Evaluation of
Fire Service Training Fires

Prepared by:
Chad M. Lannon and James A. Milke
University of Maryland
College Park, MD 20742-3031

Fire Protection Research Foundation
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FOREWORD

Each year thousands of fire fighters are injured during training, and occasionally some are fatally injured. Live fire training evolution is an effective and popular training method, but it’s also one that exposes the trainees to significant hazards. One common cause of fire fighter death and injury is a lack of understanding of the hazard assessment of live fires used for training.

This research effort is intended to further clarify the hazards of live fire training evolutions and provide data and information to support a fire hazard assessment methodology for fire training officers and fire fighters. The goal is to analyze specific fuel configurations in certain training fire evolutions and to supplement currently available practical guidance for use by training instructors based on the hazards associated with live fire training evolutions.

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The content, opinions and conclusions contained in this report are solely those of the author.
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Keywords: fire, fire service, training, training fires, hazards, burn, burn building, fuel, fuel package, flashover
PROJECT TECHNICAL PANEL

W. Edward Buchanan, ISFSI & Hanover Fire &EMS (VA)
David Clark, Illinois Fire Service Institute (IL)
D.K. Ezekoye, University of Texas at Austin (TX)
Kerby Kerber, Delaware County ESTC (PA)
Steve Edwards, NAFTD & Maryland Fire Rescue Institute (MD)
Danny Kistner, IAFC-SHS Section & McKinney Fire Dept (TX)
Dan Madrzykowski, NIST (MD)
William Peterson, NFPA 1403 Former TC Chair (TX)
Steven Sawyer, NFPA (MA)
Christina Spoons, West Dundee Fire Dept (IL)

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Chad M. Lannon and James A. Milke

Department of Fire Protection Engineering
University of Maryland

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Abstract

This study identifies the parameters that influence the development of thermal conditions during live fire training evolutions within burn facilities. As part of a previous study, tests were conducted on the third floor of the live fire training building at the Maryland Fire and Rescue Institute (MFRI). The principal measurements obtained during the training evolutions were temperatures and heat flux in the burn room. A model replicating the tests conducted in the MFRI training facility was created using CFAST version 6 and a validation was performed by comparing temperature and heat flux measurements from the test to the model’s estimation. Then, the MFRI CFAST model was used to simulate twenty one scenarios that examine the effects various fuel packages, ventilation strategies, room sizes and time between sequential burn evolutions have on the thermal conditions inside a firefighter training burn room. There are many fuel packages commonly burned during live-fire training. This study was only able to analyze fuel packages in which there is heat release rate data available, which include; stacked pallets, triangular pallets & excelsior, excelsior pile, flat pallets & excelsior, and upright pallets & excelsior (see Table 8 for more details regarding the fuel packages). Results show that of the fuel packages analyzed, the ones configured vertically (stacked pallets and the upright pallets & excelsior) have the greatest heat release rate and create the most severe thermal conditions, while triangular configured fuel packages create moderate thermal conditions and lastly, horizontally configured fuel package (flat pallets & excelsior) create the least severe thermal conditions. Horizontal ventilation causes a quick decrease in thermal conditions, while leaving remote vents open during a burn evolution limits the development of thermal conditions within the burn room. According to the model simulations where the same fuel package is burned in rooms that vary in size, the burn evolutions that occur in small rooms produce hotter conditions than ones that occur in larger burn rooms. Also, as multiple sequential burn evolutions occur over the course of training, the initial ambient temperatures inside the facility continually rise to yield thermal conditions that are even more severe than the previous evolution. When minimal time is taken between burn evolutions, conditions can become very severe after multiple evolutions. Taking more time between burn evolutions can allow the facility to cool down and reduce the severity of thermal conditions. Based on the results of this simple study, it is recommended that NFPA 1403 be modified to include a hazard assessment procedure that can enable fire instructors to properly account for the principal factors affecting the severity of the thermal conditions produced in burn evolutions.
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Executive Summary

Live fire training facilities are built to endure repeated burn evolutions so that firefighters can train in an environment that mimics the conditions of a real building fire. These training facilities generally have well insulated burn rooms. When a fuel package is burned in these structures, thermal conditions can become extreme, potentially threatening the tenability of firefighters wearing personal protective equipment. NFPA 1402 does not mandate a specific size for burn rooms in live fire training facilities and NFPA 1403 does not provide quantitative guidance to fire instructors on the types of fuel packages that are safe to burn, methods to properly ventilate and how to conduct sequential burn evolutions. This report conducts a first order analysis by using a simplified zone fire model, CFAST to replicate tests conducted in the MFRI live fire training facility and simulate various scenarios to assess the relative impact of four parameters on the thermal conditions that may develop within a burn room of a live fire training facility. The key components that determine the thermal conditions within a training facility, during a live burn are: the fuel package, ventilation strategy, room size and duration between burn evolutions. A detailed methodology for conducting a fire hazard assessment for a live fire training evolution does not exist. The analysis documented in this report should provide some assistance to fire instructors in appreciating which parameters are the most influential in dictating thermal conditions which are generated.

Of the four parameters considered, the fuel package is the most influential parameter that can affect the development of thermal conditions within the room. Specifically, the HRR of the fuel package is the principal characteristic of the fuel package governing thermal conditions which will be generated. Fuel packages vary by their orientation, composition, mass and location. Fuel packages can be oriented in some of the following ways; stacked, upright, flat, triangular and a pile. There are other ways to configure a fuel package, but his report only analyzes these fuel packages because there is published HRR data available. NFPA 1403 also states that all fuels must be composed of wood products.

Ventilation can be utilized during burn evolutions to release heat and limit the thermal conditions within the live fire training facility. Ventilation strategies include leaving a remote window or door open during a fire training evolution or opening a vent during an evolution to horizontally ventilate smoke and heat from the compartment. Leaving a window or door open in the burn room significantly decreases thermal conditions in the burn room. Having a remote window remain open can be an effective method to limit the thermal condition in the burn facility. Most importantly, when thermal conditions are too high and possibly untenable, firefighters can horizontally ventilate by opening a window close to the burn room and this will quickly decrease

* A tenability analysis is beyond the scope of this study. Research efforts by others have studied criteria to establish tenability limits for firefighters. As such, references in this report to ‘tenable’, ‘safe’ or ‘severe’ conditions are intended to be comparative and reflect a relative potential threat to firefighters.
the thermal conditions in the burn room. For fuel limited fires, horizontal ventilation can possibly turn an environment from untenable to tenable. Conversely, improper ventilation can turn can provide oxygen to a ventilation limited fire, which can subsequently cause the fire to progress towards flashover. It is imperative that the fire instructor conducting the burn evolution monitors the fire conditions to ensure that the firefighters are ventilating the structure at the proper time.

Burn room size dictates the amount of heat that is stored within the space and the amount of heat concentrated in the room determines the thermal conditions within the compartment. For a given fuel package HRR, smaller burn rooms have the potential to create more severe thermal conditions because more heat is concentrated over a smaller volume, while larger burn have more volume, so heat is distributed over a larger area and therefore thermal conditions are less severe. When a fire instructor is performing a fire hazard assessment for a live fire training evolution, they need to choose a fuel package that is appropriate for the size of their burn room. Fuel packages that possess a lower HRR should only be burned in burn rooms that are smaller in size. While fuel packages with a large HRR can be burned in burn rooms that are large in size.

Sequential burn evolutions may not be as obvious a parameter as the first three discussed, given that a particular combination of fuel HRR, ventilation and room size may provide an acceptable set of thermal conditions in the first evolution of the day. However, as sequential evolutions are conducted without sufficient time for the room to cool, the thermal conditions can be expected to increase in severity with repetitious evolutions. This transition to an unacceptable level over the course of a day may be subtle, as the temperature increase between any two consecutive evolutions may be relatively modest.

In live fire training facilities, various types of insulating materials are commonly applied to the walls and ceilings of burn rooms. These materials have thermal properties that possess the ability to have a slight impact on the development of thermal conditions within burn facilities.

When a fire instructor plans a live fire training evolution, they must perform a hazard assessment to ensure that the thermal conditions stay within a safe range. The appropriate fuel package must be chosen depending on the size of the facilities burn room. Also, some of the ventilation strategies discussed in this report can be used to reduce the thermal conditions inside the compartments. When sequential burn evolutions occur, a predetermined amount of time has to be provided between burn evolutions to allow the structure to cool. Also, the fire instructor should be monitoring changes in conditions as training progresses.
Chapter 1: Introduction

1.1 Overview

Live fire training evolutions are a popular training method utilized by many fire departments. They provide participants with an opportunity to practice firefighting techniques, as well as develop an understanding of the thermal conditions inside structural fires.

Unfortunately, every year firefighters are injured during training, and occasionally some training incidents are fatal. The dangers of structural firefighting are well recognized, but the hazards that firefighter trainees and instructors are exposed to in training environments can be significant and may not be appreciated prior to the activity. Some firefighter injuries in training incidents occur as a result of exposure to dangerous thermal conditions characterized by high temperatures and high heat fluxes. Severe thermal conditions can be generated in live fire training incidents when:

1. Unsafe fuel packages are used
2. Inadequate or improper ventilation is provided
3. Fuel packages with large heat release rate (HRR) are burned in small rooms, and
4. Sequential burn evolutions occur with minimal time between burn evolutions

NFPA 1403, Standard on Live Fire Training Evolutions, is intended “to provide a process for conducting live fire training evolutions to ensure that they are conducted in safe facilities and that the exposure to health and safety hazards for the fire fighters receiving the training is minimized.” As such, in keeping with the intent of NFPA 1403, a fire instructor planning a burn evolution for training purposes should conduct a hazard assessment to consider the thermal conditions which will be generated by the planned event. Important parameters to be considered in a hazard assessment should include fuel packages, amount of ventilation and room size.

Fuel packages have a significant impact on the thermal conditions inside a structural fire environment. NFPA 1403 provides no specific guidance on suitable fuel packages. NFPA 1403 only states that fuels must be wood products, the amount of fuel must be necessary to create the desired fire size and the fuel load needs to be limited to avoid flashover or backdraft. The resulting temperatures and heat flux firefighter trainees and instructors are exposed to inside the training environment are influenced directly by the HRR generated by the fuel packages. The composition and configuration of fuel packages affect the HRR, hence selection of fuel packages is an important step in any hazard assessment.

The properties of room enclosure materials can also affect temperature development inside a burn room. Rooms which are well insulated will generally retain heat within the compartment, thereby increasing the severity of thermal conditions experienced as compared to a room that is not well insulated.

Ventilation during a particular evolution will affect thermal conditions and the position of the smoke layer within burn rooms. The role of ventilation needs to be accounted for in a proper hazard assessment.

Room size has an influence on the thermal conditions inside the training structure. NFPA 1402 does not provide guidance on the proper dimensions of a burn room. Therefore, burn room
sizes are not uniform and the volume of space in burn rooms varies greatly for each live fire training facility. For a given fuel package, the severity of thermal conditions is decreased with increasing room size. Thus, utilizing smaller rooms for burn evolutions has the potential to increase the severity of thermal conditions experienced within the room.

In addition to the above, often multiple sequential burn evolutions are conducted over the course of a day as part of a training activity. If a subsequent burn evolution is conducted before allowing the room enclosure to cool, more severe thermal conditions will be produced than if the room is allowed to cool. As this process is repeated multiple times, the initial ambient temperature inside the facility can become even further elevated to yield an even more severe set of thermal conditions. The 2012 edition of NFPA 1403 requires the following:

7.3.1 The AHJ shall develop and utilize a safe live fire training action plan when multiple sequential burn evolutions are to be conducted per day in each burn room.
7.3.2 A burn sequence matrix chart shall be developed for the burn rooms in a live fire training structure.
7.3.2.1 The burn sequence matrix chart shall include the maximum fuel loading per evolution and maximum number of sequential live fire evolutions that can be conducted per day in each burn room.
7.3.3 The burn sequence for each room shall define the maximum fuel load that can be used for the first burn and each successive burn.
7.3.4 The burn sequence matrix for each room shall also specify the maximum number of evolutions that can be safely conducted during a given training period before the room is allowed to cool.
7.3.5 The fuel loads per evolution and the maximum number of sequential evolutions in each burn room shall not be exceeded under any circumstances.

Missing from NFPA 1403 is any guidance on the minimum amount of time that fire instructors have to wait between sequential burn evolutions. Often, after one burn evolution ends, all doors and windows are immediately closed to contain the hot smoke and the next fuel package is quickly ignited.

Firefighters may be exposed to extreme thermal condition within the burn room during training scenarios because the proper tools and information are not made available to the fire instructors to enable them to perform a hazard assessment of the planned live fire training evolutions. A hazard assessment consists of analyzing the thermal conditions that will be produced in the training exercise as a result of the fuel package, ventilation strategies, room size and repeated training evolutions within a short time period. A hazard assessment is needed so that these measures can be explicitly accounted for in order to limit the severity of thermal conditions inside the fire training building to reasonable levels so that firefighters can train within safer environments. Without explicitly conducting such an assessment, fire instructors may not be able to assess the impact of the combination of these factors, nor might they appreciate the impact of a modest change in one of the parameters which could cause conditions to exceed an important threshold condition, e.g. flashover.
A computer fire model, CFAST, was used to create a simulation that replicates the Maryland Fire & Rescue Institute’s (MFRI) third floor of the structural firefighting building. Experiments were conducted at MFRI by the National Institute of Standards and Technology (NIST) in 2005 and the results of these experiments are compared to the results of the CFAST model in order to validate the use of the CFAST model. Next, CFAST was utilized to identify the effects various fuel packages, ventilation strategies, room sizes and sequential burn evolutions have on the thermal conditions inside a typical firefighter training burn room.

Burn rooms are the location where the fuel package is burned and are often small, insulated and have limited ventilation. This report focuses on estimating the thermal conditions inside burn rooms because this is the area that has the greatest thermal hazard and also is a location where firefighters are often located during burn evolutions, along with the fire instructors responsible for igniting and monitoring the fire.

The goals of this report are to:

1. Use CFAST to determine the effects that fuel packages, ventilation strategies, room sizes and sequential burn evolutions have on the thermal conditions inside a live fire training structure.
2. Use CFAST to perform a sensitivity analysis to identify the important factors that influence the thermal conditions inside a live fire training evolution so that fire instructors can properly perform a hazard assessment of fire training evolutions.

1.2 Background

Firefighting is an inherently dangerous profession that requires extensive training to prepare for the hazards of structural firefighting. Some of the training often involves live fire training evolutions at burn facilities, either at training academies or at acquired structures.

From 1991 to 2011, there was an average of 114.7 firefighter fatalities in the United States. Of particular interest in this project are the 166 firefighter deaths that occurred during training over the 16 year period, 1996 – 2011. Of those 166 deaths, 16 (i.e. an average of one per year) are attributed to live fire training activities. Firefighter deaths that occur during training are especially disconcerting, given that training is meant to prevent deaths and injuries and not be their cause.

From 2000 – 2007, the National Institute for Occupational Safety and Health Fire Fighter Fatality Investigation and Prevention Program investigated seven incidents involving seven firefighters who sustained fatal injuries while participating in live fire training in acquired structures. These incidents are summarized in Table 1. All of these fatalities were related individuals being exposed to severe thermal conditions. One particularly disturbing aspect of these incidents is that 3 of the 7 fatalities were fire training instructors and not students. This is attributed to the instructors usually participating in considerably more evolutions per day than individual students, which may result in them experiencing multiple significant exposures during the course of a day.
Table 1. Summary of NIOSH Investigation Reports Involving Live Fire Training

<table>
<thead>
<tr>
<th>NIOSH Report #</th>
<th>Date</th>
<th>Description</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2007-09</td>
<td>Feb 09, 2007</td>
<td>Career probationary firefighter died in a live fire training evolution at an acquired structure</td>
<td>Maryland</td>
</tr>
<tr>
<td>F2005-31</td>
<td>Oct 23, 2005</td>
<td>Career officer injured during a live fire evolution at a training academy dies two days later</td>
<td>Pennsylvania</td>
</tr>
<tr>
<td>F2003-41</td>
<td>Oct 17, 2003</td>
<td>Five career firefighters injured in live fire exercise in mobile flashover training simulator</td>
<td>Maine</td>
</tr>
<tr>
<td>F2003-28</td>
<td>Aug 08, 2003</td>
<td>One recruit firefighter died and four others injured in live fire training exercise</td>
<td>Florida</td>
</tr>
<tr>
<td>F2002-34</td>
<td>Jul 30, 2002</td>
<td>Career lieutenant and firefighter died in a flashover during a live fire training evolution</td>
<td>Florida</td>
</tr>
<tr>
<td>F2001-38</td>
<td>Sep 25, 2001</td>
<td>Volunteer firefighter died and two others are injured during live burn training</td>
<td>New York</td>
</tr>
<tr>
<td>F2000-27</td>
<td>Apr 30, 2000</td>
<td>Volunteer assistant chief died during a controlled-burn training evolution</td>
<td>Delaware</td>
</tr>
</tbody>
</table>

To further describe these line of duty death events, the following are some specific details of incidents where firefighter fatalities occurred during live fire training evolutions:

1) Two firefighters were killed in one incident when they were caught in a flashover during search and rescue training in an acquired structure. One was a 20-year-old in his first week on the fire department. The fire department had no written policy concerning live burns in acquired structures. The fire involved wooden pallets, straw and a foam mattress placed on the fire after it was ignited. Others involved in the training thought the search and rescue team had left the fire room, and could not determine why they had stayed in the room. A walk-through had been done before the exercise began.

2) An 18-year-old firefighter recruit died of smoke inhalation during a training exercise where he was playing the victim in an upstairs apartment of an acquired structure. In that exercise, in addition to a burn barrel, a fire was ignited in the foam mattress of a sleep sofa in the living room downstairs, close to the bottom of the stairs and quickly burned out of control. The officer in charge of the drill was convicted of negligent homicide. There was no pre-drill walkthrough; no one knew about the sofa fire; no safety line was in place; and no emergency evacuation ladders were in place. Two other firefighters were injured. This exercise was the first time the victim, who had received no formal training, wore SCBA in fire conditions. Although he was wearing his facepiece when found, his face was burned, indicating that he had removed the facepiece during the fire development.

3) A firefighter igniting the final burn in an acquired structure died of smoke inhalation and burns after he became trapped in the attic. The victim used atomized diesel fuel through a garden sprayer on combustibles and directly on a free-burning fire in the attic, resulting
in a flash fire. The combustibles used in the exercise included hay and debris found in the attic.

Aside from firefighter fatalities, each year a significant number of firefighters are injured while engaged in training exercises. During the 2011 calendar year 7,515 firefighters were injured during all types of training activities. The types of injuries are summarized in Table 2.\textsuperscript{6}

<table>
<thead>
<tr>
<th>Type of Injury</th>
<th>Number</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burns (Fire or Chemical)</td>
<td>165</td>
<td>2.2</td>
</tr>
<tr>
<td>Smoke or Gas Inhalation</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>Other Respiratory Distress</td>
<td>105</td>
<td>1.4</td>
</tr>
<tr>
<td>Burns and Smoke Inhalation</td>
<td>55</td>
<td>0.7</td>
</tr>
<tr>
<td>Wound, Cut, Bleeding Bruise</td>
<td>1,115</td>
<td>14.8</td>
</tr>
<tr>
<td>Dislocation, Fracture</td>
<td>270</td>
<td>3.6</td>
</tr>
<tr>
<td>Heart Attack or Stroke</td>
<td>60</td>
<td>0.8</td>
</tr>
<tr>
<td>Strain, Sprain Muscular Pain</td>
<td>4,680</td>
<td>62.3</td>
</tr>
<tr>
<td>Thermal Stress (frostbite, heat exhaustion)</td>
<td>375</td>
<td>5.0</td>
</tr>
<tr>
<td>Other</td>
<td>685</td>
<td>9.1</td>
</tr>
<tr>
<td>Total:</td>
<td>7,515</td>
<td>100</td>
</tr>
</tbody>
</table>

In addition to the casualty statistics, NIST has identified that from 2005-2010 there were 89 “near miss” incidents related to live fire training incidents.\textsuperscript{7} In these 89 incidents, 37 firefighters were burned or had PPE damage.

1.3 Previous Research on Training Fires at the Maryland Fire and Rescue Institute

In 2005, MFRI and the Department of Fire Protection Engineering at the University of Maryland conducted physiology tests on fire fighters during training evolutions at the MFRI four story structural firefighting building in College Park, MD.\textsuperscript{8} These evolutions consisted of a fuel package being ignited inside the third floor burn room and fire fighters entering the structure to extinguish the fire.

On two days of the testing, engineers from the Fire Research Division at NIST instrumented the burn room, placing a thermocouple array and heat flux gauge inside the room to monitor the thermal conditions inside the structure. Seven evolutions were conducted during the two days of testing with the NIST engineers present.

1.3.1 Facility Description

The four story MFRI structural firefighting building is shown in Figure 1. The walls are constructed of concrete block and the floors are made of concrete. The footprint of the building is approximately 12.6 m × 7.8 m and each floor is approximately 2.8 m in height.\textsuperscript{7} The floor plan of the third floor, where the tests took place, is presented in Figure 2. The floor plan depicts
the configuration of the rooms and locations of the four doors, five windows and six scuppers (scuppers are provided principally for water removal but also serve as a source of ventilation for the fire). The fuel package ignited during the tests was located in the burn room. The floor area of each room on the third floor is noted in Table 3.

The walls and ceilings are protected with three types of fire resistive materials. The first is a sprayed-on fire resistive material known as Pre-Krete G-8. Pre-Krete G-8 is composed of hydraulic calcium aluminate cement. The Pre-Krete G-8 is applied to the walls of the burn room and Room 2, as shown in Figure 3. The second type of fire resistive material used in the burn structure is 51 mm thick, high-temperature tiles composed of refractory concrete placed on top of a 25 mm thick insulation known as SuperTemp_L. The high temperature tile – insulation combination is attached to the ceiling of the third floor, along with the walls in Rooms 1, 2 and 3, as shown in Figure 4. The third type of fire resistive material is Duraliner HT insulating panels. These are attached to some of the walls in Room 1 as shown in Figure 5.

![Figure 1. MFRI Structural Firefighting Building](image-url)
Figure 2. Floor Plan of the Third Floor Structural Firefighting Building

Table 3. Room Floor Area in the Third Floor Burn Building

<table>
<thead>
<tr>
<th>Rooms in the Third Floor MFRI Structural Firefighting Building</th>
<th>Floor Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn Room</td>
<td>10.7 m² (115.2 ft²)</td>
</tr>
<tr>
<td>Room 1</td>
<td>30.9 m² (332.6 ft²)</td>
</tr>
<tr>
<td>Room 2</td>
<td>11.0 m² (118.4 ft²)</td>
</tr>
<tr>
<td>Room 3</td>
<td>19.6 m² (211.0 ft²)</td>
</tr>
</tbody>
</table>
Figure 3. Pre-Krete G-8 Sprayed-On Fire Protection Material on the Walls of the Burn Room and Room 2: Located on the Right Side of the Wall

Figure 4. High Temperature Tile on the Walls and Ceiling of Rooms 1, 2 and 3
1.3.2 Instrumentation

Instrumentation in the burn room consisted of an array of thermocouples and two heat flux gauges. Both devices were located in the corner of the burn room, directly across from the fire. The eight thermocouples on the thermocouple array were located at the following heights above the floor: 2.2 m (7.2 ft), 1.9 m (6.2 ft), 1.6 m (5.3 ft), 1.3 m (4.3 ft), 1.0 m (3.3 ft), 0.7 m (2.3 ft), 0.4 m (1.3 ft), and 0.1 m (0.3 ft). The heat flux gauges were facing the fire and located at heights of 1 m (3.3 ft) and 2 m (6.6 ft) above the floor.\(^7\)

1.3.3 Fuel Package

The fuel package used during these tests consisted of a half bale of excelsior and three wood pallets arranged in a triangular configuration as shown in Figure 6. The pallets were 1.22 m × 1.02 m × 0.13 m (4.00 ft × 3.35 ft × 0.43 ft). The moisture content was between (8 – 11 %). The three pallets combined weighed between 35 kg (77 lb) and 54 kg (119 lb). The excelsior weighed approximately 31 kg (68 lb).\(^8\)

1.3.4 Ambient Conditions

The ambient temperature inside the burn building was approximately 25 °C (77 °F) with a relative humidity of 66%.\(^8\)
1.3.5 Test Procedures

A four-person hose team staged outside the structure. At the start of the test, they advanced a 60 m (200 ft) hose line through the interior stairwell and positioned at the third floor door. The fuel package was ignited by a MFRI safety officer in full personal protective equipment. The hose team then advanced the attack line onto the third floor and positioned 1.5 m (5.0 ft) from the fire, holding that position for 4 minutes. After the 4 minutes, the hose-team extinguished the fire, and exited the burn building. The interior stairwell door connecting the second and third floor was open during the tests as a result of the attack line being advanced through the doorway.8

1.3.6 Results

On the two days of testing, four burn evolutions occurred on the first day and three evolutions occurred on the second day. The temperature and heat flux measurements from the first tests conducted on each day (Tests 1 and 5) were the only results analyzed because the conditions inside the structure during the first tests began at ambient conditions and were not impacted by preheating from prior burn evolutions.

The temperatures inside the burn room during Test 1 and Test 5 are presented in Figures 7 and 8.9 The temperature measurements recorded at 2.2 m (7.2 ft), 1.9 m (6.2 ft), 1.6 m (5.3 ft), 1.3 m (4.3 ft), 1.0 m (3.3 ft), 0.7 m (2.3 ft), 0.4 m (1.3 ft), and 0.1 m (0.3 ft) above the floor are displayed in each figure. Peak temperatures inside the burn room were between 650 (1202 °F) and 700 °C (1292 °F). The figures presenting the temperature readings show a large difference in temperature between 0.7 m (2.3 ft) and 0.4 m (1.3 ft), which indicates that the smoke layer height is somewhere between these two positions. The heat flux (HF) measurements inside the Burn Room at 1 m and 2 m above the floor are presented in Figure 9 and 10. The peak heat flux was 20 kW/m² (17.6 BTU/(ft²-s)) to 28 kW/m² (24.6 BTU/(ft²-s)) at 2 m and 8 kW/m² (7.0 BTU/(ft²-s)) to 10 kW/m² (8.8 BTU/(ft²-s)) at 1 m. Suppression occurred during Test 1 at 215 seconds, whereas suppression occurred during Test 5 at 330 seconds. The average temperature
measurements from Test 1 and 5 at each elevation are presented in Figure 11. The average heat flux measurements in the Burn Room at 1 and 2 m are presented in Figure 12. Beginning at 215 seconds, the average of the two tests is ended, given that in Test 1 suppression occurs at this point. As such the black lines in Figures 11 and 12 are solely from Test 5.

The thermocouples can measure the temperature in an environment with an estimated uncertainty reported to be ± 15%. The uncertainty of the heat flux gauges is ± 8%.  

![Figure 7. Test 1: Temperatures inside the Burn Room](image)

Temperature (°F) = Temperature (°C)*9/5+32

![Figure 8. Test 5: Temperatures inside the Burn Room](image)

Temperature (°F) = Temperature (°C)*9/5+32
Figure 9. Test 1: Heat Flux inside the Burn Room

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806

Figure 10. Test 5: Heat Flux inside the Burn Room

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Some firefighters experienced initial failures of their gear including “helmet delaminationed [sic] and, on one occasion, a visor started to bubble.” Because the thermocouple array and the heat flux gauge was located closer to the fire than the firefighters were, these measurements obtained during the tests would be greater than experienced by the firefighters.
Chapter 2: Overview of the CFAST Model

2.1 CFAST Overview

CFAST is the fire model selected to simulate thermal conditions generated by training fires in this project. The initial applications of the model are intended to replicate conditions generated by the training fires at the MFRI structural firefighting building described in the previous section. Next, CFAST is used to assess the impact that changes in fuel packages, ventilation strategies, room sizes and sequential burn evolutions have on the thermal conditions inside the burn room.

CFAST was developed in 1990 by the Fire Research Division of the NIST to provide researchers and engineers with an ability to model compartment fires. CFAST can be used to determine smoke production, heat transfer, smoke movement through ventilation openings, thermal impact on targets, heat detector response, and water spray from sprinklers within a compartment fire.

CFAST is a simple two-zone fire model that divides a compartment into two control volumes, a hot upper-layer and a cool lower-layer. In the lower-layer, a fire is prescribed that creates a fire plume based on its HRR. The fire entrains air in the lower-layer, while at the same time, it releases heat and transfers mass, i.e. smoke, into the upper-layer. CFAST is able to determine the thermal conditions in each zone by solving conservation of mass and energy equations and incorporating the ideal gas law into its evaluation. CFAST has been validated and verified (V & V) for a variety of fire modeling applications identified in Table 4.

The remainder of this chapter addresses the construction of the model to simulate the third floor of the MFRI structural firefighting building. Chapter 3 provides a validation of the CFAST model by comparing model results to the MFRI test measurements presented in section 1.3 and also presents an analysis that assesses the impact of slight variations in selected input parameters on the output from the model. In Chapter 4, the application of CFAST to explore the effects of various fuel packages, ventilation arrangements, room sizes and sequential burn evolutions is described.

2.2 Input Data

Input for CFAST includes parameters such as ambient conditions, compartment dimensions, thermal properties of room enclosure materials, horizontal and vertical vents, mechanical ventilation, targets, and fire properties. All of the input data for the CFAST simulations of the burn room were obtained from references documenting the previous research and in-person inspections. Even though the inputs are adequately described in the references, uncertainty is still present for some of the input parameters, including thermal properties of room enclosure materials, the HRR of the fuel package, leakage through openings, and compartment ventilation. As noted in section 1.3.6, the uncertainty of the reported temperature and heat flux is ± 15% and ± 8%. Also, the HRR data recorded at NIST under the oxygen depletion calorimeter has an estimated uncertainty of ± 11% and the mass of the fuel has an uncertainty of ± 0.05 kg.
Table 4 - CFAST Capabilities from a Validation and Verification (V & V) study

<table>
<thead>
<tr>
<th>Fire Phenomena</th>
<th>Algorithm/Methodology</th>
<th>V &amp; V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room With Natural Ventilation</td>
<td>Two-zone control volume model with uniform conditions in a zone</td>
<td>Yes</td>
</tr>
<tr>
<td>Predicting Hot Gas Layer Temperature in a Room Fire with Forced Ventilation</td>
<td>Two-zone control volume model with uniform conditions in a zone</td>
<td>Yes</td>
</tr>
<tr>
<td>Predicting Hot Gas Layer Temperature in a Fire Room with Door Closed</td>
<td>Two-zone control volume model with uniform conditions in a zone</td>
<td>Yes</td>
</tr>
<tr>
<td>Estimating Gas Concentration Resulting from a Fire</td>
<td>User-specified time varying smoke yield from fire; global conservation of mass</td>
<td>Yes</td>
</tr>
<tr>
<td>Estimating Visibility Through Smoke</td>
<td>User-specified time varying smoke yield from fire; global conservation of mass</td>
<td>Yes</td>
</tr>
<tr>
<td>Estimating Flow Through Horizontal or Vertical Natural Flow Vents</td>
<td>Empirical correlation; global conservation of mass</td>
<td>No</td>
</tr>
<tr>
<td>Estimating Flow Through Horizontal or Vertical Forced Flow Vents</td>
<td>Global conservation of mass</td>
<td>No</td>
</tr>
<tr>
<td>Estimating Radiant Heat Flux From Fire to a Target</td>
<td>Point source radiation from fire; four-surface radiation from compartment surfaces; gray gas absorption by gas layers</td>
<td>Yes</td>
</tr>
<tr>
<td>Estimating the Ignition Time of a Target Fuel</td>
<td>One dimensional heat conduction in solid</td>
<td>No</td>
</tr>
<tr>
<td>Estimating Sprinkler Activation</td>
<td>RTI Algorithm</td>
<td>No</td>
</tr>
<tr>
<td>Suppression by Water Spray</td>
<td>Empirical correlation</td>
<td>No</td>
</tr>
<tr>
<td>Estimating Smoke and Heat Alarm Response Time</td>
<td>One dimensional heat conduction in solid</td>
<td>No</td>
</tr>
<tr>
<td>Estimating Pressure Rise Attributable to a Fire in a Closed Compartment</td>
<td>Global conservation of mass and energy</td>
<td>Yes</td>
</tr>
<tr>
<td>Estimating flow in corridor</td>
<td>Empirical algorithm based on FDS simulations</td>
<td>No</td>
</tr>
</tbody>
</table>
2.2.1 Model Geometry

There are four rooms on the third floor MFRI structural firefighting building. A floor plan for the third floor was presented previously in Figure 2. Because Rooms 1 and 3 are not rectangular, the CFAST simulation artificially divided these rooms into compartments as indicated in Figure 13. Room 1 contains Compartments 1 and 6 and Room 3 contains Compartments 3 and 4. Compartment 5 is located within Rooms 1 and is the location where the interior stairwell connects to the third floor. The burn room is located between Rooms 1 and 2. Table 5 provides the dimensions of all of the compartments used in the model.

![Figure 13. Compartment Layout of the MFRI Third Floor Live Fire Training Facility](image)

Table 5 - Compartment Dimensions in the Third Floor MFRI Live Fire Training Facility

<table>
<thead>
<tr>
<th>Compartment Name</th>
<th>Dimensions (Length, Width, Height)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn Room</td>
<td>3.38 m × 3.18 m × 2.80 m (11.09 ft × 10.43 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 1</td>
<td>5.28 m × 4.54 m × 2.80 m (17.32 ft × 14.90 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 2</td>
<td>3.45 m × 3.18 m × 2.80 m (11.32 ft × 10.43 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 3</td>
<td>5.26 m × 2.58 m × 2.80 m (17.26 ft × 8.47 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 4</td>
<td>3.12 m × 1.92 m × 2.80 m (10.24 ft × 6.30 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 5</td>
<td>1.57 m × 1.36 m × 2.80 m (5.15 ft × 4.46 ft × 9.19 ft)</td>
</tr>
<tr>
<td>Compartment 6</td>
<td>2.46 m × 1.63 m × 2.80 m (8.07 ft × 5.35 ft × 9.19 ft)</td>
</tr>
</tbody>
</table>
2.2.2  **Thermal Properties of Room Enclosure Materials**

In CFAST, the thermal properties of the room enclosure materials (floors, walls and ceilings) need to be specified. The five materials at the MFRI structural firefighting building incorporated into the CFAST model are:

1. 64 mm (2.52 in) of Pre-Krete G-8 was applied to the walls in the burn room and Compartment 2. The high temperature tiles are attached to SuperTemp_L insulation to most of the walls and all of the ceiling on the third floor.
2. Fire resistant block panels are on parts of the walls in Compartment 1.
3. The load-bearing walls in the training facility are composed of hollow-core cinder blocks and in Compartment 5 and 6 the cinder block wall is exposed.
4. All of the fire resistant materials are applied to the 32 mm (1.26 in) thick face of the hollow-core masonry block.
5. The floors are made of 200 mm (7.87 in) thick concrete.

The thermal properties of each material are provided in Appendix A. CFAST only allows the user to apply one individual material to the floor, walls and ceiling of each compartment. However, in some compartments, surfaces may be comprised of composite assemblies comprised of multiple material layers. In these cases, the material that is covering most of the surface is the one applied to the entire surface of the model. Also, there are multiple materials incorporated into the fire resistant materials and the fire resistant materials are then applied to the masonry block in the structural firefighting building. For such composite assemblies, effective properties were determined to characterize the thermal properties of the composite assemblies. The procedure for determining the effective properties of composite assemblies is presented in Appendix A. The effective thermal properties of the assemblies comprising the floors, walls and ceilings in the used in the CFAST model are presented in Table 6. Also note that the emissivity of the surfaces is assumed to be the CFAST default value of 0.9.

### Table 6 - Effective Thermal Properties of Materials used in the Model Simulation

<table>
<thead>
<tr>
<th>Material Combinations</th>
<th>Thermal Conductivity</th>
<th>Density</th>
<th>Specific Heat</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tile - Insulation – Masonry Block</strong></td>
<td>0.3448 W/mK (0.199 BTU/fhr°F)</td>
<td>1562 kg/m³ (97.5 lb/ft³)</td>
<td>1.02 kJ/kgK (0.24 BTU/lb°F)</td>
<td>0.1071 m (0.3514 ft)</td>
</tr>
<tr>
<td><strong>Spray-on Insulation – Masonry Block</strong></td>
<td>0.159 W/mK (0.092 BTU/fhr°F)</td>
<td>2087 kg/m³ (130 lb/ft³)</td>
<td>1.07 kJ/kgK (0.26 BTU/lb°F)</td>
<td>0.0925 m (0.3035 ft)</td>
</tr>
<tr>
<td><strong>Fire Resistant Block Panel</strong></td>
<td>0.340 W/mK (0.196 BTU/fhr°F)</td>
<td>1570 kg/m³ (98 lb/ft³)</td>
<td>0.9 kJ/kgK (0.21 BTU/lb°F)</td>
<td>0.0254 m (0.0833 ft)</td>
</tr>
<tr>
<td><strong>Concrete</strong></td>
<td>1.63 W/mK (0.942 BTU/fhr°F)</td>
<td>2300 kg/m³ (144 lb/ft³)</td>
<td>1 kJ/kgK (0.24 BTU/lb°F)</td>
<td>0.2 m (0.065 ft)</td>
</tr>
<tr>
<td><strong>Masonry Block</strong></td>
<td>0.881 W/mK (0.509 BTU/fhr°F)</td>
<td>1997 kg/m³ (125 lb/ft³)</td>
<td>0.94 kJ/kgK (0.23 BTU/lb°F)</td>
<td>0.0317 m (0.104 ft)</td>
</tr>
</tbody>
</table>
2.2.3 Ventilation

CFAST allows the user to place vents (scuppers, windows, and doors) on the walls of the structure. These vents can be fully open, completely closed or partially open. The location of each vent is shown in Figure 13.

The four doors on the third floor are located in Compartments 2, 3, 5 and 6. Madrzykowski and Opert state that “all but the stairwell door and the main interior door remained closed throughout all of the tests”. The stairwell door in Compartment 5 is fully open during the entire simulation because in the MFRI tests the engine company advanced the attack line onto the third floor via the stairwell doorway (in Compartment 5). The exterior doors (Compartments 2 & 3) are 0.86 m (2.82 ft) wide and 2.23 m (2.82 ft) tall, while the stairwell doors (Compartments 5 & 6) are 1.016 m (3.33 ft) width and 2.23 m (7.32 ft) tall. Each door has an 89 mm (3.5 in) gap at the base. Small gaps were assumed around the sides and top of each door to incorporate leaks around all four sides of the door. Doors comparable to the ones in the MFRI structural firefighting building possess an estimated upper-limit leakage flow area of 0.0475 m² (0.511 ft²). Dividing this flow area proportionately among the gaps on the sides and top of the doors, the gaps along the sides of the doors were assumed to be 0.0071 m (0.023 ft) wide and at the top of the door, the gap was assumed to be 0.019 m wide.

Three windows are located in Compartment 1, one in Compartment 2 and one in Compartment 3. The windows are between 0.84 m (2.76 ft) and 1.04 m (3.41 ft) wide and 1.14 m (3.74 ft) tall. The five windows located on the third floor were completely closed during the simulation. All the windows have a 12.7 mm (0.5 in) gap at the bottom. A conservative leakage flow area of 0.0475 m² (0.511 ft²) was also applied to the middle and top of the windows in the model. The middle gap, where the windows open, has a gap that is 0.0206 m (0.0676 ft) wide and the top gap is 0.0228 m (0.0748 ft) wide.

Six scuppers are located along the floor in Compartments 1, 2, 3 and 4. The scuppers are 0.4 m wide and 0.2 m (0.7 ft) tall. In order to simulate a partially open scupper, the scuppers are set to be 10% open during the simulation to estimate for the leakage through the gap at the bottom of the scuppers.

2.2.4 Fire Properties

The HRR input used in the model is based on experiments conducted at the NIST Large Fire Research Facility. NIST conducted two tests under an oxygen consumption cone calorimeter in a “false-corner” to capture the HRR of the fuel package used in the MFRI tests. Figure 14 provides a photograph of one of the tests conducted by NIST. The “false-corner” is used to represent the influence that the walls and ceiling have on the HRR of the fuel package due to thermal reradiation back to the fire. The properties of the fuel packages burned during the two tests, which are also the same as those used in the MFRI tests, are presented in Table 7.
Table 7 - NIST Oxygen Cone-Calorimeter Tests Fuel Properties

<table>
<thead>
<tr>
<th>Fuel Package Properties</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of Excelsior</td>
<td>14.8 kg (32.6 lb)</td>
<td>14.8 kg (32.6 lb)</td>
</tr>
<tr>
<td>Mass of Three Pallets</td>
<td>55.9 kg (123.2 lb)</td>
<td>53.9 kg (118.8 lb)</td>
</tr>
<tr>
<td>Total Mass of Fuel Package</td>
<td>70.7 kg (155.9 lb)</td>
<td>68 kg (150 lb)</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>6 – 11 %</td>
<td>7 – 12 %</td>
</tr>
<tr>
<td>Pallet Dimensions</td>
<td>48 x 40 x 5 in (122 x 102 x 13 cm)</td>
<td>48 x 40 x 5 in (122 x 102 x 13 cm)</td>
</tr>
<tr>
<td>Configuration</td>
<td>Triangle</td>
<td>Triangle</td>
</tr>
</tbody>
</table>

Figure 15 shows the HRR curves of Tests 1 and 2 in purple and green and also shows the average HRR of the two tests in blue. Often, fire instructors will stoke a fire prior to beginning a burn evolution so that the fire is in the growth stage once firefighters make entry into the live fire training facility. Therefore, the average HRR curve was adjusted backwards 48.5 seconds to create the black HRR curve for the CFAST model, assuming heat is released immediately following ignition.
Figure 15. HRR curves of the Triangular Fuel Packages used in the MFRI Tests

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]

In the CFAST model, the fire was placed in the corner of the burn room as shown in Figure 13 and 14. The fuel package is assumed to have a radiative fraction of 0.35 and a lower oxygen limit of 13%.\textsuperscript{13,14}

2.2.5 Environmental Parameters

Because each MFRI test took up to 350 sec prior to the suppression of the fire, every simulation was conducted for 400 seconds. The relative humidity and ambient temperature inside the model were set to 25 °C (77 °F) and 66 % respectively.\textsuperscript{8} No wind influence was considered in the model.

2.2.6 Targets

Targets that measure the temperature and heat flux were placed in the model of the burn room. These targets were positioned in the same locations as the MFRI test thermocouple array and heat flux gauges. The location was 2.61 m (8.56 ft) in the x direction or 0.61 m (2.00 ft) off the north wall and 2.57 m (8.43 ft) in the y direction or 0.77 m (2.53 ft) off the east wall. The targets faced the fuel package.
Chapter 3: CFAST Validation & Sensitivity Analysis

3.1 Fire Model Validation

A validation analysis is conducted to confirm that a fire model can realistically predict selected output parameters that are of interest for a particular application. In the context of this project, estimates of the thermal conditions, i.e. temperature of the upper layer and heat flux received at a target, are sought. For this project, the CFAST model for the MFRI structural firefighting building is validated by comparing simulation results of the upper layer temperature and heat flux in the burn room to measurements of these two outputs in the burn room. Once CFAST is validated, key input parameters can be altered to assess the effects that these inputs have on the thermal conditions within the burn room.

Measurements of the upper layer temperature in the burn room were obtained by TC’s 3, 4, 5, 6, 7 and 8. The upper layer temperature measurements prior to suppression and the simulation results from CFAST are presented in Figure 16, where the measured upper layer temperatures are averaged from Tests 1 and 5 for the three thermocouples. Figure 16 shows that the CFAST MFRI model predicts on the upper end of the temperature measurements, but temperature measurements were also not recorded above 2.2 m (7.2 ft) to the ceiling at 2.8 m (9.2 ft). Therefore the results from CFAST compare reasonably well to the temperature measurements during the MFRI test, hence validating CFAST to estimate the temperature of the upper smoke layer within the burn room.

![Figure 16. Estimated and Simulated Upper Layer Temperature in Burn Room during MFRI Tests 1 & 5](image)

Temperature (°F) = Temperature (°C)*9/5+32
The heat flux predicted by CFAST and measurements from the heat flux gauge in the MFRI tests are presented in Figure 17. Both the target in the model and the heat flux gauge in the experiment were located 2 m (6.6 ft) above the floor and approximately 2 m (6.6 ft) away from the fire. As with the temperature predictions, the estimated heat flux by CFAST compares favorably to the measurements. CFAST was unable to predict the heat flux measurements at 1 m.

![Figure 17. Estimated and Simulated Heat Flux in Burn Room during MFRI Tests 1 & 5](chart)

**Figure 17. Estimated and Simulated Heat Flux in Burn Room during MFRI Tests 1 & 5**

Heat Flux (BTU/(ft²-s) = Heat Flux (kW/m²) * 0.08806

### 3.2 Sensitivity Analysis

A sensitivity analysis is performed to help determine the input parameters of the model that are the most influential in affecting the results. In this project, the sensitivity analysis was done informally, i.e. after establishing a baseline model, selected input parameters were varied ±10% individually in order to determine the effect that the variation of that single input parameter had on the results. The sensitivity analysis done for this project focused on the following input parameters: room enclosure material’s thermal properties, the HRR of the fuel package, and leakage through vents.

The impact of increasing and decreasing the thermal properties (thermal conductivity, density and specific heat) of the building materials by ±10% is presented in Figure 18 and 19. As indicated in the Figure 18, the upper layer temperature is virtually unaffected by these changes in the thermal properties. The impact of changing the thermal properties ±10% results in a difference in heat flux of 1.0 kW/m² (0.088 BTU/ft²-s) to 1.5 kW/m² (0.13 BTU/ft²-s), representing about a 10% change in the total heat flux.
The influence of the HRR of a fuel package is depicted in Figure 20 and 21. As indicated in Figure 20, varying the HRR by ±10% results in a ±50 °C (122 °F) change in upper layer temperature. Results of varying the HRR by ±10% yields a variation of ±3 kW/m² (0.26 BTU/ft²-s) in the heat flux, as shown in Figure 21. With these results, it is evident that HRR of the fuel package is very influential in affecting the thermal conditions in the burn room. This observation is in agreement with Peacock and Reneke who observed the HRR to be the most sensitive physical input parameter included in CFAST.¹⁰

The sensitivity of the upper layer temperature and heat flux on the leakage areas through the vents and other surfaces are illustrated in Figure 22 and 23. As indicated in the figures, the thermal conditions inside the burn room are not affected significantly by the changes considered in the leakage area.

A summary of the set of simulations done to explore the impact of variations in input parameters on thermal conditions in the burn room is presented in Figure 24 and 25. These figures reinforce the comments made previously, i.e. that the changes in HRR are at the extreme ends of the set of curves and hence are noted as being the most influential.
Figure 18. Sensitivity Analysis: Upper Layer Temperature in the Burn Room when the Thermal Properties are changed ±10 %

Temperature (°F) = Temperature (°C) * 9/5 + 32

Figure 19. Sensitivity Analysis: Heat Flux at 2 m above the Floor in the Burn Room when the Thermal Properties are changed ±10 %

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Sensitivity Analysis: Upper Layer Temperature in the Burn Room when the HRR is changed ±10 %

Temperature (°F) = Temperature (°C) * 9/5 + 32

Sensitivity Analysis: Heat Flux at 2 m above the Floor in the Burn Room when the HRR is changed ±10 %

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Figure 22. Sensitivity Analysis: Upper Layer Temperature in the Burn Room when the Leakage through Vents is changed ±10%

Temperature (°F) = Temperature (°C) * 9/5 + 32

Figure 23. Sensitivity Analysis: Heat Flux at 2 m above the Floor in the Burn Room when the Leakage through Vents is changed ±10%

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Figure 24. Sensitivity Analysis: Upper Layer Temperature in the Burn Room when the Input Parameters are changed ±10 %

Temperature (°F) = Temperature (°C) * 9/5 + 32

Figure 25. Sensitivity Analysis: Heat Flux at 2 m above the Floor in the Burn Room when the Input Parameters are changed ±10 %

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Chapter 4: Key Factors that Influence the Thermal Conditions of a Live Fire Training Evolution

The intent of this chapter is to identify the components that have the greatest influence on the thermal conditions within the burn room of a live fire training facility. The analysis is conducted using CFAST to assess conditions produced in several scenarios that include a variety of fuel packages, ventilation strategies, and room sizes, thereby expanding the information gleaned from the analysis of the MFRI room. Also, the impact of sequential live fire burn evolutions is explored to identify the role of initial ambient conditions on the subsequent thermal conditions over the course of multiple burn evolutions.

The role of each of the four parameters factors (fuel package, ventilation strategy, room size and sequential live fire burn evolutions) is evaluated independently. While the specific temperatures and heat fluxes for a particular scenario may be of interest, the emphasis of this analysis is to compare the effects of changes in a selected parameter.

4.1 Fuel Packages

The fuel packages are characterized in terms of the HRR, composition, total mass, configuration and location. Data on the HRR of a few types of fuel packages commonly used during live fire training evolutions has been collected by NIST. The properties of the fuel packages used for the five scenarios (including the fuel package used during the MFRI tests) and an image of each fuel package configuration is presented in Table 8.

4.1.1 Overview of Fuel Packages

Each fuel package consists of wood pallets, bales of excelsior or both. The fuel packages vary in composition, mass, configuration and location.

1. Fuel composition: Scenario F1, Scenario F3 and Scenario F4 use fuel packages that are composed of mostly wood pallets and some excelsior, Scenario F2 has a fuel package composed of only excelsior and Scenario F5 incorporates a mix of both wood pallets and excelsior into the fuel packages. Some fuel packages contain 6 pallets, while others possess 3 pallets. One test has a full bale of excelsior while most of the other tests utilize a half bale of excelsior.

2. Fuel mass: The fuel packages vary in mass from 29.6 kg (65.3 lb) to 112.6 kg (248.2 lb). The large wood pallets are 1.22 m × 1.02 m × 0.127 m (4.0 ft × 3.3 ft × 0.42 ft) in size, weigh approximately 18.2 kg (40.1 lb) and are used in most of these fuel packages. In contrast, small wood pallets are 0.94 m × 0.94 m × 0.089 m (3.0 ft × 3.0 ft × 0.30 ft) in size, weigh about 9.2 kg (20.3 lb) and are used in the Scenario F5 fuel package. A half bale of excelsior weighs 14.8 kg (32.6 lb) and a full bale of excelsior weighs approximately 30 kg (60 lb).

3. Fuel package configuration: four configurations of fuel packages have been characterized: stacked, upright, pile, triangle, and flat. Stacked, upright and triangle orientations are often referred to as vertically oriented, while flat configurations are referred to as horizontally-oriented.

4. Location within burn room: fuel packages are commonly burned in the corner of burn rooms to maximize the HRR and take advantage of effects due to compartmentation.
When a fire is located near a wall or in a corner, it reduces the amount of air that can be entrained to the fire, which reduces the cooling effect that air has on the fire. Further, close proximity to walls enhances the burning rate of the fire by providing radiative feedback to the fuel. All of the fuel packages were burned in a false-corner under an oxygen cone calorimeter. Therefore, these fuel packages were placed in the corner of the burn room in the model.

The HRR curve of the MFRI Triangle fuel package is presented in Figure 15 and the HRR curve for the other fuel packages listed in Table 8 that were tested by NIST are presented in Figure 26 through 30. The HRR curve shown on Figure 26 through 30 were adjusted back 25 seconds to account for the delay in producing a notable heat release. The fuel packages tested by NIST took up to 50 seconds before they began releasing a noticeable amount of heat. Looking at results from the actual MFRI tests (Figure 7 through 12), the temperature rise occurs soon after the test begins and the heat flux begins rises about 25 seconds after ignition. This implies that during the MFRI tests, the fire was releasing heat soon after ignition.

The HRR curves presented in Figure 26 through 30 are the adjusted curves that were implemented into the model scenarios and the actual HRR curves reported by NIST are presented in Appendix A. Two curves are presented in each figure. The blue curve is the actual HRR curve measured by NIST prior to the 25 second adjustment. The black curve is the HRR curve of the fuel package being applied to the model. The time of the black HRR curve was adjusted backwards 25 seconds to match the correction that was made to the MFRI Triangle HRR curve.

The Stacked Pallets (Scenario F1, Figure 26) and the Upright P & E (Scenario F3, Figure 28) possess the greatest HRR with peaks of approximately 4,500 kW (1.5*10^7 BTU/hr) and 4,250 (1.45*10^7 BTU/hr) kW, respectively. Both of these tests contain 6 large wood pallets, with the greatest mass and with both oriented in a vertical manner. The Excelsior Pile (Scenario F2, Figure 27), and Small Triangle P & E (Scenario F5, Figure 30) possess the least HRR of approximately 2,000 kW (0.68*10^7 BTU/hr). It is evident that the vertically oriented fuel packages with the greatest mass also have the greatest HRR. Conversely, the fuel packages with the least mass or a flat orientation (Scenario F4, Figure 29) have the least HRR.
<table>
<thead>
<tr>
<th>Simulation No. &amp; Name</th>
<th>Composition</th>
<th>Mass</th>
<th>Configuration</th>
<th>Location in Burn Room</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRI Triangle</td>
<td>3 wood pallets, ½ bale of excelsior</td>
<td>≈ 69.3 kg (152.8 lb)</td>
<td>Triangle</td>
<td>Corner</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>F1. Stacked Pallets</td>
<td>6 wood pallets, ½ bale of excelsior</td>
<td>112.6 kg (248.2 lb)</td>
<td>Stacked</td>
<td>Corner</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>F2. Excelsior Pile</td>
<td>1 bale of excelsior</td>
<td>29.6 kg (65.3 lb)</td>
<td>Pile</td>
<td>Corner</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>F3. Upright P &amp; E</td>
<td>6 wood pallets, ½ bale of excelsior</td>
<td>98.8 kg (218.8 lb)</td>
<td>Upright</td>
<td>Corner</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>F4. Flat P &amp; E</td>
<td>6 wood pallets, ½ bale of excelsior</td>
<td>97.2 kg (214.3 lb)</td>
<td>Flat</td>
<td>Corner</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Scenario F5</td>
<td>Description</td>
<td>Triangle</td>
<td>Corner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------------------------------------</td>
<td>----------</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Triangle P &amp; E</td>
<td>3 wood pallets, ½ bale of excelsior</td>
<td>34.9 kg (76.9 lb), 49.7 kg (109.6 lb)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 26. HRR curve of Scenario F1. Stack Pallets**

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]

**Figure 27. HRR Curve of Scenario F2. Excelsior Only**

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]
Figure 28. HRR Curve of Scenario F3. Upright Pallets & Excelsior

\[ \text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412 \]

Figure 29. HRR Curve of Scenario F4. Flat Pallets & Excelsior

\[ \text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412 \]
4.1.2 Results of Fuel Package Scenarios

All of the model scenarios were simulated for 350 seconds. The HRR curve is used to characterize each fuel package because it is the primary component that influences the thermal conditions during live fire training evolutions. Figure 31 and 32 are graphs that compare the F1 fuel package HRR curve to the model’s estimation of temperature and heat flux. The HRR of a fuel package is responsible for spreading heat throughout the model and therefore it influences the temperature and heat flux in the structure. Both graphs demonstrate the correlation between the HRR profile and the temperature and heat flux curves.
Figure 31. Test 1 Pallets Stacked: Comparison of the HRR Curve to the Temperature in the Burn Room

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²)*0.08806, Temperature (°F) = Temperature (°C)*9/5+32

Figure 32. Test 1 Pallets Stacked: Comparison of the HRR Curve to the Heat Flux in the Burn Room

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²)*0.08806, Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²)*0.08806
Temperature and heat flux predictions from the various fuel package model scenarios are presented in Figure 33 and 34. The temperature and heat flux measurements are compared to results from the CFAST model of the MFRI tests (black line). The temperature of the upper smoke layer within the burn room is shown in Figure 33. In Figure 34, the heat flux to the target within the burn room is presented, where the target is 2 m (6.6 ft) high and a 2 m (6.6 ft) distance from the fire. The peak temperature and heat flux estimations for each scenario are listed in Table 9 along with the differences in these measurements compared to the baseline model of the MFRI tests. As indicated in the two figures and the table, the thermal conditions within the burn room are affected significantly by the selection of fuel package. The triangle fuel package used during the MFRI tests, being used as a baseline for comparisons, creates temperatures and heat fluxes that reach 664 °C (1227 °F) and 17 kW/m² (1.5 BTU/ft²-s) respectively.

![Figure 33. Fuel Load Effects: Upper Layer Temperature in the within the Burn Room](image)

Temperature (°F) = Temperature (°C) * 9/5 + 32
Figure 34. Fuel Load Effects: Heat Flux to the Target in the Burn Room to Target 2 m High and 2m from the Fire

Heat Flux (BTU/(ft\(^2\)-s)) = Heat Flux (kW/m\(^2\)) * 0.08806

Table 9 - Fuel Load Scenarios Compared to the Baseline MFRI Simulation

<table>
<thead>
<tr>
<th>Scenario No. &amp; Name</th>
<th>Peak Temperature</th>
<th>Temperature Differences</th>
<th>Peak Heat Flux</th>
<th>Difference in Heat Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRI Triangle</td>
<td>664 °C (1227 °F)</td>
<td>—</td>
<td>17 kW/m(^2) (1.5 BTU/ft(^2)-s)</td>
<td>—</td>
</tr>
<tr>
<td>F1. Stacked Pallets</td>
<td>990 °C (1814 °F)</td>
<td>+ 326 °C (619 °F)</td>
<td>45 kW/m(^2) (4.0 BTU/ft(^2)-s)</td>
<td>+ 28 kW/m(^2) (2.5 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>F2. Excelsior Pile</td>
<td>571 °C (1060 °F)</td>
<td>- 93 °C (199 °F)</td>
<td>12.5 kW/m(^2) (1.1 BTU/ft(^2)-s)</td>
<td>- 4.5 kW/m(^2) (0.4 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>F3. Upright P &amp; E</td>
<td>944 °C (1731 °F)</td>
<td>+ 280 °C (537 °F)</td>
<td>39 kW/m(^2) (3.4 BTU/ft(^2)-s)</td>
<td>+ 22 kW/m(^2) (1.9 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>F4. Flat P &amp; E</td>
<td>555 °C (1031 °F)</td>
<td>- 109 °C (228 °F)</td>
<td>11.6 kW/m(^2) (1.0 BTU/ft(^2)-s)</td>
<td>- 5.4 kW/m(^2) (0.5 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>F5. Small Triangle P &amp; E</td>
<td>538 °C (1000 °F)</td>
<td>- 126 °C (259 °F)</td>
<td>10.6 kW/m(^2) (0.9 BTU/ft(^2)-s)</td>
<td>- 6.4 kW/m(^2) (0.6 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>F6. Center Triangle P &amp; E</td>
<td>569 °C (1056 °F)</td>
<td>- 95 °C (203 °F)</td>
<td>10.2 kW/m(^2) (0.9 BTU/ft(^2)-s)</td>
<td>- 6.8 kW/m(^2) (0.6 BTU/ft(^2)-s)</td>
</tr>
</tbody>
</table>
4.1.3 Analysis of Fuel Package Scenarios

Based on the CFAST results provided in Figure 33, Figure 34 and Table 9, it is evident that the fuel packages arranged in a vertical manner (either stacked or vertical) release the greatest amount of energy and therefore create the most severe thermal conditions within the burn room among all the fuel packages considered in this analysis. The results also show that heavy fuel packages do not always produce large amounts of heat. The fuel package in Scenario F4 consisted of pallets and excelsior stacked flat on top of one another in a horizontal fashion. This fuel package produced a peak HRR of approximately 2,000 kW \( (0.68 \times 10^7 \text{BTU/hr}) \), even though this fuel package weighed 2 – 3 times as much as some of the other packages producing 2,000 kW \( (0.68 \times 10^7 \text{BTU/hr}) \). Compared to the fuel package burned during the MFRI tests, the flat fuel package created thermal conditions that were much less severe. Also, the flat fuel package took longer (i.e. five minutes) to reach a maximum HRR and peak thermal conditions. These fuel packages may be suitable for long-duration training evolutions.

There were two other fuel packages that had a HRR around 2,000 kW \( (0.68 \times 10^7 \text{BTU/hr}) \): Excelsior Pile and Small Triangle Pallets & Excelsior. The Excelsior Pile has a HRR curve that peaks quickly to 2,360 kW \( (0.81 \times 10^7 \text{BTU/hr}) \) and then rapidly decays, is similar to the generated temperature and heat flux histories depicted in Figure 33 and Figure 34. The Excelsior Pile fuel package enables fire instructors to quickly heat up the live fire training facility but fuel will quickly be consumed. While the Small Triangle Pallets & Excelsior utilized wood pallets that were smaller in size, with a less amount of mass and therefore produced less heat than the triangular fuel package used during the MFRI tests.

4.2 Ventilation Strategies

This section identifies the various ventilation strategies that can be used to limit the thermal conditions inside the burn room during a live fire training evolution that is fuel limited. These strategies include having a remote window or door remain open during a fire training evolution or opening a vent during an evolution to horizontally ventilate smoke and heat from the compartment. Windows are considered medium size vents, whereas doors are considered to be a large vent.

4.2.1 Overview of Ventilation Scenarios

The ventilation strategies considered in the simulated scenarios are summarized in Table 10. Scenario V1 through V6 simulate leaving a remote vent open during the entire duration of a burn evolution, whereas Simulation V7 mimics instantaneous horizontal ventilation in the burn room when thermal conditions are at their peak. The location of a vent can be: close, mid range and at a far distance from the fire. A close vent is an opening in the burn room, a mid range vent is an opening in a compartment adjacent to the burn room and a far vent is an opening that is at a distance location relative to the burn room. Table 10 shows the area of each of the vents, their distance relative to the fire, the compartment they are located in and the radial distance from the
fire. During the MFRI tests, the interior stairwell door in Compartment 5 is open throughout the test, though no vents were present in the burn room. Therefore, during these scenarios, the stairwell door is open in addition to the scenario vents.

### Table 10 - Ventilation Strategy Type

<table>
<thead>
<tr>
<th>Scenario No. and Name</th>
<th>Vent Size</th>
<th>Vent Area (m²)</th>
<th>Vent Location</th>
<th>Radial Distance from Fire (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1. Window - Close</td>
<td>Medium</td>
<td>1.23 m² (13.24 ft²)</td>
<td>Burn Room</td>
<td>2.8 m 3.3 ft</td>
</tr>
<tr>
<td>V2. Door - Close</td>
<td>Large</td>
<td>1.92 m² (20.74 ft²)</td>
<td>Burn Room</td>
<td>2.8 m 3.3 ft</td>
</tr>
<tr>
<td>V3. Window - Mid Range</td>
<td>Medium</td>
<td>0.97 m² (10.48 ft²)</td>
<td>Compartment 1</td>
<td>5.36 m 17.58 ft</td>
</tr>
<tr>
<td>V4. Door – Mid Range</td>
<td>Large</td>
<td>1.92 m² (20.74 ft²)</td>
<td>Compartment 2</td>
<td>4.72 m 15.48 ft</td>
</tr>
<tr>
<td>V5. Window - Far</td>
<td>Medium</td>
<td>1.20 m² (12.96 ft²)</td>
<td>Compartment 1</td>
<td>5.97 m 19.58 ft</td>
</tr>
<tr>
<td>V6. Door - Far</td>
<td>Large</td>
<td>1.92 m² (20.74 ft²)</td>
<td>Compartment 3</td>
<td>6.51 m 21.53 ft</td>
</tr>
<tr>
<td>V7. Horizontal Ventilation</td>
<td>Medium</td>
<td>1.23 m² (13.28 ft²)</td>
<td>Burn Room</td>
<td>2.8 m 9.2 ft</td>
</tr>
</tbody>
</table>

#### 4.2.2 Results of Ventilation Scenarios

The model estimations of the thermal conditions during the various ventilation scenarios are presented in Figure 35 and 36. The temperature of the upper layer in the burn room is shown in Figure 35 and the heat flux in the burn room at 2 m (6.6 ft) high and away from the fire is presented in Figure 36. The figures compare the temperature and heat flux estimations from the modeling scenarios to the results from the model representing the MFRI test (black line). Table 11 presents the results from these scenarios by displaying the peak temperature and heat flux estimations for scenarios V1 through V6 to the baseline model of the MFRI tests. The impact that horizontal ventilation had during scenario V7 is depicted in Table 12 by showing the temperature and heat flux decrease over a short period of time.
Figure 35. Ventilation Strategy Effects: Temperature of the Upper Smoke Layer in the Burn room

Temperature (°F) = Temperature (°C) * 9/5 + 32

Figure 36. Ventilation Strategy Effects: Heat Flux to the Target in the Burn Room 2 m High and Away from the Fire

Heat Flux (BTU/(ft²-s)) = Heat Flux (kW/m²) * 0.08806
Table 11 - Ventilation Strategy Resulting Peak Temperature and Heat Flux Compared to the Baseline MFRI Tests

<table>
<thead>
<tr>
<th>Scenario No. &amp; Name (From Largest to Least Impact)</th>
<th>Peak Temperature</th>
<th>Temperature Difference</th>
<th>Peak Heat Flux</th>
<th>Heat Flux Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRI Tests</td>
<td>664 °C (1227 °F)</td>
<td>-</td>
<td>17 kW/m² (1.5 BTU/ft²-s)</td>
<td>-</td>
</tr>
<tr>
<td>V1. Window - Close</td>
<td>562 °C (1044 °F)</td>
<td>- 102 °C (216 °F)</td>
<td>13.3 kW/m² (1.2 BTU/ft²-s)</td>
<td>- 3.7 kW/m² (0.3 BTU/ft²-s)</td>
</tr>
<tr>
<td>V2. Door - Close</td>
<td>519 °C (966 °F)</td>
<td>- 145 °C (293 °F)</td>
<td>12.2 kW/m² (1.1 BTU/ft²-s)</td>
<td>- 4.8 kW/m² (0.4 BTU/ft²-s)</td>
</tr>
<tr>
<td>V4. Door – Mid Range</td>
<td>586 °C (1087 °F)</td>
<td>- 78 °C (172 °F)</td>
<td>14 kW/m² (1.2 BTU/ft²-s)</td>
<td>- 3 kW/m² (0.3 BTU/ft²-s)</td>
</tr>
<tr>
<td>V6. Door - Far</td>
<td>596 °C (1105 °F)</td>
<td>- 68 °C (154 °F)</td>
<td>14.2 kW/m² (1.3 BTU/ft²-s)</td>
<td>- 2.8 kW/m² (0.2 BTU/ft²-s)</td>
</tr>
<tr>
<td>V5. Window - Far</td>
<td>625 °C (1157 °F)</td>
<td>- 39 °C (102 °F)</td>
<td>15.1 kW/m² (1.3 BTU/ft²-s)</td>
<td>- 2.9 kW/m² (0.3 BTU/ft²-s)</td>
</tr>
<tr>
<td>V3. Window – Mid range</td>
<td>632 °C (1170 °F)</td>
<td>- 32 °C (90 °F)</td>
<td>15.3 kW/m² (1.3 BTU/ft²-s)</td>
<td>- 1.7 kW/m² (0.1 BTU/ft²-s)</td>
</tr>
</tbody>
</table>

Table 12 - Ventilation Strategy Results for Scenario V7 Horizontal Ventilation

<table>
<thead>
<tr>
<th>Scenario No. &amp; Name</th>
<th>Temperature Decrease During Ventilation (°C)</th>
<th>Heat Flux Decrease During Ventilation (kW/m²)</th>
<th>Time Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V7. Horizontal Ventilation</td>
<td>78 °C (172 °F)</td>
<td>2.3 kW/m² (0.2 BTU/ft²-s)</td>
<td>20</td>
</tr>
</tbody>
</table>

4.2.3 Analysis of Ventilation Scenarios

Leaving a vent open in the burn room, such as a window or door, significantly decreases the thermal conditions in the burn room. Open vents that are in the burn room result in a large decrease in temperature and heat flux. An open vent in the burn room causes a majority of smoke and heat to leave the structure and therefore a limited amount will fill the rest of the rooms in the fire training structure. This strategy is an effective way to reduce the temperatures and heat flux in the burn room but it may create an inadequate training environment because of the lack of smoke in the structure.
The results also indicate that large vents, whether they are one or two rooms away from the fire, have the same effect on the thermal conditions in the burn room. Opening a smaller vent in remote rooms, such as a window, also decreases the upper layer temperature and heat flux, though at a lesser amount than the large vents.

Another ventilation strategy that is effective at quickly lowering thermal conditions inside the training facility is horizontal ventilation. As indicated in Figure 35, Figure 36 and Table 12, within 20 seconds thermal conditions in the burn room quickly decrease as a result of horizontal ventilation.

4.3 Room Size

This section reports the influence that burn room size has on the thermal conditions within that room during a training burn evolution. Room size (i.e. volume) dictates the distribution of heat within the space. When a fire occurs in a large volume of space, it has more space to distribute smoke and therefore heat is less concentrated. Conversely, rooms with small volumes distribution heat to less area resulting in more severe thermal conditions in that room.

4.3.1 Overview of Room Size Scenarios

The burn room floor areas and volumes for each modeling scenario are presented in Table 13. All the models utilize a burn room with a ceiling height of 2.8 m (9.2 ft) so that the variation in floor area is assessed. The MFRI burn room has a floor area of 3.38 m × 3.18 m (11.1 ft × 10.4 ft). The remaining include floor areas that range from being small to large. In order to maintain the layout of the MFRI third floor live fire training facility, the other compartments in the live fire training facility had to be increased or decreased once the burn room dimensions were increased or decreased. The MFRI Triangle fuel package and HRR curve was used during each room size simulation.

<table>
<thead>
<tr>
<th>Test No. &amp; Name</th>
<th>Floor Area (m × m)</th>
<th>Ceiling Height (m)</th>
<th>Room Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRI Burn Room</td>
<td>3.38 × 3.18 m × m</td>
<td>2.8 m (9.2 ft)</td>
<td>30.1 m³ (1063 ft³)</td>
</tr>
<tr>
<td>R1. 2 × 2</td>
<td>2 × 2 m (6.6 ft × 6.6 ft)</td>
<td>2.8 m (9.2 ft)</td>
<td>11.2 m³ (395.5 ft³)</td>
</tr>
<tr>
<td>R2. 4 × 4</td>
<td>4 × 4 m × m (13 ft × 13 ft)</td>
<td>2.8 m (9.2 ft)</td>
<td>44.8 m³ (1582 ft³)</td>
</tr>
<tr>
<td>R3. 5 × 5</td>
<td>5 × 5 m × m (16.4 ft × 16.4 ft)</td>
<td>2.8 m (9.2 ft)</td>
<td>70 m³ (2472 ft³)</td>
</tr>
<tr>
<td>R4. 6 × 6</td>
<td>6 × 6 m × m (19.6 ft × 19.6 ft)</td>
<td>2.8 m (9.2 ft)</td>
<td>100.8 m³ (3560 ft³)</td>
</tr>
</tbody>
</table>
4.3.2 Results of Room Size Scenarios

The results from the room size scenarios are presented in Figure 37 and 38. The temperature of the upper layer in the burn room is displayed in Figure 37, while the heat flux in the burn room at 2 m (6.6 ft) high and 2 m (6.6 ft) away from the fire is presented in Figure 38. The peak temperature and heat flux estimations for each room size scenario are presented in Table 14 along with the differences in these measurement compared to the baseline model of the MFRI tests.

![Figure 37. Burn Room Size: Temperature of the Upper Smoke Layer in the Burn Room](image)

Temperature (°F) = Temperature (°C)*9/5+32
Figure 38. Burn Room Size: Heat Flux in the Burn Room at 2 m

Heat Flux (BTU/(ft\(^2\)-s)) = Heat Flux (kW/m\(^2\))\(*0.08806

Table 14 - Room Size Scenario Results: Comparing the Peak Temperature and Heat Flux of each Room Size Scenario to the Conditions during the MFRI Model

<table>
<thead>
<tr>
<th>Scenario No. &amp; Name</th>
<th>Peak Temperature</th>
<th>Temperature Difference</th>
<th>Peak Heat Flux</th>
<th>Heat Flux Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRI Burn Room</td>
<td>664 °C (1227 °F)</td>
<td>-</td>
<td>17 kW/m(^2) (1.5 BTU/ft(^2)-s)</td>
<td>-</td>
</tr>
<tr>
<td>R1.  2 × 2</td>
<td>746 °C (1375 °F)</td>
<td>+ 82 °C (180 °F)</td>
<td>38.3 kW/m(^2) (3.4 BTU/ft(^2)-s)</td>
<td>+ 21.3 kW/m(^2) (1.9 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>R2.  4 × 4</td>
<td>617 °C (1143 °F)</td>
<td>- 47 °C (117 °F)</td>
<td>14.2 kW/m(^2) (1.2 BTU/ft(^2)-s)</td>
<td>- 2.8 kW/m(^2) (0.2 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>R3.  5 × 5</td>
<td>558 °C (1036 °F)</td>
<td>- 106 °C (223 °F)</td>
<td>12.1 kW/m(^2) (1.1 BTU/ft(^2)-s)</td>
<td>- 4.9 kW/m(^2) (0.4 BTU/ft(^2)-s)</td>
</tr>
<tr>
<td>R4.  6 × 6</td>
<td>507 °C (945 °F)</td>
<td>- 157 °C (315 °F)</td>
<td>12.7 kW/m(^2) (1.1 BTU/ft(^2)-s)</td>
<td>- 4.3 kW/m(^2) (0.4 BTU/ft(^2)-s)</td>
</tr>
</tbody>
</table>
4.3.3 Analysis of Room Size Scenarios

In Chapter 4.3, the size of the MFRI burn room was varied with all other parameters kept the same as in the MFRI tests. In Figure 37, Figure 38, and Table 14 the smallest room is observed to have the most severe thermal conditions, whereas the largest room has the least severe conditions.

4.4 Time Between Sequential Burn Evolutions

This section of the report uses the MFRI model to simulate multiple burn evolutions over a short period of time to identify the trend that thermal conditions continually increase over the course of consecutive burn evolutions. The results of these scenarios will be used to identify the role that ambient temperature have on the upper layer peak temperature and heat flux within the burn room.

4.4.1 Overview of Sequential Burn Evolutions Scenarios

The details of each modeling scenario used to determine the effects that sequential burn evolutions have on the initial ambient and peak thermal conditions within the burn room of the MFRI live fire training facility are presented in Table 15. Each fuel package is burned for 350 seconds, prior to a simulated suppression taking place, where the HRR decreases to 0 immediately. Once the simulated suppression occurs, another fuel package is ignited after the set amount of time, shown in Table 15. For the four scenarios, the duration of time between sequential burn evolutions was: 1 minute, 5 minutes, 10 minutes and 20 minutes. Due to model limitations, a vent can only be open or closed once during a simulation. In order to simulate ventilation due to the stairwell doors being open during burn evolutions and closed between evolutions, the interior stairwell door was set to be halfway open. This simulates the loss of heat and smoke while the stairwell door is open during an evolution, but also limits the heat lost much like a closed door would do while all vents are closed between evolutions.

<table>
<thead>
<tr>
<th>Scenario No. and Name</th>
<th>Duration Between Burn Evolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. 1 Minute **</td>
<td>60 seconds</td>
</tr>
<tr>
<td>S2. 5 Minutes</td>
<td>300 seconds</td>
</tr>
<tr>
<td>S3. 10 Minutes</td>
<td>600 seconds</td>
</tr>
<tr>
<td>S4. 20 Minutes</td>
<td>1200 seconds</td>
</tr>
</tbody>
</table>

** A one minute duration between sequential burn evolutions is unrealistic but it is evaluated in this report to provide an array of results to compare
4.4.2 Results of Sequential Burn Evolutions Scenarios

The results from the four scenarios where a one, five, ten and twenty minute pause occurred between each burn evolution are displayed in Figure 39 and 40. The initial ambient and peak temperatures in the burn room over the course of five consecutive burn evolutions are presented in Figure 39. The initial and peak heat flux in the burn room at 2 m (6.6 ft) high and 2 m (6.6 ft) away from the fire in the burn room over the course of five consecutive burn evolutions are presented in Figure 40. Each scenario’s estimation of the initial and peak temperature and heat flux for the first and fifth burn evolution are listed in Table 16. The results presented in Table 16 demonstrate how the time between burn evolutions makes an impact on the thermal conditions inside the live fire training facility over the course of five sequential burn evolutions.

![Figure 39. Duration Between Burn Evolutions: Temperature of the Smoke Layer in the Burn Room](image)

Temperature (°F) = Temperature (°C) × 9/5 + 32
Figure 40. Duration Between Burn Evolutions: Heat Flux at 2 m Height in the Burn Room

Heat Flux (BTU/(ft$^2$-s)) = Heat Flux (kW/m$^2$) * 0.08806

Table 16. Time Between Sequential Burn Evolution: Initial and Peak Temperature and Heat Flux during Burn Evolution 1 Compared to Burn Evolution 5

<table>
<thead>
<tr>
<th>Scenario No. &amp; Name</th>
<th>Burn Evolution 1</th>
<th>Burn Evolution 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Temp.</td>
<td>Peak Temp.</td>
</tr>
<tr>
<td>S1. 1 Minute</td>
<td>23.9 kW/m$^2$</td>
<td>168 °C (334 °F)</td>
</tr>
<tr>
<td></td>
<td>0 kW/m$^2$</td>
<td>841 °C (1546 °F)</td>
</tr>
<tr>
<td></td>
<td>25 °C (77 °F)</td>
<td>13.3 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.2 kW/m$^2$</td>
<td>56.5 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.2 BTU/ft$^2$-s</td>
<td>(5.0 BTU/ft$^2$-s)</td>
</tr>
<tr>
<td>S2. 5 Minutes</td>
<td>24.8 kW/m$^2$</td>
<td>133 °C (271 °F)</td>
</tr>
<tr>
<td></td>
<td>0 kW/m$^2$</td>
<td>824 °C (1515 °F)</td>
</tr>
<tr>
<td></td>
<td>2.2 kW/m$^2$</td>
<td>7.3 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.2 BTU/ft$^2$-s</td>
<td>(0.6 BTU/ft$^2$-s)</td>
</tr>
<tr>
<td></td>
<td>25 °C (77 °F)</td>
<td>49.6 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>0 kW/m$^2$</td>
<td>(4.4 BTU/ft$^2$-s)</td>
</tr>
<tr>
<td>S3. 10 Minutes</td>
<td>25.5 kW/m$^2$</td>
<td>111.5 °C (233 °F)</td>
</tr>
<tr>
<td></td>
<td>0 kW/m$^2$</td>
<td>808 °C (1486 °F)</td>
</tr>
<tr>
<td></td>
<td>2.2 kW/m$^2$</td>
<td>4.9 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.2 BTU/ft$^2$-s</td>
<td>(0.4 BTU/ft$^2$-s)</td>
</tr>
<tr>
<td></td>
<td>713 °C</td>
<td>44.6 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.2 kW/m$^2$</td>
<td>(3.9 BTU/ft$^2$-s)</td>
</tr>
<tr>
<td>S4. 20 Minutes</td>
<td>26.1 kW/m$^2$</td>
<td>99 °C (210 °F)</td>
</tr>
<tr>
<td></td>
<td>0 kW/m$^2$</td>
<td>798 °C (1468 °F)</td>
</tr>
<tr>
<td></td>
<td>2.3 kW/m$^2$</td>
<td>3.5 kW/m$^2$</td>
</tr>
<tr>
<td></td>
<td>2.3 BTU/ft$^2$-s</td>
<td>(0.3 BTU/ft$^2$-s)</td>
</tr>
</tbody>
</table>
4.4.3 Analysis of Sequential Burn Evolution Scenarios

The trend of rising peak thermal conditions inside the burn room over the course of multiple sequential burn evolutions is illustrated in Figure 39, Figure 40 and Table 16. The results in Figure 39, Figure 40 and Table 16 also show that as more time is taken between burn evolutions, the conditions inside the burn room become less severe. When 1 minute is taken between sequential burn evolutions, thermal conditions inside the burn room are the most severe. Thermal conditions inside the training facility continually rise during each burn evolution, but the peak conditions are the least severe when longer periods of time are taken between burn evolutions.
Chapter 5: Conclusion

5.1 Summary

During live fire training evolutions within training structures, firefighter trainees and instructors are sometimes exposed to dangerous thermal conditions that possess extreme temperatures and high heat fluxes. These incidents are preventable and have caused injuries and deaths. Live fire training becomes dangerous when unsafe fuel packages are burned, inappropriate ventilation is provided, exercises are conducted in small rooms and sequential burn evolutions occur with minimal time between burn evolutions. NFPA 1403 provides minimal guidance to fire instructors as to the suitable fuel packages that may be burned, how to properly ventilate during training, appropriate burn room sizes and safe methodology for conducting sequential burn evolutions. It is proposed that a hazard assessment is incorporated into NFPA 1403 which will enable fire instructors who are planning live fire training to assess the potential thermal conditions that will be generated during their planned burn evolution.

This simple study focused on identifying the factors that influence the thermal conditions during a live fire training evolution. Tests were conducted at MFRI as part of a previous study to simulate a typical live fire training evolution and temperature and heat flux measurements were recorded within the burn room of the structure. A computer fire model, CFAST was used to replicate the third floor of the MFRI live fire training building and simulate the tests that occurred. The results of the model compare reasonably well to the measurements of temperatures and heat flux at a 2 m (6.6 ft) height taken during the MFRI tests which validates the use of the model for this analysis. The model was unable to validate the heat flux at a 1 m (3.3 ft) height.

A sensitivity analysis was then performed by varying the key input parameter: room enclosure material’s thermal properties, the HRR of the fuel package, and leakage through vents ±10% in order to determine which components have the most influence on the results of the model. HRR has the most influence on the final results, followed by leakage through vents and room enclosure material’s thermal properties.

The model was then used to simulate multiple scenarios with a range of fuel packages, ventilation strategies, room sizes and time between sequential burn evolutions in order to determine the factors that have the greatest influence on the thermal conditions within the burn room of the MFRI training facility.

Of the four parameters considered, the fuel package is the most influential in affecting the development of thermal conditions within the burn room. Every fuel package has a HRR that depends on its composition, mass, configuration and location. Of the fuel packages considered in this analysis, vertically oriented fuel packages that are either stacked or upright create the most severe thermal conditions, triangular configured fuel package create moderate thermal conditions, and horizontally oriented fuel packages that are stacked in a flat configuration, create
the least severe thermal conditions. Also, an excelsior pile quickly reaches its peak thermal conditions but rapidly decays. The appropriate fuel package size and configuration should be selected based on the burn building, the level of the students, and the training objectives for each evolution.

Ventilation plays a key role during training evolutions. When a fire is fuel limited, ventilating will cool the structure by releasing hot smoke and gases. If the fuel package being burned inside a compartment does not have enough oxygen to burn sufficiently, it is ventilation limited and ventilating will supply the fire with oxygen, increase the HRR of the fuel and the thermal conditions inside the structure will elevate. Ventilation strategies for a fuel limited fire include; leaving a remote window or door open during a training evolution or horizontally ventilating. Leaving windows or doors open in the burn room and adjacent rooms causes a significant reduction in thermal conditions. Horizontally ventilating quickly reduces the temperature and heat flux in the burn room over a short period of time.

The size of the rooms that the fuel package is burned in is another important parameter that dictates the thermal conditions within the training structure. Given the same fuel packages and HRR input, small room have the potential to have the most severe thermal conditions, whereas larger rooms will have the least severe thermal conditions.

During training, multiple live fire evolutions occur over the course of a day. It was observed that as sequential burn evolutions occur, the initial ambient temperature inside the training facility continually rises and yields peak thermal conditions that are more severe than the previous burn evolution. When minimal time is taken between sequential burn evolutions, thermal conditions can quickly become severe. As the duration between burn evolutions is extended, the severity of the thermal conditions inside the structure is decreased.

In live fire training facilities, various types of insulating materials are commonly applied to the walls and ceilings of burn rooms. These materials have thermal properties that possess the ability to have a slight impact on the development of thermal conditions within burn facilities under the limited set of conditions examined and limitations of the model.

5.2 Future Research

1. Use a CFD model to determine the impact that fuel package location has on the conditions within a burn evolution
2. Heat release rate measurements need to be conducted to characterize a broader range of fuel package that is typically burned during live evolutions. This includes fuel packages with excelsior, straw, pallets, gas burners in varying configurations and masses.
3. Perform multiple field experiments in live fire training structures and measure the thermal conditions created when well characterized fuel packages are burned. Tests will occur in burn rooms that vary in size and are composed of differing building construction materials. Tests also need to analyze the effect that fuel package location has on the
thermal environment inside the training facility and how the various methods used to cool the facility between evolutions affect the thermal conditions.

4. Develop a validated hazard assessment tool that fire instructors can use to estimate safe fire conditions for their proposed live fire training evolution. The tool will allow the instructor to select the fuel package being burned and input details about the training facility (room dimensions and wall materials) and estimate the resulting thermal conditions.

5. Validate the hazard assessment tool by conducting field experiments in training buildings and acquired structures that have an array of construction types representing acquired structures (e.g., masonry, uninsulated steel, insulated steel panels, gypsum over wood frame construction, etc). Calculations that predict the minimum HRR needed to flashover the space in training facility will be validated.
Appendix A

The individual thermal properties for each material are presented in Table A1. Some of the thermal properties are reported by manufacturers of the product and others are estimated based on the average of the noted references.

Table A1 - Thermal properties of the building materials and fire resistive materials in the MFRI fire training facility

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity</th>
<th>Density</th>
<th>Specific Heat</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PreKrete G-8</td>
<td>0.113 W/mK$^a$</td>
<td>2197 kg/m$^3$</td>
<td>1.2 kJ/kgK$^{17}$</td>
<td>0.064 m $^7$</td>
</tr>
<tr>
<td></td>
<td>(0.0653 BTU/fthr°F)</td>
<td>(137 lb/ft$^3$)</td>
<td>(0.29 BTU/lb°F)</td>
<td>(0.21 ft)</td>
</tr>
<tr>
<td>High Temperature Tiles</td>
<td>1.53 W/mK$^b$</td>
<td>2403 kg/m$^3$</td>
<td>0.92 kJ/kgK$^{18}$</td>
<td>0.05 m $^7$</td>
</tr>
<tr>
<td></td>
<td>(0.902 BTU/fthr°F)</td>
<td>(150 lb/ft$^3$)</td>
<td>(0.22 BTU/lb°F)</td>
<td>(0.16 ft)</td>
</tr>
<tr>
<td>SuperTemp_L</td>
<td>0.105 W/mK$^{22}$</td>
<td>288 kg/m$^3$</td>
<td>1.2 kJ/kgK$^{17}$</td>
<td>0.025 m $^{22}$</td>
</tr>
<tr>
<td></td>
<td>(0.0607 BTU/fthr°F)</td>
<td>(18 lb/ft$^3$)</td>
<td>(0.29 BTU/lb°F)</td>
<td>(0.08 ft)</td>
</tr>
<tr>
<td>Duraliner HT</td>
<td>0.34 W/mK$^{25}$</td>
<td>1570 kg/m$^3$</td>
<td>0.92 kJ/kgK$^{18}$</td>
<td>0.03 m $^7$</td>
</tr>
<tr>
<td></td>
<td>(0.196 BTU/fthr°F)</td>
<td>(98 lb/ft$^3$)</td>
<td>(0.22 BTU/lb°F)</td>
<td>(0.1 ft)</td>
</tr>
<tr>
<td>Hollow-Core Cinder Block</td>
<td>0.881 W/mK$^c$</td>
<td>1997.3 kg/m$^3$</td>
<td>0.94 kJ/kgK$^c$</td>
<td>0.032 m $^{27}$</td>
</tr>
<tr>
<td></td>
<td>(0.509 BTU/fthr°F)</td>
<td>(125 lb/ft$^3$)</td>
<td>(0.22 BTU/lb°F)</td>
<td>(0.1 ft)</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.63 W/mK$^{26}$</td>
<td>2300 kg/m$^3$</td>
<td>1.0 kJ/kgK$^{26}$</td>
<td>0.2 m $^7$</td>
</tr>
<tr>
<td></td>
<td>(0.942 BTU/fthr°F)</td>
<td>(144 lb/ft$^3$)</td>
<td>(0.24 BTU/lb°F)</td>
<td>(0.06 ft)</td>
</tr>
</tbody>
</table>

Notes:

$^a$ Based on the average of the following references: 17 18
$^b$ Based on the average of the following references: 18 20
$^c$ Based on the average of the following references: 24 25 26

A.1 Effective Thermal Properties

CFAST only allows one material to be applied to the surface of the floors, walls and ceiling, even though there are multiple materials on a majority of these surfaces. For instance, the walls in the burn room have a spray on insulation covering the cinder block wall. Effective thermal properties had to be determined that would adequately define the combination of these materials. The following methods is used to determine the effective thermal conductivity for the spray on
insulation (PreKrete G-8) covering the cinder block and the high temperature tile applied to the insulation (SuperTemp_L) that is applied to cinder block.

Effective Thermal Conductivity

Equation 1 is the conduction heat transfer equation to determine heat flux through multiple materials.

\[ q'' = \frac{\Delta T}{L_1/k_1 + L_2/k_2} \]  \[ 1 \]

Where \( q'' \) is heat flux, \( \Delta T \) is the temperature change, \( L \) is the length of the materials and \( k \) is the thermal conductivity of the respective materials.

Focusing on \( L_1/k_1 + L_2/k_2 \), the effective thermal conductivity can be determined based on equation 2 and 3.

\[ \frac{L_{\text{eff}}}{k_{\text{eff}}} = \frac{L_1}{k_1} + \frac{L_2}{k_2} \]  \[ 2 \]

\[ k_{\text{eff}} = \frac{L_{\text{eff}}}{L_1/k_1 + L_2/k_2} \]  \[ 3 \]

Where \( k_{\text{eff}} \) and \( L_{\text{eff}} \) is the effective thermal conductivity and effective length of the combined materials. \( L_{\text{eff}} \) is total thickness of the combined materials.

Average Density and Average Specific Heat

The combined materials have a density and specific heat that is based on the average of the individual thermal properties making up the combined materials.
Appendix B. HRR Curves for the Fuel Packages

The following is figures display the HRR curves for the fuel packages used in the scenarios in Chapter 4.1. The parameters for each fuel package are presented in Table 8.

Figure B1. HRR curve of Scenario F1. Stack Pallets

\[ \text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412 \]

Figure B2. HRR Curve of Scenario F2. Excelsior Only

\[ \text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412 \]
Figure B3. HRR Curve of Scenario F3. Upright Pallets & Excelsior

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]

Figure B4. HRR Curve of Scenario F4. Flat Pallets & Excelsior

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]

Figure B5. HRR Curve of Scenario F5. Small Triangle Pallet & Excelsior

\[
\text{HRR (BTU/hr)} = \text{HRR (kW)} \times 3412
\]
References

11. Floyd JE (2002) Comparison of CFAST and FDS for Fire Simulation with the HDR T51 and T52 Tests, NISTIR 6866, National Institute of Standards and Technology, Gaithersburg, MD
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