized correlations discussed above. It is however important not to extend these correlations to imply high levels of quantitative accuracy or the relative importance of a given thermocouple measurement with respect to overall heat transfer to participants in every training situation.

## 4.6 Effect of Ambient Conditions on the Fire Environment

The effects of ambient conditions on the fire environment were analyzed using two metrics: heat flux to each of the four heat flux gauges, and the time taken for the upper layer to achieve and remain above 200°C as approximated by thermocouple T7 and discussed in Section 4.5.1. This temperature threshold is an arbitrary temperature chosen because the average upper layer temperatures often did not rise to the previous benchmarks of 320°C and 550°C [36]. Table 29 presents the heat flux at the four HFGs along with the ambient temperature and relative humidity. Figure 103 shows the total heat transfer to each of the four HFGs as a function of ambient temperature, while Figure 104 does the same for relative humidity.

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**Table 29: Effect of ambient conditions on heat transfer**

| Date | Temperature (°C) | Humidity (%) | Fuel type | Total Heat Transfer (MJ/m$^2$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | H1 | H2 | H3 | H4 |
| 6-Aug-15 | 23.9 | 44 | FB | 3.12 | 1.98 | 4.00 | 2.29 |
| 10-Aug-15 | 25.5 | 44 | FB | 4.03 | 2.90 | 4.79 | 4.17 |
| 21-Aug-15 | 24.2 | 62 | FB | 3.04 | 2.26 | 3.41 | 1.65 |
| 5-Oct-15 | 14.9 | 59 | FB | 4.67 | 2.98 | 5.52 | 2.85 |
| 6-Jun-17 | 23.0 | 53 | PB | 2.53 | 2.61 | 3.32 | 1.86 |
| 13-Jun-17 | 14.8 | 88 | PB | 1.79 | 1.08 | 1.83 | 0.82 |
| 15-Jun-17 | 24.2 | 59 | PB | 2.39 | 2.00 | 2.91 | 1.37 |
| 19-Jun-17 | 21.4 | 38 | PB | 2.35 | 1.62 | 2.24 | 1.56 |
| 5-Jul-17 | 25.0 | 38 | PB | 2.15 | 1.56 | 3.87 | 2.65 |
| 6-Jul-17 | 25.6 | 54 | PB | 1.36 | 0.96 | 3.87 | 2.09 |
| 11-Jul-17 | 24.5 | 74 | PB | 1.73 | 1.26 | 4.15 | 1.99 |

Table 30 presents the times taken for the upper layer temperature to reach 200°C, as well as the time at 200°C, again with ambient temperature and relative humidity, while plots of the two times against ambient temperature are shown in Figure 105 and against relative humidity in Figure 106. The effects of ambient conditions on total heat transfer were examined for a smaller number of tests due to missing and erroneous heat flux data during tests conducted in 2016. Note: All plots in this Section present tests using fibreboard as blue circles and those using particleboard as red triangles.

While a separate analysis of the role of fuel type was not presented in Section 4.4.2 some general trends are observable here. Total heat flux is generally higher for the tests using fibreboard as a fuel, although differences between the two fuels as they relate to upper layer conditions is less clear. It should be noted that most of the fibreboard tests were conducted earlier in the research project when the OFS instructors involved were less experienced. As such, these higher heat transfer values might also be partially associated with instructor experience rather than entirely with the fuel type. However, both the OFS instructor cadre as well as the SMEs reported that the

fibreboard fires were more difficult to control, while producing smoke with lower optical density [108]. These observations would support the finding of higher total heat transfer across those tests.
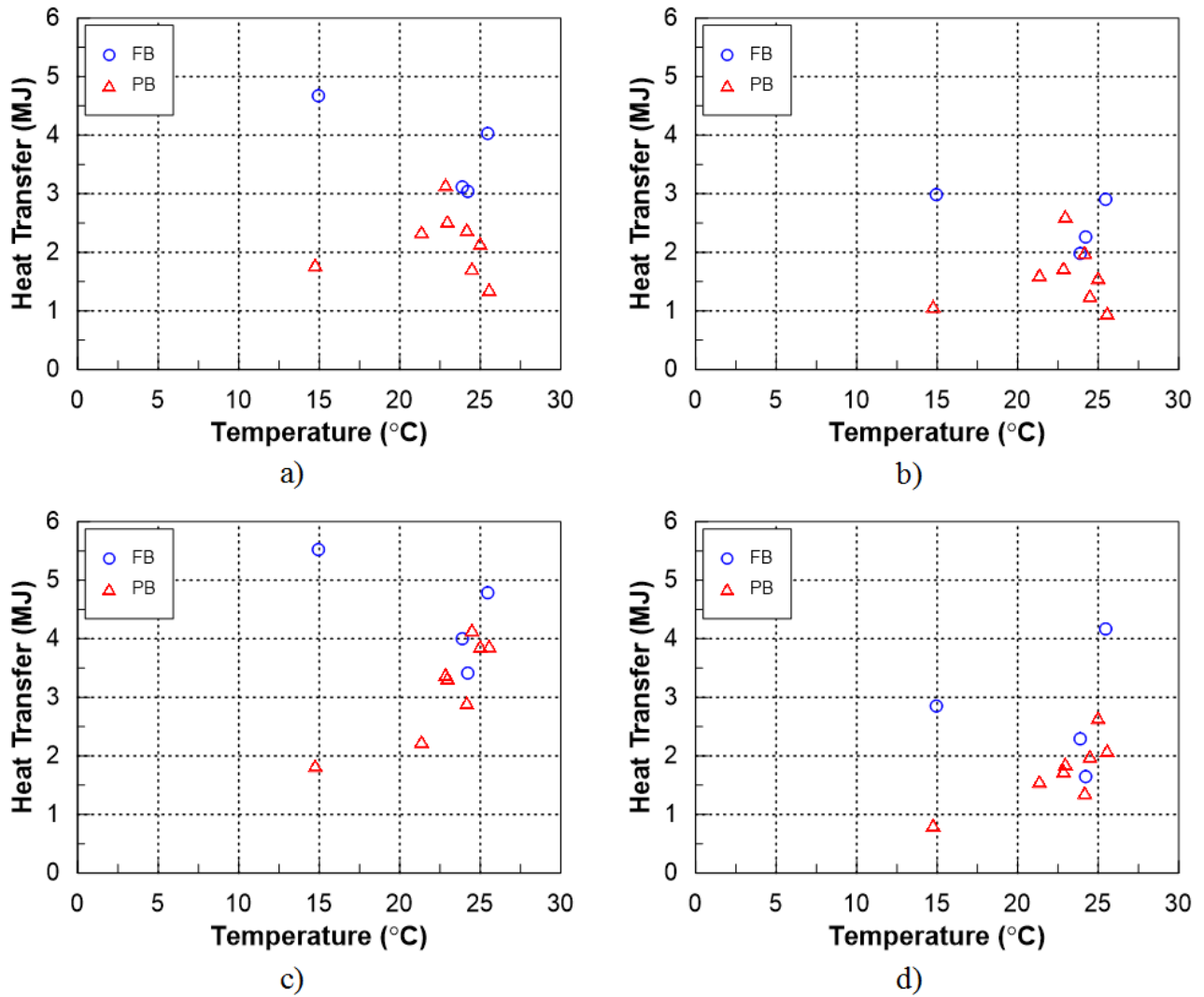


**Figure 103: Effect of ambient temperature on total heat transfer for fiberboard (FB) and particleboard (PB) for: a) H1; b) H2; c) H3; and, d) H4**
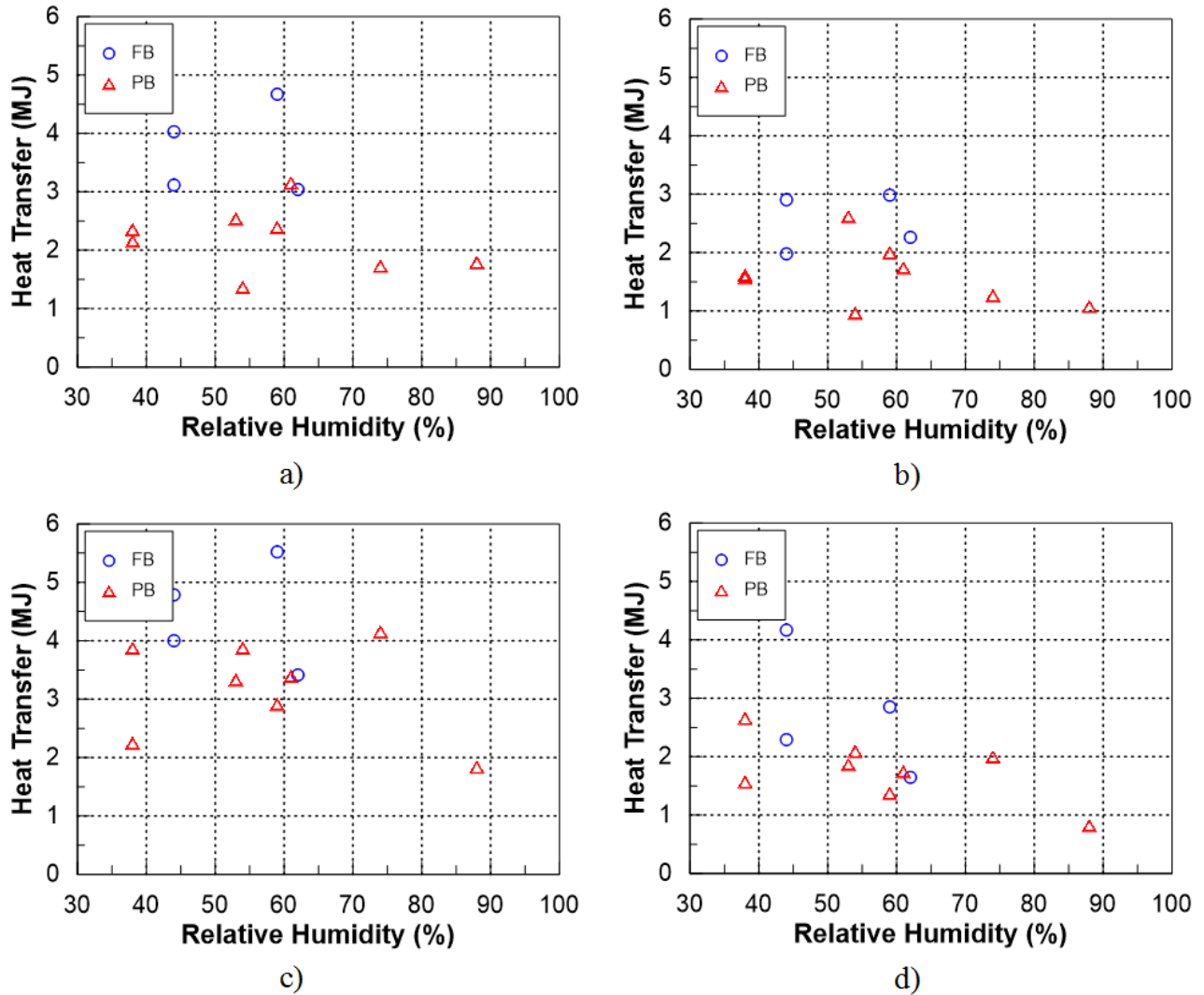
**Figure 104: Effect of relative humidity on total heat transfer for fiberboard (FB) and particleboard (PB): a) H1; b) H2; c) H3; and, d) H4**

While some general trends related to the impact of ambient conditions on the fire environment might be observable, the association appears to be low, and it should be remembered that many other variables were changing during these experiments as well. Perhaps the strongest association can be seen between the time for the upper layer to reach 200°C and the ambient temperature as shown in Figure 105a. In general, and not unexpectedly, the upper layer takes longer to reach this temperature as ambient temperatures decrease.

**Table 30: Effect of ambient conditions on the upper layer**

| Date | Temperature (°C) | Humidity (%) | Fuel Type | Time to 200°C | Time above 200°C |
|------|------------------|--------------|-----------|---------------|------------------|
| 2015-08-06 | 23.9 | 44 | FB | 11:56 | 06:57 |
| 2015-08-10 | 25.5 | 44 | FB | 06:27 | 23:32 |
| 2015-08-21 | 24.2 | 62 | FB | 08:25 | 21:36 |
| 2015-10-05 | 14.9 | 59 | FB | 08:57 | 21:04 |
| 2015-10-06 | 15.0 | 67 | FB | 05:56 | 20:43 |
| 2016-10-12 | 12.8 | 46 | PB | 09:00 | 21:01 |
| 2016-10-20 | 10.9 | 93 | FB | 14:33 | 11:36 |
| 2016-10-21 | 9.7 | 90 | FB | 19:15 | 10:46 |
| 2016-11-03 | 8.3 | 94 | FB | 06:14 | 22:33 |
| 2016-11-04 | 2.1 | 72 | PB | 18:28 | 11:26 |
| 2016-11-07 | 6.2 | 76 | PB | 20:16 | 09:45 |
| 2016-11-09 | 8.6 | 53 | PB | 17:01 | 12:56 |
| 2017-05-31 | 23.0 | 53 | PB | 08:26 | 19:49 |
| 2017-06-06 | 14.8 | 88 | PB | 12:04 | 07:45 |
| 2017-06-13 | 24.2 | 59 | PB | 07:54 | 21:56 |
| 2017-06-15 | 21.4 | 38 | PB | 11:20 | 17:11 |
| 2017-06-19 | 22.9 | 61 | PB | 09:16 | 20:14 |
| 2017-07-05 | 25.0 | 38 | PB | 08:27 | 19:06 |
| 2017-07-06 | 25.6 | 54 | PB | 14:32 | 08:55 |
| 2017-07-11 | 24.5 | 74 | PB | 08:53 | 12:56 |
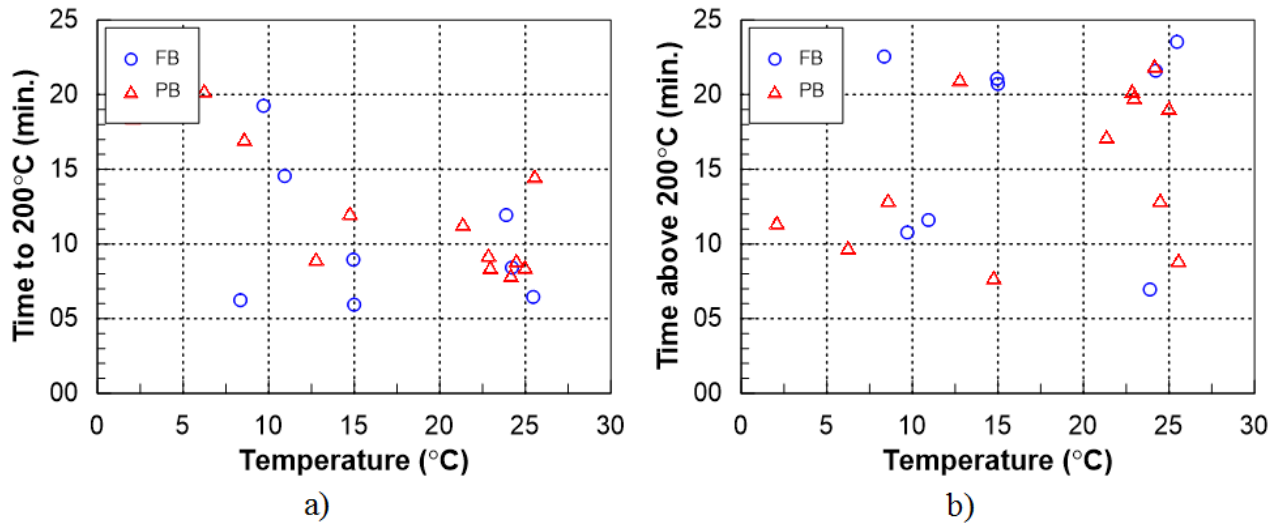
**Figure 105: Effect of ambient temperature on the upper layer:**

**a) time to reach 200°C; and, b) time above 200°C**
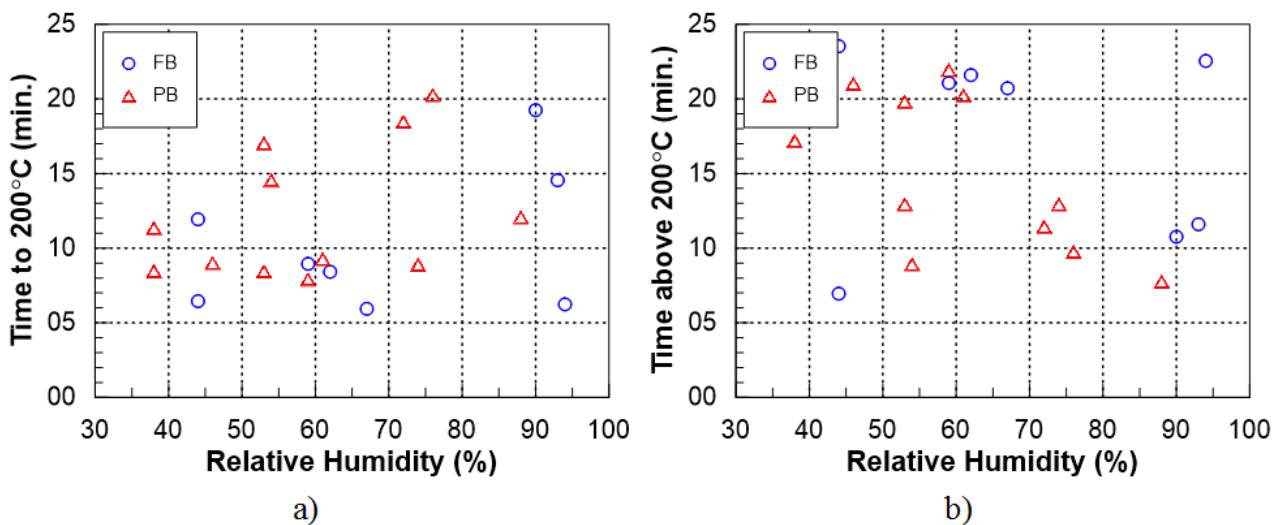


**Figure 106: Effect of relative humidity on the upper layer:**

**a) time to reach 200°C; and, b) time above 200°C**

Upper layer temperatures in the EFDS under a variety of different conditions were modelled using NIST's Consolidated Model of Fire and Smoke Transport (CFAST) in a research project by the author for ME 765: Advanced Enclosure Fires [124] and the results are shown in Figure 107 and described in greater detail in Appendix D – CFAST Modelling. Consistent with the present data, this modelling work predicted that the fire development would be slowed due to lower ambient temperatures, but interestingly that peak temperatures would be higher. The increase in fire

development time is not surprising, as in lower temperatures, both the air and the EFDS are cooler, and act as a heat sink for the developing fire.
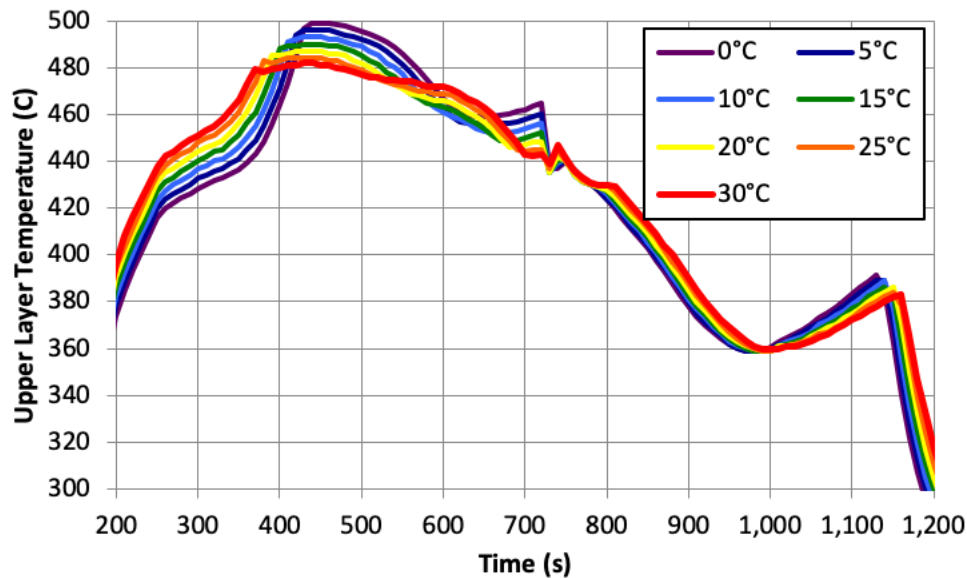


**Figure 107: CFAST modelling of time-dependent upper layer temperature variations due to ambient temperature changes in the EFDS [124]**

Humidity could presumably play a similar role, as might wind direction. As all three of these ambient variables might affect the fire development, a more detailed investigation into how ambient conditions affect fire development and conditions might seek to combine their contributions as heat lost from the enclosure. Such an investigation is beyond the scope of this research project; however, the following guidance can be provided to instructors using simulators such as the EFDS.

1) The fuel loads that were tested were able to achieve suitable fire conditions to achieve the learning objectives independent of the ambient conditions during these tests. There is little need to add additional fuel, and the total fuel load should be maintained according to an organization's safety documents [23].

2) Instructors should be aware of longer fire development times in cold and/or damp conditions and adjust their teaching appropriately. In particular, instructors should monitor this increased fire development time as it relates to the duration of air provided by participants' SCBA.

The range of ambient temperatures and relative humidities included in the present set of tests is representative of the training environment in Ottawa, and likely to that in many other Canadian jurisdictions. This range extends from just above 0°C to just below 30°C. Below freezing, live fire training becomes difficult as the water in hoses can freeze, and there is a significant increase in slip hazards from ice. As the ambient temperature increases, the risk of heat injury to participants increases. Within the OFS, there is an upper limit of 30°C with humidex for any physical training [125]. As such, the characterization of the fire environment was conducted over the whole range of temperatures that can be expected for training evolutions.

The EFDS was moved from the inside testing area at the NRC's Mississippi Mills facility to an outside location run by Ottawa Fire Services. The first five burns (between October 12th and October 21st, 2016) that were conducted at this new location were done prior to the installation of a roof on the EFDS. Given the problems in heat flux data collection during this period, a more complete analysis of the effect of this roof has not been undertaken. Another complicating factor is that the roof is intended to mitigate the effects of weather, particularly precipitation, but there is no way to duplicate ambient conditions, or indeed firefighter interactions to allow for a rigorous analysis of the effects of the addition of the roof. As such, no further analysis of this feature will be conducted in this research project.

## 4.7 Summary

The goal of the FKTP Project was to provide a curriculum for the Canadian Fire Service that addressed perceived gaps between the fire science community and frontline firefighters. The development of the EFDS, along with guidance on fuel loads, training evolutions, and safety recommendations, were intended to complement an in-class curriculum. As such, the lessons learned from this research project are intended to inform other agencies if they choose to construct similar training simulators and use the provided lesson plans. In testing with so many different variables, the research project has been able to characterize the fire environment over a range of conditions that reflects some of the variations that can be expected to be experienced during training, both in Ottawa as well as in other jurisdictions.

While the adoption of a steel jig to reduce the labour associated with building wood cribs looks to result in slower fire growth in the first 5-10 minutes of the burn, any impact on the fire

environment for the remainder of the burn is less clear. While the fuel type and configuration were not analyzed specifically, the data presented to characterize the thermal environment, as well as to compare differences in that environment resulting from ambient conditions, demonstrate that the fibreboard fuel was associated with test burns with increased temperature and heat flux over the particleboard fuel. Testing in different weather demonstrates the ability of the EFDS to operate in a range of conditions, while changing the crib design and fuel load demonstrate that the training environment is relatively insensitive to many of these changes.

Upper layer temperature, lower layer temperature, and heat flux at the positions and orientations for the four heat flux gauges that were used in this research project were used to characterize the fire environment. While the operating time exceeded the recommendations of both NIST Technical Note 1474 [59] and Utech [63], an argument can be made that both of these present overly conservative guidance on appropriate levels of heat exposure, based on both the lack of injury to participants of this research project as well as a more detailed breakdown of the heat flux exposure during the burns.

# Chapter 5: Conclusion

In conclusion, the project goals will be reviewed, alongside a discussion of the EFDS design and fuel load from Chapter 3, and key results from Chapter 4. Following that, recommendations for future work that might extend or improve the results will be discussed.

## 5.1 Review of Project Goals

This project was closely associated with the FKTP Project and was motivated by the desire to provide the characterizations and documented evolutions necessary to provide evidence-based guidance on live fire training simulators for the Canadian Fire Service. Towards this end, the project goals as outlined in Chapter 3 are as follows:

1) Test and characterize different fuels and fuel configurations to achieve a learning environment that meets the learning objectives of certain training evolutions.

2) Understand how sensitive the fire environment is to a range of different fuel types and configurations and thereby recommend a fuel type and configuration for the fire service end users.

3) Characterize and document the range of conditions that are experienced by both instructors and students during the test burns to ensure that the training environment meets safety requirements.

4) Based on objectives 1) through 3), recommend a design for the EFDS including improvements to interior and exterior features seen in comparable training units and specifically with respect to ease of use related to operation in Canadian weather.

5) Develop and provide guidance on a simple instrumentation plan that can improve safety for participants and be reviewed to help to achieve learning objectives and improve instructor capabilities. Such instrumentation is currently required in the United Kingdom, but not in other jurisdictions [21], although recent work by the UL FSRI recommends instrumentation as well [41].

6) Determine that the final design is in full compliance with the existing guidance laid-out in NFPA 1403 for live fire training [6], as well as anticipating future developments that may be required to improve safety and hygiene of both instructors and trainees.

The objective of this research project was to develop a quantitative characterization of the EFDS so as to provide guidance to other Canadian fire services to increase the effectiveness and safety of live fire training. The primary goal of this work should be considered improving safety accomplished by defining a suitable fuel load used within a proven simulator design as well as the development of a simplified instrumentation plan.

### 5.1.1 Fuel Load

This Section will address goals 1), 2) and 6) all of which are related to the fuel load.

Throughout this research project the crib, the fuel type, and the fuel configuration were all varied. Currently, the final design for the crib, consisting of 2"x2" pine lumber cut into 2' (61 cm) lengths loaded into a steel jig, is being used by OFS for ongoing training evolutions. A small subset of tests was analyzed to determine if there were quantitative differences between this design and the other two that were tested: a standard nailed together pine crib, and one that was built from particleboard strips. This final design shows a slower growth rate as determined by time for the plume as well as the top thermocouple in Rake #1 (T20 and T1, respectively) to reach the threshold temperatures of 320°C and 550°C [36], which is consistent with feedback from OFS instructors [121]. Time above these threshold temperatures does not show a definitive relationship with a specific fuel crib design, which implies that while initial fire growth might be slowed through use of the jig, there is no quantitative association with a change in eventual interior fire conditions.

Fuel type was not analyzed directly, but rather was extracted from the analysis of the thermal environment, as well as the analysis of the effect of ambient conditions. Total heat transfer, as well time that the interior environment fell within Thermal Class III [58] and Ordinary Operating Conditions [63], were all higher during test burns that used fibreboard as fuel, which is consistent with the experience of subject matter experts [114]. The choice of particleboard addresses concerns with the elevated thermal conditions, as well as the structural integrity issues that were identified in initial tests conducted by the NRC [106]. It should once again be noted that these more severe interior thermal conditions might also be affected by the training experience levels of the instructors controlling fire conditions.

Too few tests where only the fuel configuration was changed were conducted to do a complete analysis of the CFBT [24] and DNVFRS [69] fuel configurations. However, no evidence of a clear distinction between the two in the present results is an indication that either of these fuel loads are appropriate.

Currently OFS is using a pine crib with a steel jig with particleboard as fuel using the CFBT configuration. The continued use of the crib jig is recommended as it reduces the labour required to build cribs, and is not seen to have adversely affected the ability of instructors to develop fire conditions that will achieve the learning objectives associated with the FKTP curriculum. Use of particleboard is recommended over fibreboard based on both quantitative and qualitative feedback [114]. Either the CFBT [24] or DNVFRS [69] fuel loads configurations are appropriate and provide a safe learning environment, and additional fuel should not be added, even in cold and damp conditions. An additional 1/3 sheet of particleboard is placed within the EFDS and is relocated above the crib later in the burn if the heat released by the crib is not found to be sufficient. This fuel is not always added, and is added later in the burn, so is less likely to add to the peak heat release rate during the training evolution. This fuel load has been used by OFS for multiple types of training evolutions and has been found to generate appropriate conditions for all of these evolutions [72, 73, 74] without the addition of further fuel load (considering the 1/3 board mentioned above).

It should also be noted that this fuel load meets the requirements set forth in NFPA 1403 [6], as well as subsequent guidance issued by the IAFF in 2014 [52]. While further guidance might tighten the current restrictions pertaining to fuel used in live fire training, the lack of further restrictions since 2014 indicates these changes are likely not imminent.

### 5.1.2 Design Recommendations for Live Fire Training Simulators

This Section will address goals 4) and 6) which are both related to the design of the EFDS.

The design for the EFDS is largely based on those used by CFBT jurisdictions throughout the world [9, 20, 43, 44, 68, 69, 70, 71, 76, 78]. A roof was re-designed from the example provided by the Dublin Fire Brigade [81], and is seen as important given the expected role of temperature and humidity in fire development, particularly given live fire training evolutions can take place at or near freezing temperatures in Canadian jurisdictions.

The other two notable changes to the design both involve fuel loading. After many different design attempts, a new method was found to load fuel on the walls of the EFDS. This new design involves a piece of angle iron which sits in two braces. This new design facilitates fuel loading and is adaptable to different fuel loads and types. In particular, this design would allow for supporting mesh to be added to the fuel load if fibreboard, or some other fuel with low structural integrity was chosen in the future. The second design change involves the crib jig. This new design element was introduced in an attempt to reduce the labour involved in preparing cribs for training evolutions, and it succeeded in this goal without a clear negative impact on achievable interior fire conditions. NFPA 1403 should be observed when inspecting all live fire training simulators [6].

### 5.1.3 Characterization and Safety of the Interior Fire Environment

This Section will address goals 3) and 5) which are both related to firefighter safety during training evolutions as well as to instrumentation towards that end.

The range of ambient conditions experienced during testing for this research project represents the range of recommended conditions for live fire training [125] for OFS. While there are two standards that are proposed to assess the safety of the operating environment for firefighters [58] [63], there is reason to believe these are overly conservative as no injuries or burns were experienced by the OFS instructor cadre who participated in the testing, and no equipment was damaged, despite the recommendations from both being exceeded during testing. Further to this, heat stress as a result of either the test burns or training evolutions can be managed by following the safety document developed by the FKTP Project and ensuring that all participants are given time to recover and cool down following a burn [23]. A time-dose model where the cumulative heat transfer to participants is considered to be more appropriate than the use of the heat flux limits as is recommended by the UL FSRI study [41],

Instrumentation of live fire training simulators is advised as required in the United Kingdom [21] and recommended by the UL FSRI study [41]. A reasonable approximation of the upper layer temperature can be obtained from a single thermocouple, while the heat transfer to participants based on the four heat flux measurements taken during this research project can be approximated using five additional thermocouples. The proposed thermocouple locations along with the heat flux locations that are approximated are shown in Figure 108.

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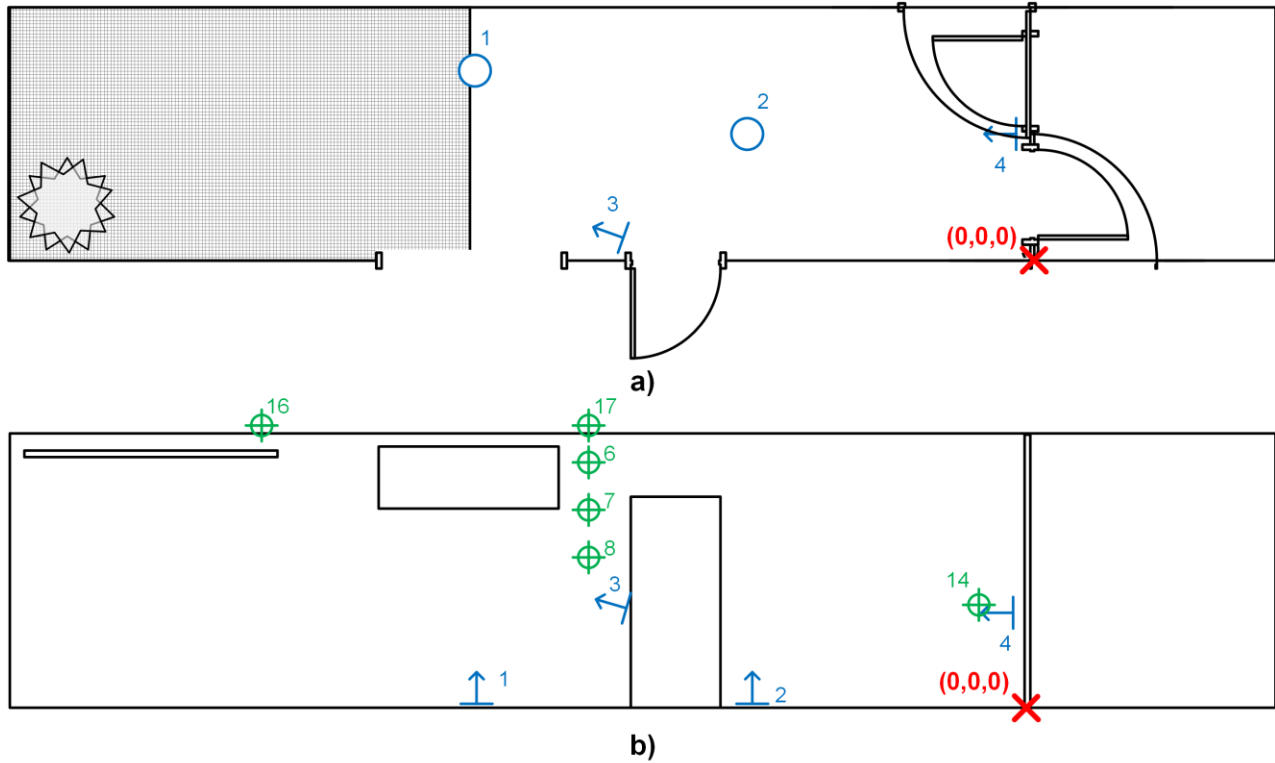
**Figure 108: Heat flux association to temperature**

The equations for upper layer temperature and heat flux approximations are presented in Table 31.

**Table 31: Upper layer and heat flux approximations**

| Approximated Measurement | Equation |
|---|---|
| Upper Layer Temperature | $\dot{T}_{UL} = T_{tc7} + 9.5$ |
| Heat Flux at the Floor – Forward | $HF_1 = 0.124\sigma T^4_{tc6} + 0.123\sigma T^4_{tc16}$ |
| Heat Flux at the Floor – Middle | $HF_2 = 0.071\sigma T^4_{tc6} + 0.139\sigma T^4_{tc17}$ |
| Heat Flux at the Safety Door | $HF_3 = 0.092\sigma T^4_{tc6} + 0.855\sigma T^4_{tc8}$ |
| Heat Flux at the Vestibule Bulkhead | $\dot{HF}_4 = 0.029(T_{tc14} - 305.2)$ |

If these equations are used to determine safety, upper limits should be determined by the end user in accordance with their departmental guidelines, and these limits should be re-evaluated based on ongoing experience and feedback from participants. It should also be noted that substantial changes in the simulator design, fuel type, or fuel configuration are not taken into account in these associations, and therefore their use should be limited to cases where the design of these three

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things remains largely unchanged. The collection of these data present three other opportunities beyond setting safe operating limits for burns. The first is the use of the collected temperature data as part of the post-burn debrief. This debrief is meant to correct mistakes on the part of participants, review health and safety issues that arose during the training evolution, and to monitor participants for any signs of illness or distress [23]. It is also an ideal time to reinforce learning outcomes, and this could be aided if data and video were collected and then reviewed at this time. The second use would be in monitoring the progress of instructors as they gain experience in setting interior fire conditions. The collection and analysis of this data for individual instructors would allow for a quantitative analysis of instructor abilities both as instructors gain experience, as well as in comparison with their peers. Despite the overall safety demonstrated with the suggested fuel load and EFDS design over a range of environmental conditions, the proper training of instructors is paramount to long term success and effectiveness of live fire training. Finally, should injury or damaged equipment occur, the collection of data can help to determine what went wrong as well as to demonstrate the employer's duty to ensure safety and competent supervision under clause 25(2) of the Occupational Health and Safety Act [126].

## 5.2    Recommendations for Future Work

This research project has established the safety of the EFDS and similar live fire training simulators under a range of ambient conditions, fuel types and configurations, and instructor interactions. However, there is ample room for future investigation.

The role of ambient temperature and humidity in fire growth and eventual interior fire conditions could be explored in more detail. As these conditions are difficult to prescribe, perhaps the best way to undertake this investigation would be the collection of a large data set with few other variables to provide more data points and allow a more thorough correlation. In addition, a more in-depth model that might consider the added energy required to heat both the EFDS as well as the air involved in combustion would allow for the effects of both temperature and humidity to be combined, which might also help in building more conclusive correlations. The goal of this would be to provide guidance to instructors so that they are better prepared to handle these changes and therefore increase their confidence and the safety of other participants.

A more in-depth examination of the two different fuel configurations – CFBT [24] and DNVFRS [69] – could be undertaken as well. The instrumentation setup suggested in the previous Section should allow for sufficient characterization of the interior fire environment without the need for instrumentation with heat flux gauges that are both more expensive and more difficult to operate. Further, extinguishment of the fire after a given time, and the weighing of any remaining fuel might offer some interesting information as to the relative efficiency of these two fuel configurations, or indeed new configurations. One additional metric that would be of use in this comparison would be the opacity of the smoke generated. Additional instrumentation and observation of the smoke thickness and quantity might offer more conclusive evidence than the current anecdotal guidance from current instructors and subject matter experts [114].

While a steel jig using 2"x2" pine for the crib has been adopted by OFS and has been further recommended as a means to reduce the labour required to prepare these cribs prior to live fire training evolutions, the effect of the jig has been demonstrated to slow the rate of early fire development. Further work in this area to reduce the amount of steel used in this jig might result in reducing the labour required, while also reducing the adverse effect on early fire growth. Further modifications within the bounds of the different crib designs tested in this work would not be expected to pose a serious safety risk given the overall safety established during testing.

As was previously noted by the UL FSRI study [41], a time-dose evaluation of the fire environment, both in training as well as during actual responses, might provide better guidance for the risks involved in operating in these environments. This task is complicated not only by the various different methods of characterizing the thermal environment – temperature, heat flux, and total heat transfer – but also the role and limitations of firefighting PPE [55, 56, 57] as well as consideration of the physiology of individual firefighters. While a basic instrumentation setup has been recommended that will allow for a characterization of the fire environment, it is important to note that the association to heat flux applies only to infinitesimal surfaces as located and oriented as the four heat flux gauges during testing. As such, this does not apply to every location or orientation within the EFDS, nor does it take into account the geometry and orientation of participants during live fire training evolutions and how this will affect the heat transferred to them. Further testing or modelling might provide a more rigorous analysis of the interior

environment and as such demonstrate how applicable the current association is to participant safety as well.

The FKTP Project was initiated in the goal of producing a curriculum that would better train the Canadian Fire Service, and to bridge a perceived gap between fire science and firefighting practice. The characterization of the EFDS as a safe live fire training simulator supports this objective and it is hoped that this research project will enhance both the understanding of the EFDS, as well as the safety of live fire training evolutions in general. A big part of achieving this goal is the use of the FKTP curriculum to other users across Canada, and the deployment of live fire simulators similar in design to the EFDS. An example of this deployment is the adoption of the curriculum as well as the EFDS training by the Ontario Fire College (OFC) in Gravenhurst Ontario [127]. The EFDS used during this research project was moved to the OFC's site in 2019 and is now being used as a training unit (Figure 109).



**Figure 109: EFDS testing unit at the OFC campus in Gravenhurst [128]**

The OFC began offering courses based on the FKTP curriculum in 2019, including live fire evolutions conducted in the EFDS used for testing. It is fitting that this unit which supported the testing involved in this research will now allow firefighters from across Ontario to continue to

learn about fire dynamics. The goal of the FKTP Project was to improve firefighter safety through increased fire dynamics knowledge in the Canadian Fire Service, and the EFDS test unit is therefore the embodiment of this goal.

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**Appendix A – Design Drawings from New South Wales Fire Brigades**

Isometric View ( 1 : 100 )

SWINGABLE MAIN INTERNAL DOOR WITH SECONDARY ACCESS DOOR REFER DRG. NFB11373-EQP-10655

MAIN EXTERNAL DOORS

SIDE AIR VENT 1760 x 580

AIR VENT CONTROL OUTSIDE HANDLE

End View ( 1 : 50 )

2570

2440

NOTCH IN SWINGABLE DOOR FOR PURPOSE OF RUNNING HOSE THROUGH

Plan View ( Top Removed ) ( 1 : 50 )

EXISTING WOODEN FLOOR

2380

AIR VENT CONTROL MECHANISM 1 OFF DUEL HANDLE AND 2 OFF SINGLE HANDLE REFER DRG. NFB11373-EQP-10654

REPLACE WOODEN FLOOR OVER THIS AREA WITH SHEET METAL AND BRICK PAVERS REFER DRG. NFB11373-EQP-10653

FUEL SHEET SUPPORT FRAMEWORK REFER DRG. NFB11373-EQP-10653

4500

2475

50

183

1885

325

2440

Elevation ( 1 : 50 )

AIR VENT REFER DRG. NFB10360-EQP-CON-10654

12192

834

6065

1760

3740

75

2475

1650

225

460

2037

2 OFF - SINGLE HANDLE AIR CONTROL MECHANISM OPERATED FROM INSIDE

SIDE ACCESS DOOR REFER DRG. NFB11373-EQP-10656

1100

2290

1360

840

FUEL SHEET SUPPORT BRACKET

A ( 1 : 25 )

FUEL SHEET SUPPORT BRACKET SEE DRG. NFB11373-EQP-10653

BACKING PLATE

SECURE WITH M12 HEX BOLTS WASHERS & NUTS

DIMENSION IN MILLIMETERS

DRAFT Only
Not For Manufacturing

VERSIONS

| VERSION | CHANGE | DRAW / DATE | APP /DATE |
|---------|--------|-------------|-----------|
| 01-A | | | |

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**REVISIONS**

| VERSION | CHANGE | DRAW / DATE | APP./DATE |
|---|---|---|---|
| 01-A | Original Issue | | |

DIMENSION IN MILLIMETERS

**ISOMETRIC VIEW**

HINGED INTERNAL DOOR
WOODEN CONSTRUCTION
OPENING OUTWARD

1.2 THK SHEET STEEL SKIN
ON BOTH SIDES

**NOTE:**

MATERIAL: STEELWORK TO AS1163-C350
WELDED CONSTRUCTION
FINISH TO BE PAINTED GREY
DOOR TO BE WOODEN CONSTRUCTION

SUITABLE HEAVY DUTY
BUTT HINGES
TYPICAL 4 PLACES

Ø36 ROLLER

32
30

'A' (N.T.S.)

50 x 50 x 2.5 THK.
RHS - AS1163-C350

2010
830
840
2280
592
292
720
300
300
2020
2280
50
25

'A'

DRAFT Only
Not For Manufacturing

**NSW FIRE BRIGADES** TEL.: (02) 9742 7440 FAX: (02) 9742 7484
ENGINEERING SERVICES
AMARINA AVENUE, GREENACRE, NSW 2190

TITLE
DEMO /ATTACK FIRE CELL
12.2 METRE CONTAINER
REAR SWINGING ACCESS DOOR

| DRAW/DATE | TC 27/07/2007 |
| CHECKED/DATE | - |
| APRVD/DATE | - |
| PART NO | 10655 |

DRAWING NO
NFB11373-EQP-10655

VERSION 01-A
SHEET 1 of 1
SHEET SIZE A3
SCALE 1:16
WEIGHT 0

AIR VENT ASSEMBLY

SEE DETAIL 'A'

Ø20

3 PL.

2000 REF.

1760

600

600

16

16

DETAIL 'A'

600

16

266

530

65

65

20

TYP. 2 PLACES

**NOTE:**
MATERIAL: ALL STEELWORK TO AS 1163-C350
FINISH : PAINTED GREY
FOR CONTAINER ASSEMBLIES REFER DRAWING
NFB11373-EQP-10648 & 10650

DIMENSION IN MILLIMETERS

20 x 8 THK. x 200 LONG

LINK ARM
35 x 8 THK.
x 135 LONG

100 x 50 ANGLE X 100 LONG
BRACKETS. POSITION TO BE
DETERMINED DURING
CONSTRUCTION OF ASSEMBLY

Ø34 SHAFT MS

6000

**SHAFT AND LINK ARM ASSEMBLY**

Ø34 SHAFT
1800 LONG

60 TYP.

40 TYP.

112 TYP.

35 x 8 THK.
x 230 LONG

Ø25 HANDLE
600 LONG

Ø20 x 200 LONG
SHAFT

**DUEL ARM MECHANISM**

Ø34 SHAFT
1800 LONG

35 x 8 THK.
x 230 LONG

Ø25 HANDLE
600 LONG

**SINGLE ARM MECHANISM**

**REVISIONS**

| VERSION | CHANGE | DRAW / DATE | APP./DATE |
|---------|--------|-------------|-----------|
| 01-A | Original Issue | | |

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**Isometric View ( 1 : 25 )**

REFRACTORY PAVERS

DRILL APPROX 20 HOLES
Ø20 IN STEEL PLATE TO
AID WITH THE DRAINAGE
OF WATER DURING HOSE
DOWN OF WET AREA

EXISTING CONTAINER
WOODEN FLOOR

LINE FLOOOR AREA
WITH BED OF SAND

3 mm THICK MS PLATE

2300

4500

3 THK
13
75

DIMENSION IN MILLIMETERS

REVISIONS

| VERSION | CHANGE | DRAW / DATE | APP./DATE |
|---------|--------|-------------|-----------|
| 01-A | Original Issue | | |

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# Appendix B – City of Ottawa Purchase Order

City of Ottawa / Ville d'Ottawa

**Purchase Order / Bon de commande**    45079888

PO created: 2015/03/20
Page: 1 of/de 2

Vendor # - No.de vendeur: 300759

RECEIVER GENERAL FOR CANADA
NATIONAL RESEARCH COUNCIL CANADA
FINANCE BRANCH
1200 MONTREAL ROAD BLDG M 58
OTTAWA ON K1A 0R6

Tel./Téléphone: 613-993-0915
Fax/Télécopieur: 613-998-7151

E-mail invoice to/Envoyer facture à:
AP-CF@ottawa.ca            OR

Mail invoice to/Envoyer facture à:
City of Ottawa
Accounts Payable
P.O. Box 3426 Stn D, Ottawa, ON K1P 0B9

Invoice Contact Name/Nom du contact:
Peter McBride

Please Ship to/Expédier à:
Fire Services
City of Ottawa
1445 Carling Avenue
Ottawa ON K1Z 7L9

Contracting authority: David Baird
Autorité contractante:
Contact Phone: 613-580-2424 Ext. 25118
Téléphone:
Contact Fax: 613-560-2126
Télécopieur:

Terms of payment/Modalités de paiement:
Net 30 Days

Terms of delivery/Conditions de livraison :
FOB Destination

| Item#<br>Artic<br>le N° | Material<br>Article | Vendor Material<br>N° article fournisseur | Description | Delivery Date<br>Date de<br>livraison<br>y/a m/m d/j | Quantity<br>Quantité | Unit<br>Unité | Price per Unit<br>Prix unitaire | Extended Price<br>Prix calculé |
|---|---|---|---|---|---|---|---|---|
| | | | Professional services to undertake the Development of Fire Dynamics Training Tools for the training of Fire Fighters. Approved by the Deputy City Manager, City Operations on 20 March 2015. Work to be completed in accordance with: | | | | | |
| | | | a) NRC Collaborative Research Agreement accepted on behalf of the City of Ottawa by the General Manager, Emergency and Protective Services on 17 March 2015. | | | | | |
| | | | Period of Contract: Two (2) years from 20 March 2015 to 31 March 2017. | | | | | |
| | | | Basis of Payment: Total Cost of Time and Materials of $216,854.00, excluding taxes, based on estimated person-hours, materials and incremental expeneses, and in accordance with the deliverables listed in the Collaborative Research Agreement. | | | | | |
| | | | Method of Payment: Payments shall be made in accordance with "Annex $P - Schedule of Payents to NRC" of the Collaborative Research Agreement following receipt and acceptance of the an invoice by the Project Authority. | | | | | |

Contracting authority/Autorité contractante

HST Account / Compte de TVH    86393 5995 RT0001

**Purchase Order**
**Bon de commande**

**45079888**

PO created: 2015/03/20
Page: 2 of/de 2

| Item# Artic le N° | Material Article | Vendor Material N° article fournisseur | Description | Delivery Date Date de livraison y/a m/m d/j | Quantity Quantité | Unit Unité | Price per Unit Prix unitaire | Extended Price Prix calculé |
|---|---|---|---|---|---|---|---|---|
| | | | Limitation of Expenditure: The City's liability to the Contractor under this contract shall not exceed $216,854.00, exceeding taxes, unless otherwise authorized in writing by the Contracting Authority. | | | | | |
| 10 | | | Fire Dynamics Training Tools<br>Invoice Contact Name: Peter McBride - Division Chief - Satety & Innovation 613-580-2424 x29412 | 2015/03/17 | 1.000 | 1 Serv. u | 216,854.00 | 216,854.00 |
| | | | The item covers the following services: | | | | | |
| | | | Expected value of unplanned services: 216,854.00 | | | | | |
| | | | | | | | Sub-total | 216,854.00 |
| | | | | | | | HST | 28,191.02 |

Total includes all applicable taxes
La somme comprend les taxes applicables

CAD 245,045.02

Contracting Authority/Autorité contractante

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**Appendix C – Ottawa Fire Services GO 1 SA 04.1**

| Classification | # | GO 1 SA 04.1-2003 | Safety- Occupational Health and Safety |
|---|---|---|---|
| Subject | | Firefighter Heat Stress Management Guideline- Revised | |
| Authority | | **Fire Chief** | |
| Date Issued: | | GO 1: Issued:July 24, 2003 | SOP: |

## Purpose

To ensure that Suppression personnel take the necessary precautions to prevent metabolic heat injuries during firefighting and/or training operations

## Scope

Urban and Rural Suppression personnel

## Rationale

To define guidelines to manage potential heat stress during training and/or emergency operations

## Directive

- Officers shall monitor the condition of their assigned personnel during fire operations, emergency scenes, stand-by, or training exercises that require the use of Full PPE whenever the actual temperature exceeds 22° C.

- All training or related activities that *require physical effort* shall be suspended whenever the actual temperature or the adjusted humidex reading rises to 30°C or higher. If full PPE is required during training exercises, the work vs. recovery times shall be consistent with the guidelines in the Permissible Heat Exposure Threshold Limit Values table. (See attached.)

- Personnel should drink at least one cup of water or any cool liquid (10° C - 16°C) every 20 minutes. Caffeine and/or highly carbonated beverages should be avoided.

- Pre-hydration is the most effective way to protect yourself from heat related symptoms and members are encouraged to make a personal water bottle part of their turnout gear and to sip water while en route to all emergency calls.

- Water shall be made available for personnel to drink at all training locations and emergency scenes.

- Incident Commanders shall ensure that sufficient personnel are assigned to incidents to allow operating crews to receive sufficient rest breaks and fluid replacement.

- No firefighter suspected of being ill from heat stroke should be sent home or left unattended unless an attending physician has specifically issued such an order. If Paramedics are not on scene, Command shall request an Ottawa Paramedic Service to assess and treat the firefighter.

| Last Revision: September 29, 2009 | Page 1 of 5 |
|---|---|
| GO 1 SA 04.1-2003- Firefighter Heat Stress Management Guideline- Revised | |

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## References and Related Areas of Interest

U.S. Department of Labour – OSHA Technical Manual Section III, Ch. 4.
SOP SA 01.1-2001  Fireground Rehabilitation – Revised

## Attachments

Appendix "A" – OHSA Applicable Legislation for Supervisors
Symptoms and treatment for Heat Exhaustion and Heat Stroke
Workload Assessment Table
Activity Example Table
Permissible Heat Exposure Threshold Limit Values table
WBGT correction factors in degrees Celsius table
Enviro/Weather Considerations

*(Original signed by A/Fire Chief Ullett)*
_____

J. Ullett
A/Fire Chief
Ottawa Fire Services
Emergency and Protective Services

**Station Officers shall review this order with all assigned personnel.  All personnel shall sign the back of this document to signify that they have read the material and are aware and understand the content of this Part 1 Order.**

| Last Revision: September 29, 2009 | Page 2 of 5 |
| --- | --- |
| GO 1 SA 04.1-2003- Firefighter Heat Stress Management Guideline- Revised | |

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<u>**Appendix "A"**</u>
**OHSA Applicable Legislation for Supervisors**

Under Section 25(2)(h) of the Occupational Health and Safety Act, workers, employers and supervisors have a duty to take every precaution reasonable in the circumstances for the protection of the worker. This includes developing policies and procedures to protect workers in hot weather.

For compliance purposes, the Ministry of Labour recommends the Threshold Limit Values (TLVs), for Heat Stress and Heat Strain published by the American Conference of Governmental Industrial Hygienists (ACGIH).

These values are based on preventing un-acclimatized worker's core temperatures from rising above 38 degrees Celsius.

<u>**Symptoms and Treatment**</u>

Workers/Supervisors shall make themselves aware of the signs and symptoms of heat stress and heat stroke in order to recognize those signs in their fellow workers during emergency operations and training sessions.

**Heat Exhaustion**    **Symptoms:** heavy sweating, cool moist skin, body temperature over 38 degrees C, weak pulse, normal or low blood pressure; person is tired and weak and has nausea and vomiting; is very thirsty or is panting or breathing rapidly; vision may be blurred.

    **Treatment:** Get medical aid. This condition can lead to heat stroke, which can kill. Move the person to a cool shaded area and loosen or remove excess clothing; provide cool water to drink, fan and spray with cool water.

**Heat Stroke**    **Symptoms:** High body temperature (over 41 degrees) and any one of the following; the person is weak, confused, upset or acting strangely; has hot dry, red skin; a fast pulse; headache or dizziness. In later stages, a person may pass out and have convulsions.

    **Treatment:** Call Ambulance. This condition can kill a person quickly. Remove excess clothing; fan and spray the person with cool water; offer sips of cool water if the person is conscious.

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| --- | --- |
| GO 1 SA 04.1-2003- Firefighter Heat Stress Management Guideline- Revised | |

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| Workload Assessment Table | |
|---|---|
| Light Work | Burns up to 200 kcal/hour |
| Medium Work | Burns 200 – 350 kcal/hour |
| Heavy Work | Burns 350 – 500 kcal/hour |

| Activity Examples |
|---|
| Heavy work one arm: hammering nails, (shoemaker, upholsterer) |
| Light work two arms: filing metal, planning wood, raking the garden |
| Moderate work with the body: cleaning a floor, beating a carpet |
| Heavy work with the body: railroad track laying, digging, debarking trees |

| Calories Per Hour rating | | |
|---|---|---|
| Work: One arm | Light | 1 |
| | Heavy | 1.7 |
| Work: Both arms | Light | 1.5 |
| | Heavy | 2.5 |
| Work: Whole body | Light | 3.5 |
| | Moderate | 5.0 |
| | Heavy | 7.0 |
| | Very heavy | 9.0 |

| Permissible Heat Exposure Threshold Limit Values | | | | |
|---|---|---|---|---|
| Work/Rest Regimen | Light Work | Moderate Work | Heavy Work | Heavy Work W/PPE |
| 75% work – 25% rest per hour | 30.6°C | 28°C | 25.9°C | 16 - 18°C |
| 50% work – 50% rest per hour | 31.4°C | 29.4°C | 27.9°C | 19 -21°C |
| 25% work – 75% rest per hour | 32.2°C | 31.1°C | 30.0°C | 22.0° C and above |

** The above assumptions are based on acclimatized, full-clothed workers with adequate water and salt intake. These workers should be able to function effectively under the given working conditions without exceeding a deep body temperature of 38°C.

These figures in the previous table are based on a physically fit individual wearing light summer clothing. If heavier clothing that impedes sweat or has a higher insulation value is required, the permissible heat exposure TLVs must be reduce by the corrections as shown below and identified above in the Heavy Work with PPE column.

| Type of Clothing | Temperature correction to above table |
|---|---|
| Summer lightweight clothing | No correction |
| Cotton coveralls | Minus 2°C |
| Winter work clothing | Minus 4°C |
| Water barrier, permeable | Minus 6°C |
| Fully encapsulating clothing, gloves, boots and hood | Minus 10°C |

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|---|---|
| GO 1 SA 04.1-2003- Firefighter Heat Stress Management Guideline- Revised | |

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# Firefighter Heat Stress Medical Observation Guidelines

All firefighters reporting to rehab should be interviewed by a Rehab Officer or by OPS' personnel if they are on scene. A simple Glasgow Coma Scale examination is all that will be required in most instances.

If the firefighter is presenting a high temperature (41°C+), complaining of weakness, confused, upset or acting strangely, has hot dry red skin, a fast pulse, headache or dizziness. A Paramedic shall be summoned to attend to this patient. These are all signs and symptoms of Heat Stroke, which can be fatal.

If the firefighter is sweating profusely, extremely flushed in the face and/or neck, complaining of any signs or symptoms that might indicate cardiac distress or a heat related condition they shall:

- Have their temperature taken and recorded, preferably prior to drinking any water.
  - If the temperature exceeds 38°C they shall remain in rehab until their temperature has dropped below 38°C.
- Have a radial pulse taken and recorded. The radial pulse should be taken for 60 seconds.
  - If the radial pulse exceeds 110 beats per minute, the next work cycle shall be shortened by one third.
  - In these cases, a second radial pulse shall be taken 2 ½ minutes after the rest period begins. If the difference between the first radial pulse and the second radial pulse has:
    - Dropped by more than 10 beats, the recovery rate is in the normal range.
    - If the difference is only 10 beats, the firefighter requires extended rehab time and additional monitoring.
    - If the difference is less than 10 beats or the heart rate has increased, the firefighter shall be removed from duty and further medical monitoring is required.
- Drinking water and nutritional supplements shall be made available at all incidents and training scenarios during hot weather. The firefighter rehab vehicle carries a large complement of drinking water and energy replacement bars.

## Weather and Environmental Indicator Triggers

1. Humidex reaching or exceeding 35 degrees Celsius
2. Environment Canada Humidex advisory (air temperature exceeding 30 degrees Celsius and Humidex exceeding 40 degrees Celsius) or Ontario Ministry of the Environment smog alerts
3. Heat waves (three or more days of temperatures of 32 degrees or more)

The Company Officer shall assess the demands of the training session and have monitoring and control strategies in place.

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|---|---|
| GO 1 SA 04.1-2003- Firefighter Heat Stress Management Guideline- Revised | |

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# Appendix D – CFAST Modelling

This appendix provides background on the CFAST model that was presented in Figure 107. This model comes from an assignment prepared by the author in 2015 for the course ME 765: Advanced Enclosure Fires.

The Consolidated Model of Fire and Smoke Transport (CFAST) is a two-zone model that is a combination of two previous programs written by NIST. CFAST calculates temperature, smoke, and fire gas distribution over time throughout different user-defined compartments. A model with roughly the same dimensions and boundaries as the EFDS was built, and a fire of origin was built relying on the work of Obach [53], which informed the design of the crib used in this research project. In addition, sheet fuel was added in the form of ½" thick plywood in three locations: the back wall, the side wall adjacent to the crib, and the ceiling. The resultant plumes from these sources can be seen in Figure 110.
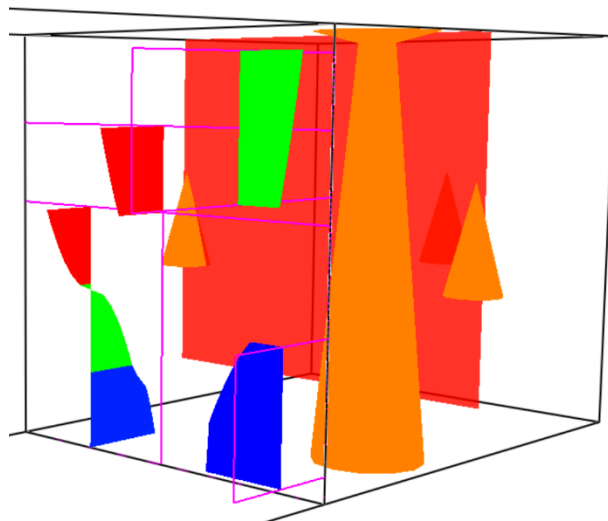


**Figure 110: Plume development within the CFAST model**

The ventilation of the EFDS within this model was then run with different ventilation conditions by varying the opening fractions of the ventilation openings. From these different scenarios, a ventilation profile where the opening fraction was 75% was chosen. After 6 minutes, the opening fraction was reduced to 25% in an attempt to maintain higher upper layer temperatures. These different ventilation runs are shown in Figure 111.
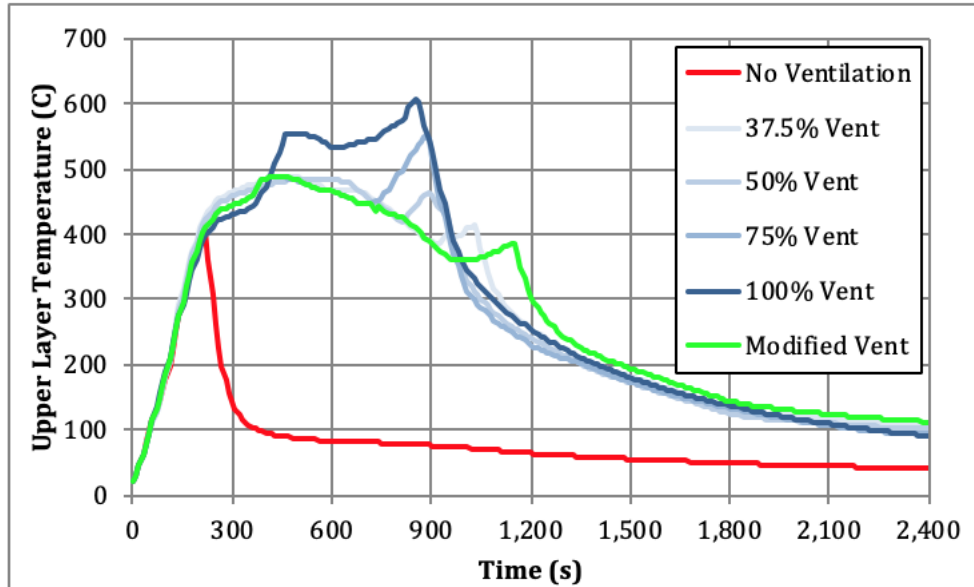
**Figure 111: Ventilation runs within CFAST**

This fire of origin and ventilation profile was then run over multiple different ambient conditions by varying the ambient temperature in the model from 0 to 30°C in 5°C increments. The upper layer temperatures for these seven scenarios are plotted for the first 20 minutes of the burn in Figure 107. The results show that lower ambient temperatures result in a delay in fire growth, but a corresponding higher peak temperature. One explanation for this is how CFAST handles combustion. Whether this is a realistic model of how the EFDS performs is unclear, but the delayed initial fire growth would seem to be a plausible outcome as a result of a heightened requirement to overcome the thermal mass of both the EFDS and the environment to attain the same upper layer temperatures.

# Appendix E – Letters of Permission

**From:** Nancy Schwartz <███████████@███.███>
**Sent:** Friday, June 12, 2020 7:49 AM
**To:** Randall, Geoffrey <██████████████@██████████>
**Subject:** Geoff Randall Copyright request RE: NFPA Copyright request - 00424887 [ ref:_00D5077Vx._5001T1N1Auz:ref ]

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Ben Evarts informed me that you are submitting your thesis tomorrow.  I am sorry you have not received a response from our legal department.

As I know that you would be given permission to use the figure, with proper citation, feel free to keep the figure in your thesis.   Our library provided me with the Chicago Style citation for Figure 1 in the 2018 fire loss in the US report.   See below:

**Note**: Ben Evarts, *Fire Loss in the United States During 2018*, (Boston: National Fire Protection Association, 2019), 6, https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fire-loss-in-the-United-States.

 B**ibliography**: Evarts, Ben. *Fire Loss in the United States During 2018*. Boston: National Fire Protection Association, 2019. https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fire-loss-in-the-United-States

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I hope that this email provides you with the appropriate authorization to include the figure in your thesis.

Thank you for your patience and good luck with your thesis.

Nancy

Nancy Schwartz
Manager, Communications and Operations | **NFPA**
Applied Research
1 Batterymarch Park
Quincy, MA 02169-7471

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|---|---|
| Position/Title: | Founding Editor, *IFSJLM* |
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| --- | --- |
| Position/Title: | District Officer Dublin Fire Brigade |
| Date: | 9-6-20 |
| Signature: | *John Chubb* |

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If you need anything alse, please let me know.

All the best and good luck,

Jens

_____

**_Jens Stiegel_**

Assistant Chief, Chief of education and training

Frankfurt am Main Fire and Rescue Services, Headquarters
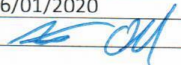
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|---|---|
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| Date: | 06/01/2020 |
| Signature: | |

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Doc. ref. no:    D20/42152


Mr Geoff Randall
19 Trevor Crescent
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K2H 6H7  Canada


3 June 2020

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Yours sincerely,

**Janet Ruecroft**
Assistant Commissioner
Education and Training Directorate

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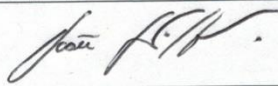
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| Date: | May 29, 2020 |
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**Ian Bolton**███████████████████                          Tue, Jun 2, 2020 at 6:03 PM
To: Geoff Randall ███████████████████

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Cheers,

Ian

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>
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>
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>
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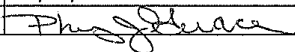>
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