Costa Rica National Fire Academy Live-Fire Training Structure

An Interactive Qualifying Project Report

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science by:

Hannah Borges

Liam Spence

Ava Schlesinger

Connor Sullivan

Sponsored by:

EL BENEMÉRITO CUERPO DE BOMBEROS DE COSTA RICA

Professor James Chiarelli, Co-Advisor

Professor Pratap Rao, Co-Advisor

ABSTRACT

The Bomberos of Costa Rica are the country's only firefighters and they do not conduct any live-fire training, which is not only impractical but also dangerous. Our goal was to define the requirements needed for a live-fire training structure tailored to their needs. This was achieved by conducting extensive research and interviews with professionals. In doing so, our final recommendations were compiled into an optimized design, modeled in 3D software, and cost analyzed, to present to the Bomberos.

ACKNOWLEDGEMENTS

We are extremely thankful for all who participated in this project and made it a successful one. Our team would like to extend our sincere gratitude to our sponsors, El Benemérito Cuerpo de Bomberos de Costa Rica, with a special thanks to Allan Rodríguez, Alejandro Rosales, Norman Chang, and Cindy Quesada. Allan and Alejandro made our communication with Costa Rica go very smoothly and were always available to answer any questions. With the current COVID-19 setting, their dedication to our project was extremely helpful to obtain all the information we needed.

We would like to thank all of the professional firefighting individuals and organizations that took time out of their day to speak with us and answer our questions. Each interview provided us with new information and insight into fire training and tower design. Without them, this project never would have been possible. We would like to thank the Worcester Fire Department; the Massachusetts Firefighting Academy; the Troy, NY Fire Department; the Rhode Island Fire Academy; WHP Training Towers; and the WPI Fire Protection Engineering Department.

We would also like to thank our advisors, Professors Jim Chiarelli and Pratap Rao, for providing us with the support and feedback to see this project through to its completion. Their guidance allowed us to achieve our goal.

Finally, we would like to thank Worcester Polytechnic Institute for continuing to enable us to engage in this project, despite the unusual global situation. We are grateful that we were still able to have the experience of the Interdisciplinary Qualifying Project even with the pandemic.

EXECUTIVE SUMMARY

The fire department of Costa Rica, known as El Benemérito Cuerpo de Bomberos de Costa Rica (The Meritorious Team of Costa Rican Firefighters), is a government organization that is responsible for controlling fires and maintaining the safety of Costa Rican citizens. The Bomberos have to prepare for potential disasters caused by the rapidly increasing population by training to handle fires in multiple-story buildings. They respond to emergencies related to hazardous material management, natural disasters, extreme weather events, and anything else that involves helping people in distress. The firefighters live for their mission, which is to provide prevention and protective services in order to safeguard life, property and the environment (Bomberos, 2020).

The Bomberos were seeking design recommendations for a new live-fire training structure that will be specifically crafted to mimic real life fire scenarios they will encounter. This structure will allow different kinds of practices, as well as the use of real fire, which is a pressing need for the Costa Rican academy. There were many considerations that needed to be made, so our team performed extensive research in order to gain an understanding of the firefighters' needs, the budget for the project, and learn the necessary requirements to design a safe and effective training structure.

Goals, Objectives and Methodology

The goal of our project was to investigate and define the elements needed to design a live-fire training structure on the Bomberos' training ground. This structure will be capable of enhancing the firefighters' emergency response abilities by providing a myriad of new evolutions

that were not achievable with their existing training tower. We focused on maintaining high levels of safety while accounting for feasibility to ensure that the training structure is well-received by the Bomberos. The following were determined to be the objectives for the project:

1. Develop an understanding of existing live-fire training structure technology as well as the current needs of the Bomberos;
2. Research and analyze the National Fire Protection Association (NFPA) code;
3. Interview various professionals in the area of fire;
4. Establish a set of requirements needed to construct a live-fire training structure for the Bomberos of Costa Rica;
5. Electronically model our recommended tower.

Major Findings

Through extensive research on fire training structures, interviews with firefighting professionals and analysis of the National Fire Protection Association (NFPA) code, we acquired our five major findings.

1. Types of Training Procedures. Fire training structures are a vital aid in training and practicing life-saving rescues and procedures in the event of a fire. These drills are known as evolutions, also known as the prescribed actions that result in an effective training activity (NFPA 1402, 2019). NFPA 1001 (2019) requires firefighters to have the ability to conduct a search and rescue in a structure while operating as a member of a team with a given assignment and obscured vision conditions. The goal of a search and rescue is to search all assigned areas, locate and remove all victims, maintain team integrity and safety, and ensure respiratory protection is not compromised (NFPA 1001, 2019). The most commonly trained forms of rescue are rope rescue and laddering. According to the National Fire Protection Agency, rope rescue training includes understanding, directing and operating simple rope-lowering systems from various heights in both high- and low-angle environments (Sturkol, 2018). These evolutions are practiced by use of a training tower, and arguably the most valuable form of skill and knowledge training is live-fire training. A live-fire training structure is defined as a structure utilized for conducting live-fire training evolutions on a repetitive basis. All fire departments in the United States train with a live-fire structure to teach and practice the necessary skills to work as a professional firefighter.

2. Existing Tower. The current on-site tower at the San José National Fire Training Academy is an open-air structure consisting of eight floors, an interior stairwell, and concrete slab floors. According to our sponsor, the Bomberos train by teaching the proper extinction practices and giving theoretical training on the subject, however they do not practice extinguishing fires inside a structure. This is a major concern, and therefore, the need for a new training tower equipped with the capability of producing live-fire is an absolute necessity to properly train the firefighters of Costa Rica.

3. Functionality of Requested Design Elements. The Bomberos' original requests consisted of a four-story, above ground live-fire structure with two below-grade basements and an interior stairwell. Other considerations requested were an LPG fuel system, thermal imaging, smoke suppression and ventilation systems. These requests were then compared with NFPA standards to determine what had to be included and then researched for practicality and associated costs to develop a cohesive final design.

4. Tower Design Iterations. Once we had developed an understanding of the Bomberos' needs, our team began brainstorming basic tower designs. Rather than immediately attempting to model an entire facility, we decided to propose a basic layout and make continuous improvements over the course of the project.

5. **Feasibility of Tower Implementation.** In order to make educated decisions during the modeling process, we decided to define three separate towers. Each of these had certain features that were attractive based on the Bomberos' needs, but there were some trade-offs that had to be made as well. To streamline our approach in making these decisions, we utilized a weighted Pugh matrix. Using the Pugh Matrix helped us prioritize each of the requests that the Bomberos made. By developing the list of general criteria, each of the three tower designs could be compared effectively. Since there were multiple considerations that needed to be made, the matrix was instrumental in establishing the team's rationale.

Recommendations

Based on our findings, the team came up with a specific set of recommendations with regards to the design of the tower. Although there are additional considerations that can be addressed, we provided a definitive list to avoid any sort of ambiguity with the design.

We recommend that El Cuerpo de Bomberos constructs a concrete structure. In communications with professionals and in research, we found concrete is the better choice for the fire training tower material because of its greater resistance to repeated exposure to extreme temperatures. Additionally, a concrete tower is more resistant to high winds and earthquakes, and its installation is not as complicated as that of steel.

We recommend that El Cuerpo de Bomberos uses a liquid petroleum gas system. The liquid petroleum gas system was initially requested by the Bomberos. During our research and interviews, the group confirmed that it is the most ideal for the Bomberos' needs. This system is more environmentally friendly than burning hay and pallets. It allows a clean burn in comparison to other types of fire ignition systems that produce more harmful emissions. The system is controlled by an external control center where the fire can be monitored by adjusting valves and regulating the gas flow to ensure safety during evolutions.

We recommend that El Cuerpo de Bomberos constructs a half-basement. During our discussions with various professionals from fire departments, we learned that implementing a full below-grade basement equipped with live-fire into the tower design would not meet NFPA standards. It would also be too dangerous so the team concluded that the best alternative would be for the Bomberos to construct a half below-grade basement at the base of the structure. This layout offers many features of a traditional basement, but also ensures that firefighters will have more than one form of egress from the fire. The floor plans and model that we designed show the half below-grade basement and additional features that meet NFPA design requirements for means of egress by use of window and door placement.

Conclusion

The goal of this project was to define the requirements of a live-fire training structure and recommend a design for the National Fire Academy in San José. We achieved this goal by researching, conducting interviews and consulting NFPA codes. This helped to gain a foundational understanding of firefighter training requirements and how these can be carried out utilizing a live-fire training structure. We then justified the Bomberos' need for a tower and compared their initial requests with the feasibility of inclusion. Upon determining the necessary elements, three potential towers were designed and quantitatively analyzed to determine the best option in regard to several considerations. The final option was further developed by including an in depth three-dimensional model and cost analysis. The implementation of a new fire-training tower will not only drastically enhance the Bomberos' knowledge and skill in regards to safeguarding property, but will help them save hundreds of lives lost to fire.

Table of Authorship

Section	Primary Author(s)	Editor(s)
Abstract	Ava	All
Acknowledgements	Connor	All
Executive Summary	All	Hannah
1. Introduction	All	All
2. Background	All	All
2.1 El Cuerpo de Bomberos	Hannah	All
2.2 Firefighter Training	Hannah	All
2.2.1 Training Practices Around the World	Hannah	All
2.2.2 Training Practices in Costa Rica	Hannah	All
2.3 Future Considerations and Aspirations	Liam	All
2.3.1 Current Designs in the United States	Liam	All
2.3.2 Tower Design	Connor, Liam	All
2.3.3 Water Collection and Smoke Suppression	Connor	All
2.3.4 LPG	Ava	All
2.3.5 Thermal Imaging	Ava	All
2.4 The National Fire Protection Association	Ava	All
2.4.1 Global Influence	Ava	All
2.4.2 NFPA Codes in Costa Rica	Ava	All
2.5 Conclusion of Background Review	Liam	All
3. Methodology	Connor, Liam	All
3.1 Understand Existing Fire Training Structures	Liam	All
3.2 Research and Analysis of Fire Protection Code	Ava	All
3.3 Interviews with Fire Professionals	Ava	All
3.4 Define Requirements of New Fire Structure	Connor, Liam	Liam
3.5 Iterations of Chosen Design	Hannah	All
4. Findings	All	All
4.1 Types of Training Procedures	Ava	All
4.1.1 Search and Rescue	Ava	All
4.1.2 Rope Rescue and Laddering	Ava	All

4.1.3 Live-Fire Simulations	Ava	All
4.2 Existing Tower	Ava	All
4.3 Functionality of Requested Design Elements	Liam	All
4.3.1 Material Properties	Connor	All
4.3.2 Structure	Ava	All
4.3.3 Fire Fuel Systems	Hannah	Liam
4.3.4 Ventilation and Smoke Suppression	Hannah	All
4.3.5 Fire Suppression and Temperature Control	Hannah	All
4.3.6 Water Collection System	Liam	All
4.4 Feasibility of Tower Implementation	Liam, Connor	All
4.5 Tower Design Iterations	Liam	All
4.6 Cost Analysis	Connor	All
5. Recommendations	Liam	All
5.1 Proposed Design Recommendations	All	All
5.2 Recommendations for Future Projects	Liam	All
6. Conclusion	All	All
References	All	Liam
Appendix A: Floor Plans	Ava	All
Appendix B: Cost Analysis	Connor	All
Appendix C: Existing Schematics	Liam	All
Appendix D: Interview Question Sets	Liam	All
Appendix E: Interview Summaries	Hannah, Liam	All

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

Costa Rica is a Central American country known for its biodiversity and environmental awareness. The country has an abundance of natural resources including its soil, climate, water, and minerals (Agudelo, 2018). Although the average rainfall is approximately 132 inches each year, Costa Rica has a dry season between the months of November and April (Koonce, 1992). This season causes the natural landscape to dry out, which creates kindling for potential fires. This phenomenon poses a serious threat to some of Costa Rica's densely populated areas.

The area surrounding San José is known as the Greater Metropolitan Area (GAM), and "accommodates more than 50% of the Costa Rican population in less than 4% of the national territory" (Guevara, 2020). This is an issue of overpopulation and has resulted in taller buildings with distance between them as little as 70 centimeters of space (Guevara, 2020).

The fire department of Costa Rica, known as El Benemérito Cuerpo de Bomberos de Costa Rica (The Meritorious Team of Costa Rican Firefighters), is a government organization that is responsible for controlling these fires and maintaining the safety of Costa Rican citizens. The Bomberos have to prepare for potential disasters caused by the rapidly increasing population by training to handle fires in multiple-story buildings. Due to the fact that the country abolished their military, the firefighters have more duties than those of other countries (Future Policy, 2020). They respond to emergencies related to hazardous material management, natural disasters, extreme weather events, and anything else that involves helping people in distress. The firefighters live for their mission, which is to provide prevention and protective services in order to safeguard life, property and the environment (Bomberos, 2020).

The Bomberos of Costa Rica are composed of three Directorates: General, Operational and Administrative, all under the leadership of a Board of Directors. A branch of the Bomberos includes training services through the National Fire Academy. Several courses are offered, which encompass many topics such as brigade organization, passive and active protection, first aid, control of fire principles, and fixed fire protection (Bomberos, 2020). Since the firefighters have heightened responsibilities, they participate in extensive training sessions to prepare for real emergency response and develop a desired skill set. The training takes place at the Academy, and focuses on building their expertise related to critical thinking and making effective decisions.

The Bomberos were seeking design recommendations for a new live-fire training structure that will be specifically crafted to mimic real life scenarios they may encounter and allow them to improve their current training. This is a pressing need for the Costa Rican academy. Windows, stairways and hallways will be crucial to challenge the firefighters' ability to navigate inside buildings with obscured vision. Ventilation and gas ignition systems will help them manage the flow of smoke and intensity of the fire while trainees are inside. There were many considerations that needed to be made, so our team performed extensive research in order to gain an understanding of the firefighters' needs, the budget for the project, and learn the necessary requirements to design a safe and effective training structure.

The objective for this training structure is to be able to adequately prepare the firefighters for any kind of situation. In addition to testing how they respond to situations with smoke and intense flames, some other exercises that could be conducted are victim search and rescue, attack hose drills, and thermal camera search and rescue. The structure should accommodate both indoor and outdoor exercises, and allow the Bomberos flexibility in their training procedures.

The goal of our project was to investigate and define the elements needed to design a live-fire training structure on the Bomberos' training ground. The final product is a comprehensive analysis of the structural and design aspects the Bomberos should incorporate into a training tower. This structure will be capable of enhancing the firefighters' emergency response abilities by providing a myriad of new exercises that were not achievable with their existing tower. We focused on maintaining high levels of safety while accounting for feasibility to ensure that the training structure is well-received by the Bomberos.

2. BACKGROUND

This chapter provides information on the history of El Benemérito Cuerpo de Bomberos de Costa Rica as well as their firefighter training practices and structures. It also discusses procedures conducted with fire structures on an international level, as well as design details that could be included in a future tower for the Bomberos. This chapter concludes with information on the codes and standards required to design and construct live-fire training structures.

2.1 EL CUERPO DE BOMBEROS

The history of firefighters in Costa Rica can be traced back to January 24, 1864. That was when the citizens of San José started to petition for an official fire department, after a particularly devastating fire. Individual contributions led to the purchase of a fire engine for San José and shortly after, documents were submitted to the government establishing a fire department in Costa Rica in 1865 (Bomberos, 2018). The first professional fire department, El Benemérito Cuerpo de Bomberos de Costa Rica, began operating through the government with the assistance of police officers because of a lack of funding. Initially, the department was inexperienced and limited in their knowledge, and therefore many fires weren't attended to properly. As a result, people took advantage of the poor response to fires and attempted arson to collect insurance money. The government realized and shifted the organization's funding to the National Insurance Institute (Bomberos, 2018). With that change of budget, the quality of the equipment offered to the firefighters improved. They were equipped with better gear, and many new fire stations were built. Today, there are 76 fire stations across the country, each of them having their own personnel, specialized units and community. They collectively respond to over 35,000 emergencies annually (Volunteer BaseCamp, n.d.).

The Bomberos of Costa Rica are an organization that has a mission greater than just fire protection; they respond to a variety of emergencies in order to protect the population. These firefighters are responsible for structural fires of houses, any public/private property, and fires on vehicles like boats and planes. They also are known for helping with hazardous materials, collapsed structures, and problems with Africanized bee attacks, which are common in Costa Rica (Volunteer BaseCamp, n.d.). Though they are not as common, the Bomberos even provide their assistance when Costa Rica is challenged by natural disasters such as hurricanes, floods, earthquakes, and volcanic eruptions.

2.2 FIREFIGHTER TRAINING

Fire training around the world has aimed to replicate more realistic scenarios in which new firefighters can train and practice their skills. Most of the common training required for professional firefighters involves the use of a set, prop or structure. A fire investigation set is a collection of furniture, fixtures, or equipment that has been arranged intended for burning as part of an investigation training (NFPA 1402, 2019). A fire prop is a vehicle or a vessel specifically built to be set on fire for training purposes (NFPA 1402, 2019). Finally, a fire training structure is a permanent structure acquired or specifically built to facilitate training evolutions, also known as the prescribed actions that result in an effective training activity (NFPA 1402, 2019). Training structures are typically built as towers due to the need for multiple stories while not taking up too much area. There are two types of fire training structures, those which are built for any type of fire training and those that are built solely for non-fire practices. A fire training structure that is not designed for live-fire is used to practice stairs, hose, and rope rappelling drills. A live-fire training structure involves either gas fuel or combustible material fires inside the structure to train live-fire evolutions on a regular basis (NFPA 1402, 2019).

Nearly every fire department today typically has some type of fire prop or training structure they use for their evolutions because they are better able to train new firefighters. They offer more lifelike and advanced situations they may encounter in their future careers. Another bonus of these structures is the availability of newer technology such as thermal sensors which can monitor conditions inside live-fire structures to not only learn more about the behavior of fire but also to keep trainees as safe as possible while they learn (NFPA 1402, 2019). In summary, fire training evolves constantly to adapt to all of the new situations and dangers that arise when fires break out. The most effective way to practice these evolutions are by use of live-fire training props and structures.

2.2.1 Training Practices Around the World

Countries throughout the world have built specialized facilities that help influence the progression of firefighter training. The West Midlands Fire Rescue Service (WMFRS) in the United Kingdom has built a training structure to simulate wind-driven fire scenarios for their local conditions. They reproduced common residential and commercial floor plans in the area and integrated fans that allowed for simulation of wind. This system allows their firefighters to train in very realistic conditions of wind-driven fires and gain proficiency in that area (O’Donnell, 2015).

Another example of a facility is the one built by The Metropolitan Fire Brigade (MFB) in Melbourne, Australia. They created an entire campus with 10 large-scale buildings which provides over 50 scenarios for compartment fire behavior training. Their system uses a propane burner to ignite the materials, and once that happens the propane is shut down, allowing the fire to grow naturally. They can control the airflow in the buildings, seeing how different flow paths can change the fire behavior. This technology helps control the buildings' temperatures safely and keeps the air clean by limiting black smoke emissions (O'Donnell, 2015).

An issue with firefighter training is the tendency of builders to follow a consistent floor plan when designing the layout of buildings. Firefighters start to get familiarized with their surroundings and no longer need to think critically about how they navigate through the flames. In the City of Tilburg in the Netherlands, they constructed a facility that has moveable interior walls as well as exchangeable facades to ensure the firefighters can constantly train in a new environment. It prevents firefighters from getting familiarized with the building layouts or the exterior appearance (O'Donnell, 2015).

The Carmel Fire Department in Indiana has employed digital fire technology for their training. This technology is suited to train for initial fire attack, search and rescue, practicing stream patterns, water placement and hose line management. They use LEDs to recreate flames and their patterns, thermal sensors to detect the application of a hoseline, and sound and smoke to make the training environment more realistic (O'Donnell, 2015).

Learning about the practices that other countries have for their firefighting training allowed the IQP team to expand on what is possible for these training facilities. Many of these techniques used around the world were helpful when thinking about structures and the training tower we designed for the Academia Nacional de Bomberos in Costa Rica.

2.2.2 Training Practices in Costa Rica

The Academia Nacional de Bomberos (ANB) is located in San José, the capital of Costa Rica. The foundation of this academy defined the standard of firefighter training in the country. Their preparation consists of basic training alongside technical training, with a variety of courses offered to teach a wide range of skill sets. The courses encompass many topics such as brigade organization, passive and active protection, first aid, control of fire principles, and fixed fire protection. This technology can offer real life skills for a wide variety of emergencies that the Bomberos may be called for. They have a total of 29 courses for all the firefighters and support staff, and they also offer nine courses that are open to the public (Boie et al., 2018).

As with any fire department, the Costa Rican Fire Department uses typical equipment including fire hoses, fire trucks, and protective equipment (e.g. helmets and insulated clothing). However, there are some interesting advancements that have been made over the years to help improve the ease of fighting fires. One example of new equipment includes motorcycles with water tank attachments. These advanced bikes give firefighters the opportunity to arrive at large fires much faster than a regular fire truck or even just eliminate the need for trucks if the fire is small enough (Greaser, 2018). Additionally, the firefighters have been making more general improvements. Two new fire stations were completed, and they are equipped with solar panels to help promote environmentally friendly practices (TCRN Staff, 2019). These improvements are not necessarily equipment to be used when fighting fires, but they help exemplify the continuous developments that the fire department is undergoing.

The Academy has a large space dedicated to them, as seen in Figure 1, with several different buildings that suit distinct purposes. In terms of training, firefighters have to practice dealing with fires that spread to multiple floors of a building. The way that they train for this type of scenario is by using a tower with multiple floors. The firefighters have to scale the staircases while wearing heavy equipment in order to build strength and practice what would be necessary in a real situation.

Figure 1: Aerial Photograph of the National Training Academy (Norman Chang, 2017)

In addition to the tower, there is a training area adjacent to it. This flat area is used for maneuverability training; the firefighters practice using the hoses while navigating through a wooden maze in order to mimic moving through small areas in a burning building (Boie et al., 2018). The firefighters also have the ability to rearrange the walls in one of their training areas so that they don't get accustomed to a certain floor layout. This is important to ensure that the firefighters are always prepared by having them constantly thinking about how to efficiently control fires.

2.3 FUTURE CONSIDERATIONS AND ASPIRATIONS

Firefighters have to be prepared to continuously adopt new training practices so that they are well-equipped to handle any type of emergency. Constant developments are being made as researchers make new discoveries related to fire safety, so it is especially important to recognize and account for any changes to established standards. The most effective way for the firefighters to strengthen their abilities is by engaging in a variety of training exercises. Traditionally, this is achieved through the use of common equipment such as fire hoses and axes. However, the implementation of evolutions with live-fire can be seen as one of the most powerful methods to develop advanced firefighting skills.

2.3.1 Current Designs in the United States

The most sophisticated fire training exercises in the U.S. involve the use of training towers. These structures can have simple or elaborate designs, but it is evident that the architectural requirements have evolved over time. As more studies related to effective fire protection are conducted, the tower layouts are modified to ensure that firefighters are prepared for any type of emergency situation.

There are organizations in the U.S. that provide fire departments with the option of designing their own training structures. The needs of a department may vary based on the region that it is operating (i.e. climate and local infrastructure), so this technology helps streamline the training. Customization is a powerful alternative to purchasing a traditional tower since the firefighters may need to focus on a specific set of exercises. For example, the topography of Worcester, Massachusetts is uneven, with steep hills covering the majority of the terrain. As a result of this, the Worcester Fire Department trains with various roof props to replicate some of the steep pitches that they may encounter. Their triple-decker tower is also designed to be similar to houses that are commonly found in the city (Worcester Fire Department, personal communication, December 3, 2020).

The company “Fire Facilities” is one of the organizations providing these customizable tower designs. They stress the importance of live-fire training by stating how it “provides conditions similar to actual fire calls: Searing heat. Smoke filled halls and rooms. Multiple floors where victims may be in the need of rescue” (Fire Facilities Staff, 2020). There are many other conditions that could provide firefighters with challenges, but these towers are the most practical way to prepare for unexpected issues. For example, the structures provided by “Fire Facilities” offer training in terms of roof penetration, confined space exercises, ventilation, and even helicopter deployment if it is desired (Fire Facilities Staff, 2020).

The figures shown below depict some of the training towers that have been constructed for official use. Figure 2 shows a more traditional design that is commonly used to emphasize training for fires in multiple-story buildings.

Figure 2: Traditional Fire Training Tower (Fire Facilities Staff, 2020)

If a fire department is hoping to purchase a training tower that can accommodate many firefighters at once, there are some more elaborate designs that are available. There are financial considerations that need attention when exploring models like these since they are state-of-the-art training structures. An example of this type of tower is provided in Figure 3 below. The main difference from the tower in Figure 2 is that there are closed windows and balconies to act as additional features to the unique main body of the structure (Fire Facilities Staff, 2020).

Figure 3: Elaborate Fire Training Tower (Fire Facilities Staff, 2020)

2.3.2 Tower Design

The Bomberos expressed their interest in developing a new tower to enhance their training procedures. The subsequent sections of this chapter will delve into the specific requests that they made. We optimized the design as much as possible so that it can serve as an essential element for training firefighters before they begin dealing with real fire situations.

While much of the criteria for the project came from the Bomberos themselves, it was also necessary to be mindful of San José's regulations and environment when developing ideas for the tower. In recent years, Costa Rica has expanded its environmental protection laws and regulations by passing decrees and signing agreements to establish provisions for sustainable development. It was necessary to adhere to these regulations and take the environmental impact of the project into account.

2.3.3 Water Collection and Smoke Suppression

Costa Rica's Ley Orgánica del Ambiente (Organic Law of the Environment) states that the "integral management of water is aimed at its conservation, guaranteeing the conditions of quality, availability and quantity”. Regulation for water usage in Costa Rica is established in the Ley de Agua No. 276 (Water Law No. 276). It offers information on the ownership of water in regards to property, which has encouraged the Bomberos to collect rainwater for their training exercises (Organización de las Naciones Unidas para la Alimentación y la Agricultura, 2006).

The Ley Orgánica del Ambiente (Organic Law of the Environment) provides many guidelines and provisions for managing the environment and contributing to sustainability (Food and Agriculture Organization of the United Nations, 2009). An example of these guidelines is one which states how “the integral management of the atmosphere is aimed at ensuring its conservation and guaranteeing its quality conditions.” Additionally, Costa Rica has become much more concerned about reducing its carbon emissions, coming out with a National Decarbonization Plan for 2050 and signing the Paris Agreement to reduce emissions. However, a live-fire structure could generate a lot of carbon emissions due to the constant burning of fires that are needed for training exercises to take place (Climate Action Tracker, 2020). Appropriate measures must be put in place to ensure containment of the emissions.

This environmental concern, along with the Bomberos’ explicit concern, introduced the request for a system to suppress smoke from entering the atmosphere. Even if fires are not producing smoke, they will still be emitting carbon dioxide gas, so controlling the flames is an important step in designing a suppression system that is environmentally friendly.

2.3.4 LPG

LPG stands for liquified petroleum gas, which is a portable, clean and efficient energy source (WLPGA, 2020). It is primarily obtained from natural gas and oil production, but it is also produced from renewable sources, making it a versatile energy source that is used in over 1,000 different applications. In live-fire structures, LPG systems are installed to produce intentional, controlled fires. Existing structures incorporate LPG systems with controls in a secondary location, allowing the operator to monitor the progress inside the structure, as well as control the intensity and production of fire.

2.3.5 Thermal Imaging

Thermal Imaging Cameras (TIC) are non-contact temperature measurement devices that determine apparent temperature from the infrared radiation emitted by objects (Press, 2009). TIC are composed of an infrared optical system. It collects information through a detector and outputs a video signal which is displayed for the viewer to observe.

TIC are extremely valuable for fires as it provides first responders with critical information to assess a fire incident, track fire growth, locate victims and other firefighters, and establish egress routes. In circumstances where firefighters may rely on TIC, they will employ a wide field of vision (FOV) in the range of 40-60 degrees (Press, 2009). In the circumstance of using TIC in a live-fire training evolution, the imaging will allow those in training to visualize the plan of attack and locate dangerous areas. A common type of TIC is the handheld camera and they are designed to perform reliably in high temperatures, flames, and the presence of water. This will ensure that all evolutions performed in a structure are safe and reliable for multiple uses over the course of many years.

2.4 THE NATIONAL FIRE PROTECTION ASSOCIATION

The National Fire Protection Association (NFPA) is a global, self-funded, nonprofit organization established in 1896. It is devoted to eliminating death, injury, property and economic loss due to fire, electrical hazards, and other related emergencies. Founded in Boston, Massachusetts, the original mission of the small group of professionals was to create a standard for the uniform installation of sprinkler systems in buildings (NFPA, 2021). Now, as a global organization that is consistently improving and expanding to new parts of the world, their main function is to deliver information and knowledge through many outlets such as codes, standards, research, training, and education. The organization has over 300 consensus codes and standards relating to all fields associated with fire, including codes on qualifications for professional firefighting and training procedures, as well as code and standards on fire structures, such as training facilities and towers (NFPA, 2021).

2.4.1 Global Influence

As part of the NFPA's International Operations Department, the organization has expanded international offices into several nations across the world covering the Asia/Pacific Region, Europe, and Latin America (NFPA, 2021). As stated by their website, fire is universal, and therefore, all countries should have the information and expertise to protect their citizens and property. The organization spreads their mission and expertise by working closely with foreign government and industry officials to develop and host educational programs, as well as host seminars and conferences concerning fire, building and life safety around the world (NFPA, 2021). Additionally, their codes have been translated into several different languages to promote accessibility.

The NFPA maintains a large presence in Latin America including chapters in Argentina, Colombia, the Dominican Republic, Mexico, Puerto Rico, and Venezuela. Said established chapters offer training seminars in Spanish and maintain a constant flow of information by way of NFPA Journal Latinoamerica, a bilingual fire and life safety magazine published in Spanish and Portuguese, released every 1-2 months, with an online version available 24/7 (NFPA, 2021).

2.4.2 NFPA Codes in Costa Rica

Costa Rica’s Benemérito Cuerpo De Bomberos has adopted numerous NFPA codes and standards as well as being a longtime supporter of the organization's work. Examples of adopted codes include: NFPA101, Life Safety Code, NFPA 13, Installation of Sprinkler Systems, and NFPA 70, National Electrical Code, among many others (NFPA, 2021). The Bomberos rely on these codes to carry out their training, inspect buildings, consult professionals regarding public safety, and most importantly identify the standards needed to be met in order to be qualified as a professional firefighter.

2.5 CONCLUSION OF BACKGROUND REVIEW

The information presented in this chapter introduced the sponsor of this project and offered a brief review of the necessary information needed to proceed. The group was able to broaden the scope of their understanding of basic fire structures and the evolutions that are carried out inside them. The new knowledge provided a foundation of information that could be relied on as the project progressed. The group then built on this information and moved on to establish methods of reaching the ultimate goal.

3. METHODOLOGY

The goal of our project was to define and recommend the essential elements of a live-fire training structure for the Bomberos of Costa Rica. By optimizing both the design and safety of the tower, we aimed to enhance the firefighters' training procedures in order to help them develop the critical skills needed when tending to their daily responsibilities. To streamline our approach and accomplish this mission effectively, we implemented qualitative and quantitative methods to gather the information required for our goals. The following were determined to be the objectives for the project.

1. Develop an understanding of existing live-fire training structure technology as well as the current needs of the Bomberos;
2. Research and analyze the National Fire Protection Association code;
3. Interview various professionals in the area of fire;
4. Establish a set of requirements needed to construct a live-fire training structure for the Bomberos of Costa Rica;
5. Electronically model our recommended tower.

The methodology chapter includes a detailed description of the manner in which our team collected essential data for this project. An analysis of each objective was conducted, explaining how each played an important role in the development of our design for a training tower at the Academia Nacional de Bomberos in San José, Costa Rica.

3.1 UNDERSTAND EXISTING FIRE TRAINING STRUCTURES

One of the first things considered when designing any type of structure is the existing technology that is being utilized. For our case, we analyzed various fire training towers that are actively used in the United States.

Conducting qualitative and quantitative research on the implementation of training towers was critical to the success of this project. Learning about specific characteristics of the structures helped us understand what adds the most value to firefighters' training. To collect that information, we performed extensive research, consulting article databases to learn more about live-fire training structures and firefighting practice. In addition to that, we researched the four particular areas of interest originally expressed by the Bomberos:

- Water collection system;
- Smoke suppression system;
- Liquified petroleum gas;
- Thermal imaging.

In order to fully understand all the needs the Bomberos had for their tower, we conducted several meetings with them and asked various questions related to the structural and design aspects they desired in a tower. These conversations were fundamental so that we could define certain elements for our final recommended tower design. Due to COVID-19 we were not able to visit the location ourselves, but the Bomberos provided documentation to ensure we understood the area we were working within.

Figure 4: Image of the National Academy on Google Earth.

Figure 4 provides a visual of the ANB as seen on Google Earth. Although the image is not of the highest quality, the location where the Bomberos plan to construct a live-fire training structure is depicted with the superimposed floor plan that is bordered in white. This image represents the ground floor of the tower with an area of approximately sixty-five square meters.

An in-depth analysis helped us determine which characteristics of our proposed fire training structure were the most suitable once we considered each of the tower's suggested features as provided by the Bomberos in the early stages of the project.

3.2 RESEARCH AND ANALYSIS OF FIRE PROTECTION CODE

We researched and analyzed NFPA 1001, Standard for Fire Fighter Professional Qualifications, and NFPA 1402, Standard on Facilities for Fire Training and Associated Props. The team was able to access the 2019 edition of the codes through their online source.

NFPA 1001 outlines which standards must be achieved to be considered a professional firefighter, either a FireFighter I or a FireFighter II, meaning they have demonstrated the knowledge and skills to function as an integral member of a firefighting team as outlined in Chapter 4 and 5 of the code respectively (NFPA 1001, 2019). By reading this code, the team understood how fire training structures are necessary for firefighters to practice certain skills needed for a professional certification. We were able to determine what aspects a structure needs in order to accommodate these teachings.

NFPA 1402 outlines the necessary standards for fire training facilities, including details on those structures which are equipped with live-fire fueled by gas. We used this in order to determine which of the Bomberos’ original design requests could be satisfied while adhering to the code. Any requests that violated code were properly addressed in order to ensure NFPA compliance.

Analyzing these two codes allowed us to determine exactly what is needed to prepare a professional firefighter. It helped outline which building standards must be met to ensure the future tower contains all of the necessary elements to train the Bomberos of Costa Rica in the safest and most effective manner.

3.3 INTERVIEWS WITH FIRE PROFESSIONALS

Our sponsors expressed the need for a few technologies that are used in the United States, so for that reason, we decided to conduct our interviews with local firefighters. Due to the dynamic situation provided by the pandemic, all of our interviews were conducted online, through Zoom. The team chose to use a semi-structured interview format throughout all of our interviews. The questions can be found in Appendix D. We chose this style because it allowed us to ask follow-up questions and expand conversations based on what each professional was more familiar with. The notes from all the interviews are included in Appendix E.

The first fire department we contacted was located in Worcester, Massachusetts. We spoke with an individual who is involved with the city's training operations in order to learn more about the design of their live-fire training structure. Getting insight from a knowledgeable source was a critical step in developing our understanding of different towers in the United States and in determining which groups we were interested in interviewing next. Since our team did not have direct experience with training structures, assistance from others was instrumental for guiding us in the right direction.

Since we were unable to observe any facilities in person, we continued the interview process with professionals who work in state-of-the-art facilities. Our team spoke with a representative from the Massachusetts Firefighting Academy (MAFA), since they have a system in place to recycle water used during training exercises (Worcester Fire Department, personal communication, December 3, 2020). This helped us as we considered that element of the structure's design.

Interviews with fire departments based in New York and Rhode Island helped us acquire valuable insight for additional aspects of the project. We quickly realized that speaking with firefighters from different areas offered fresh perspectives on the variety of situations that they prepare for. We also contacted the Fire Protection Engineering program at WPI, and that discussion prompted us to consider seeking advice from industry professionals such as Kidde Fire Systems.

3.4 DEFINE REQUIREMENTS OF NEW FIRE TRAINING STRUCTURE

From our team's earliest communications with the Bomberos they had several specific requirements for the training tower. This included requests for water collection and smoke suppression systems, usage of LPG gas and thermal imaging, and having a structure with multiple floors both above and below grade.

In order to begin considering the implementation of these ideas, it was necessary to define the requirements of each proposed element. This was achieved through extensive research. We recognized that understanding these technologies from a logistical standpoint would be critical in addressing the needs of the Bomberos and all the difficulties that could be encountered when using them. We considered physical space, safety, and conformity to ecological and structural laws while performing this research.

Our interviews were an influential factor in selecting these requirements. Speaking to professionals that work in the firefighting industry helped the group understand what is common among current training structures. That information helped us grasp the advantages and disadvantages certain design features can have on their training evolutions.

After collecting the information on potential design elements, materials, and structural layout, the group defined three towers that were potential choices for the Bomberos. Each tower was unique in design and focused on different needs in particular. Not all requested elements could be compiled in one structure, so the three towers allowed our group to include and compare certain elements based on importance. We did this by creating a weighted Pugh Matrix which offers a way to make decisions based on a quantitative analysis. They employ a point system that assigns value to each specific need based on their importance. Based on the Pugh Matrix, the group selected the tower with the highest score and further developed the structure.

3.5 ITERATIONS OF CHOSEN DESIGN

The group used AutoCad Revit for our 3D modeling to help create an accurate rendering of the chosen tower design. This software, provided by Autodesk Inc., allowed us to create a visually appealing image of the tower for presentations. It also gave our team the capability to have a visual aid when explaining specific features of the design to the Bomberos.

Once we gathered the dimensions and information of the space available for the tower, the group started to design different floor plans within Revit. The Bomberos requested a four-story building, with dimensions not exceeding 8m x 8m with an external enclosed stairwell. Throughout the design process, we went through a few different schematics and discussed them with the sponsors to seek their opinions. Most of their suggested modifications were related to the arrangement of walls or placement of the windows. Taking this feedback into consideration, our group continued to develop floor plans that were practical for the Bomberos. The process continued until we had developed a structure equipped with up-to-date technology so that the firefighters could have confidence in the relevance of their training while meeting code.

Apart from the considerations that were made when designing the structure itself, we frequently analyzed the budget of the project. This was significant so that we could maintain our focus on the ultimate goal and prevent excessive expenses. We acknowledged that building a tower would be a considerable investment for the Bomberos of Costa Rica and made our best efforts to provide them with an economically feasible option. We estimated costs by doing a substantial amount of research on the necessary materials and procedures required to construct our chosen design. These rough estimates were compiled into a table so the Bomberos could gain an understanding of the potential cost of the tower.

4. FINDINGS

This chapter begins with an evaluation of the importance of a fully operational fire training tower. It outlines the current tower on the Bomberos' property, including the advantages and disadvantages of the current design, and the original requests made for the new tower. Evidence from interviews of various professionals in fire related fields as well as consultation of NFPA codes were used to identify the required design elements for modern training structures and to compare with the Bomberos' original requests. Upon completing specific structural and elemental research, three potential tower designs were created. A final tower was determined after performing a quantitative analysis of each tower. Then the group further developed this design through several iterations which were presented to the Bomberos for feedback. Final floor plans were constructed and the entire tower was modeled in a three-dimensional online modeling software. This chapter concludes with an analysis of the cost associated with the chosen tower. Our findings ultimately led the group to make specific recommendations for the Bomberos with respect to the implementation of a fire training tower at the National Training Academy.

4.1 TYPES OF TRAINING PROCEDURES

Fire towers are a vital aid in training and practicing life-saving rescues and procedures in the event of a fire. Typically designed as a multi-story building similar to an apartment building, with simple floor plans, windows, and interior stairs, firefighters utilize the towers for a variety of different practices. Towers can range from a very simple design with a handful of applicable uses, to million-dollar structures with the newest technology for firefighting drills and practices. According to the Rhode Island Fire Academy (RIFA), a typical tower is used by a variety of people both within and outside the fire company. However, the main purpose of a tower is to teach new firefighters the skills they need to handle different situations and provide a safe and accurate environment in which they can practice those skills (RIFA, personal communication, February 19, 2021). These practices are forms of technical rescue, defined as those aspects of saving life or property that employ the use of tools and skills that exceed those normally used in firefighting, medical emergency, and rescue (Sturkol, 2018). Both technical rescue and live-fire skills are extremely important and necessary to the practice of firefighting. Having access to a tower equipped for both kinds of training is required for the development of a fire department's abilities and knowledge. A few of the most common training procedures conducted to meet NFPA requirements are described in more depth below. Details regarding the necessity of a training tower to successfully instruct new firefighters is discussed.

4.1.1 Search and Rescue

NFPA 1001 (2019) requires firefighters to have the ability to conduct a search and rescue in a structure while operating as a member of a team with a given assignment and obscured vision conditions. The goal of a search and rescue is to search all assigned areas, locate and remove all victims, maintain team integrity and safety, and ensure respiratory protection is not compromised (NFPA 1001, 2019). The necessary skills include the ability to use self-contained breathing apparatus (SCBA) to exit through restricted passages, set up and use ladders, rescue another firefighter, and assess areas to determine tenability (NFPA 1001, 2019).

Many kinds of search evolutions exist, but one of the most common forms of search is known as a primary search, which are time-sensitive searches dedicated to finding survivors and keeping firefighters safe (Spell, 2020). Firefighters must always search with a partner to maintain safety, and will do so using different techniques. One particular technique that requires a structure is an oriented person search. The use of a structure in this evolution is important because one firefighter will direct teammates around the building while maintaining constant contact with walls and other team members. They sweep the walls by hand to be able to feel for doors, windows, furniture, appliances or victims which cannot be carried out accurately without a structure (Spell, 2020).

Without training on methods of rescue as well, search evolutions would be far less useful in terms of training within a structure. There are multiple methods of rescue that firefighters should have knowledge and practice on. In most situations a victim is conscious and ambulatory, however firefighters must prepare for unconscious victim rescue.

Figure 5: Example of Rescue Drill (Worcester Fire Department, 2020)

In the event that the victim is unconscious or unable to move, methods such as the extremity carry can be used. The extremity carry requires the victim to be carried by their arms and legs by two firefighters. Figure 5 depicts a rescue drill conducted in the event that a victim is unconscious and needs two firefighters' attention. Regardless of the method of rescue used they must be practiced extensively to ensure the victim is safe and unharmed prior, during and post rescue. The use of a training structure for rescue is extremely important because not only do the floor plans pose challenges to the firefighters alone, they must also learn how to maneuver these layouts in the event they are carrying an additional person.

4.1.2 Rope Rescue and Laddering

The most commonly trained forms of rescue are rope rescue and laddering. According to the National Fire Protection Agency, rope rescue training includes understanding, directing and operating simple rope-lowering systems from various heights in both high- and low-angle environments (Sturkol, 2018). This type of training includes how to safely ascend and descend fixed-rope systems (known as rappelling) as well as how to operate a rope-rescue system. These skills are taught with any structure capable of carrying out the drills safely, meaning the structure is equipped with anchor points that have been designed in accordance with NFPA 1402 and there are walls sturdy enough to support the weight of a firefighter rappelling down the side of the structure.

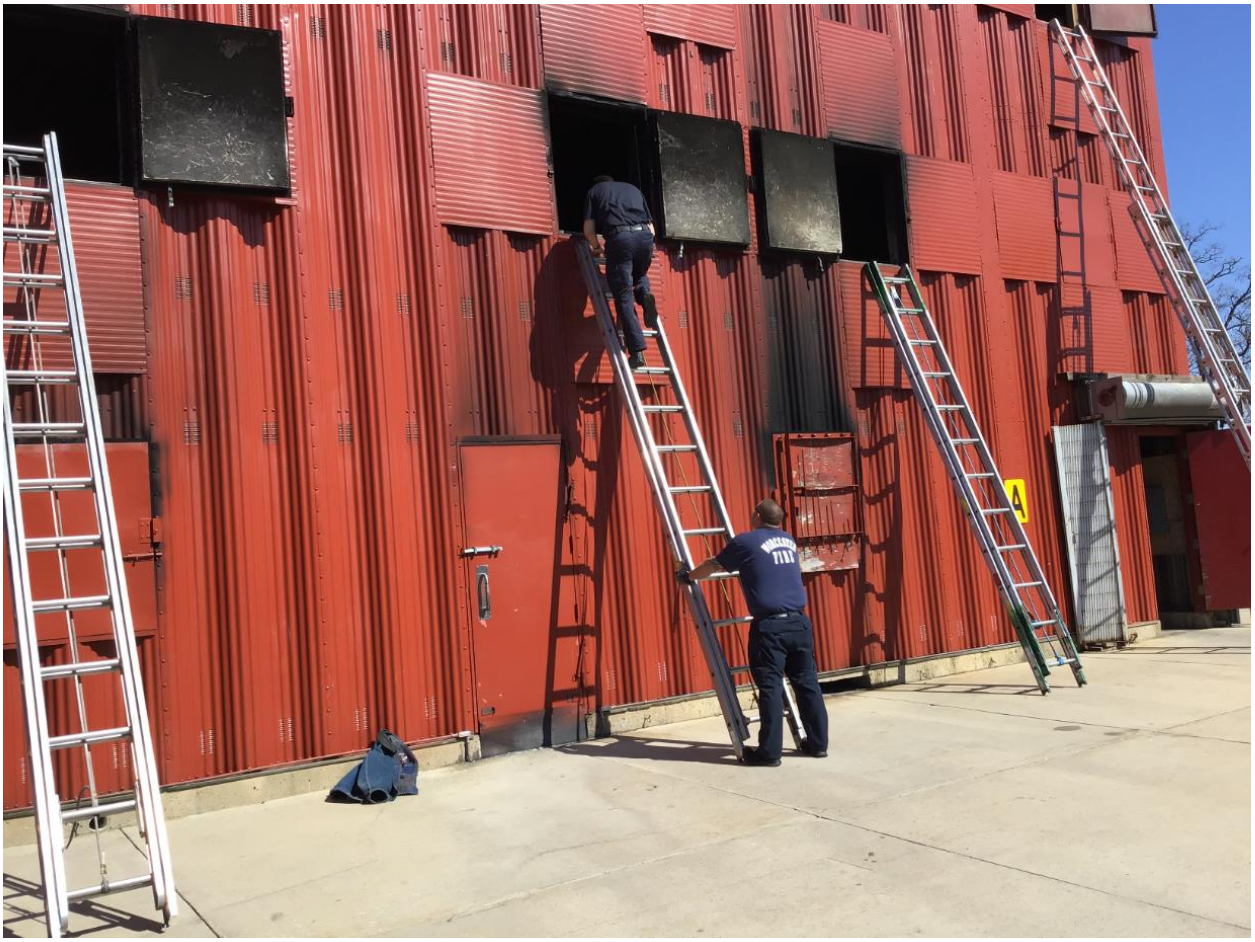

Figure 6: Ladder Training Drill (Worcester Fire Department, 2020)

In addition to rope rescue training, ladder training is also a requirement of all firefighters, according to NFPA 1001 (2019). The skills are defined such that firefighters shall have the ability to carry, raise and extend ladders, as well as the ability to determine that a wall and structure will support the ladder. Figure 6 shows an example of what this type of training can entail. They also must be able to accurately judge extension ladder height requirements and place the ladder to avoid hazards. Finally, they are required to mount, ascend or descend and dismount the ladder properly (NFPA 1001, 2019). Towers that are enclosed with various levels and entryways are extremely important for these types of drills. They provide a variety of potential scenarios for ingress and egress depending on where the fire is located within a building and which entryways may be unsafe.

4.1.3 Live-Fire Simulations

Arguably the most valuable form of skill and knowledge training is live-fire training. In the United States, not every department owns a tower capable of live fire due to the cost of construction and maintenance. Instead, these departments travel to nearby structures that do have gas-fuel systems due to the importance of training on a real fire while being able to remain safe and not harm civilian lives or property (Troy Fire Department, personal communication, February 15, 2021).

Training within a live-fire structure is limited only by the user's imagination (RIFA, personal communication, February 19, 2021). A typical structure consists of several rooms and passageways with special rooms that are designated as burn rooms. A burn room is defined as a space or compartment inside a live-fire structure in which live-fires are conducted (NFPA 1402, 2019). These rooms are specially equipped with fire resistant materials which are often more expensive, and therefore towers typically only contain a few burn rooms. Within the burn rooms are fire props, a non-combustible assembly used for repeatable live-fire training exercises containing the gas burners of the gas-fueled training appliance (NFPA 1402, 2019). When conducting a training exercise, the company will turn on the fuel to the tower and ignite the fuel prop(s) for the areas they intend to train in. The remainder of the training is completely customizable to the desires or needs of the department. The overwhelming response received from interviews was that a tower needs to fit the requirements of those who will be using it. In this type of construction, the end-user (the Bomberos), are the most important people to consult.

4.2 EXISTING TOWER

The current on-site tower at the San José National Fire Training Academy is an open-air structure consisting of eight floors, an interior stairwell, and concrete slab floors. Due to the current design, the Bomberos are limited in their ability to conduct drills. It is estimated that they use their tower only 10 days per month for a few hours each day (Bomberos, personal communication, February 25, 2021). In comparison, the Rhode Island Fire Academy, who have a 4-story gas ignition fire structure, estimate their tower is used almost every single day of the month for an average of 8-10 hours each use (RIFA, personal communication, February 19, 2021). The Bomberos do not use their tower as frequently as departments in the United States do, however fire training is not as developed in Central America as it is in other parts of the world. There are currently no live-fire training structures across the entirety of the region. Most neighboring countries to Costa Rica do not even have a simple structure similar to the one at the San José National Academy, much less one equipped for live-fires (Bomberos, personal communication, February 25, 2021). By researching NFPA codes 1001 and 1402, we were able to determine the training requirements that the Bomberos are not able to complete due to the limitations of their current tower.

NFPA 1001 states that in order to be considered a professional FireFighter I, one must be able to extinguish both exterior and interior structure fires operating as a member of a team (NFPA 1001, 2019). The Bomberos currently have limited practice for extinguishing fires. According to our sponsor, the Bomberos train by teaching the proper extinction practices and giving theoretical training on the subject, however they do not practice extinguishing fires inside a structure. For these reasons, their current training practices do not comply with NFPA standards. This is a major concern, and therefore, the need for a new training tower equipped with the capability of producing live-fire is an absolute necessity to properly train the firefighters of Costa Rica.

4.3 FUNCTIONALITY OF REQUESTED DESIGN ELEMENTS

In order to make the features of the tower more comprehensive, we directed our efforts to in-depth research of each potential element. According to NFPA 1402 (2019) live-fire training structures must be designed by a licensed design professional to meet the structural requirements of the building code. Therefore, the information our team has gathered and assessed is a recommendation for the Bomberos so that they may be able to present it to a professional for the actual planning and construction of a tower.

The original request by the Bomberos included this basic information:

- A five-story structure, with two basements in an 8x8m maximum area
- Enclosed structure with limited windows and equipped with gas fuel for ignition
- Enclosed stairwell, separate from the main body of the tower
- Flat roof for storage

4.3.1 Material Properties

When considering what material to build the tower out of, the two main options our group settled on were concrete and steel. Both are common building materials, but they behave very differently. When deciding which option to pick, there were many considerations involved, such as safety, functionality, price, and time to completion.

Concrete is a ceramic, and it has excellent compressive strength. Its density makes it resistant to high winds and seismic activity, and is resistant to softening against high temperatures (Skyciv, 2020). What concrete lacks, however, is shear and tensile strength. This could be remedied by reinforcing the concrete with rebar and stirrups, which greatly improves the integrity of the tower. In comparison, steel exhibits sufficient compressive, tensile, and shear strength, and with its ductility, can absorb forces such as winds and seismic activity without breaking.

Over time, the stresses that the tower experiences might cause plastic deformation in the steel. Additionally, without the appropriate fireproofing applied, the high temperatures from the fires that the building would regularly experience would contribute to a substantial reduction in the steel's strength over time (Swanton Welding, 2016). In several of our team's interviews, fire training professionals brought up spalling as a problem in concrete fire towers. Spalling occurs when water enters concrete and the pressure causes the surface to start flaking or popping off (Weintraub, 2020). Considering the interior fires are extinguished with a high pressure hose, the concrete would be experiencing significant force by the water during each evolution. In order to remedy this issue, the tower could be designed with protective panels to cover the concrete walls, therefore lessening the effects of spalling.

In terms of cost associated with construction, a steel tower would be constructed much faster than concrete but would likely require specialized construction vehicles and specialized workers. In comparison, concrete would require a longer time to mix, pour, cure, install reinforcements, and repeat, but is simpler to construct and could be done by most contractors (Madsen, 2005).

Although both concrete and steel offer their own benefits and detriments, our group decided that concrete would be the best option for the Bomberos. Due to their location, design needs, and budget, concrete is the more feasible choice.

4.3.2 Structure

From the ground level up, there were several considerations to be made regarding specific structural components requested by the Bomberos. Beginning at the base of the structure, their initial request was for two basements, both below grade level. Although basements are not common in Costa Rica, the Bomberos felt the ability to train for basement fires would be beneficial for skill development. In order to determine the feasibility of an underground burn room, our group consulted NFPA code. According to NFPA 1402, a burn area fully below grade level is prohibited. However, burn areas that are below-grade but have a full, at-grade walkout at a minimum of one full side are permitted (NFPA 1402, 2019).

According to the Troy Fire Department of New York, their tower includes a basement, but in order to meet code there are no live-fires burned in it. Instead, they incorporate smoke machines, which produce smoke similar to a real fire and do not give off heat. It is a much safer option to be used in below-grade training (Troy Fire Department, personal communication, February 15, 2021). The Massachusetts Firefighting Academy does not have a true basement below grade level either. Instead, the tower is built into a hill, having one side completely underground while the other side is grade level (Worcester Fire Department, personal communication, December 3, 2020). Due to the Bomberos' request for a basement with live-fire, we recommended in Tower A a half below-grade first floor to simulate a basement similar to the Massachusetts Academy structure. One full side will have a large door that opens to grade level in order to meet code. Other means of egress will include the stairwell and windows which can either be open or closed depending on which evolution they are training.

With respect to floor plan options for an enclosed tower, NFPA standards insist that all burn rooms must have either: a minimum of two doors that exit the burn room (to an adjacent room, exterior grade, balcony, roof or stairs), or one door and one window (NFPA 1402, 2019). Due to the available area the Bomberos are planning to construct this tower on, we had to be innovative to meet their needs and requests. For this reason, most of the floor plans followed the second option of one door and one window; to comply with code while accounting for the small space.

In regards to the stairs, the Bomberos requested the stairwell be separate from the main body of the tower to ensure a sufficient area of burn rooms, while still being able to feel the conditions of the fire from inside the stairwell. Due to NFPA code, making the stairwell a burn room itself would be more costly, and require more windows, not to mention extremely dangerous. We decided a closed off stairwell without burners and without windows was their best option. Due to the convective heat transfer between the concrete walls, the stairwell will feel the effects of the fire, and therefore provide a practical training environment, without directly endangering the safety of the firefighters.

The final request made by the Bomberos included a flat roof for storage purposes. NFPA code states that as long as roofs are designed by a professional to support the dead load and minimum live load of 50 lb/ft^2, the slope does not have to meet a certain angle (NFPA 1402, 2019). Therefore, a flat roof is an acceptable design choice that complies with code, and therefore was implemented into the tower iterations.

4.3.3 Fire Fuel Systems

After the structural elements were researched for feasibility, the team turned towards understanding the more minute details which would be considered for the design. The most important element considered was the method of which fire would be created within the structure. There are two common options, the burning of materials to produce thick smoke and fire, or a more organized system of a gas fuel for ignition. The most common materials burned in non-gas fuelled structures are wooden pallets and hay. This option allows for a local and controlled burn, however there are several drawbacks for this method of ignition. One must consider how to properly feed the fire if a specific temperature is desired and the flames cannot be extinguished without the complete burn of the material (Cole, 2005). Additionally, the emissions from these fires are significant, having a larger production of smoke that is released into the atmosphere. Due to the intensity of these fires, there is considerable water usage and a higher chance of damaging the firefighters protective gear (Mason, 2006). Although this option is considerably cheaper than a gas-fuel system, Costa Rica is a country that is extremely conscious about their carbon footprint and is very invested in reducing their pollution any way possible. Therefore this option would not be the Bomberos' primary choice.

On the other hand, gas-fuelled systems seemed to be the best approach for the new tower. During our conversation with the WPI Fire Protection Engineering program, we learned a great deal on different kinds of ignition systems that can be present in live-fire training props and structures. The system the WPI fire protection lab uses contains propane gas. It is very similar to liquid petroleum gas (LPG), which is the system the Bomberos mentioned was their preference. They are both clean fuels that leave no residues. LPG is a mixture of fluids composed primarily of propane and butane alongside other chemicals, while a propane system uses propane with no additional constituents (Cheng, 2019).

These gases are ideal for firefighter training since they have a higher density than air, which causes them to settle at the bottom of any compartment as well as disperse throughout the area. LPG and propane gas are typically stored in their liquid form inside a tank, normally underground. According to the NFPA 58 (2019), liquified petroleum gas code, the gas tank should not be placed inside of the building. When use is required, liquid is drawn from the tank turning it into high pressure vapor that is then delivered to the intended burner location. The external temperature can affect the vaporization of the gas, because it needs to draw heat from the surroundings. The system at WPI, however, is prepared for that situation, allowing the gas to vaporize, independently of the outside temperature by controlling the pressure inside the tank. Small quantities of the liquid can generate large amounts of vapor and after that release, it mixes with air in order to create a flammable mixture. LPG also has significant thermal expansion, meaning that any tank should only be filled 80-85% of the way (WPI Fire Protection Engineering Department, personal communication, February 19, 2021).

Although gas-fueled systems have many benefits, they can have a lot of dangers associated with them. Many considerations should be made when planning a facility with LPG or propane ignition. Some of these are related to the layout of pipes, spacing between buildings, distance of pressure vessels, drainage, and containment control. All of those precautions help avoid extensive fire damage. It has an extremely high calorific value, so it is prone to rapid, intense chemical explosions, in the case of leakage. It burns or explodes when met with an ignition source (Cole, 2005). For that reason, the NFPA requires that any gas burner system is separately equipped with at least two safety fuel gas shutoff valves that automatically cut the fuel in the event of emergency (NFPA 1402, 2019). These separate valves are located remotely in what are known as control rooms. They are close enough for the monitoring party to be able to clearly see the evolutions inside the structure, without being too close that it would be dangerous.

Although gas-fuel systems are expensive and pose potential dangers, they are more environmentally conscious than wooden pallets and hay and are a better option for long-term usage in a live-fire structure. LPG and propane have similar chemical properties, cost and requirements for installation. Therefore, the deciding factor of which to implement in our tower came down to the Bomberos initial request of LPG. We chose to move forward with an LPG system.

4.3.4 Ventilation and Smoke Suppression

Ventilation is not only a method to provide fresh air to a room or building, but it is also a tactic taught and practiced in the field of firefighting. The point of ventilating a building during a fire is to make firefighting operations safer by controlling the flow of air into the building so that conditions inside improve and flashover is prevented (Avsec, 2018). In order to control heat, smoke and unburned gas in a live-fire training structure, NFPA 1402 (2019) requires the implementation of an exhaust ventilation system in each of the designated burn rooms. The Rhode Island Fire Academy structure contains a ventilation system that automatically triggers fans to turn on depending on the temperature inside the burn room (RIFA, personal communication, February 19, 2021). Due to ventilation systems being required by code, we recommend the Bomberos consult a design professional to install a fan system in each floor.

Smoke suppression systems are extremely elaborate systems that involve the filtering of smoke produced from fire and purifying it to be safely returned to the atmosphere (Avsec, 2018). During initial tower communication, the Bomberos had expressed interest in a smoke suppression system. However, the WPI Fire Protection Engineering department made it clear that a suppression system capable of filtering the air flow and contaminants is extremely expensive. Although this kind of system would be beneficial in helping align the Bomberos training practices with the environmental ideals of the country, it is not economically responsible. Instead, by burning LPG (a clean fuel) the Bomberos could reduce their environmental impact while controlling the budget and therefore a smoke suppression system was not implemented in our recommended design.

4.3.5 Fire Suppression and Temperature Control

In addition to smoke suppression, to control the flames it is recommended to implement a sprinkler system to guarantee the complete extinguishment of flames after training evolutions, as well as in case of emergencies (NFPA 1402, 2019). More detailed information on fire suppression systems was provided by Kidde Fire Systems and is included in Appendix C. These systems are necessary to cool down the burn areas if they reach dangerous temperatures and to be able to assist firefighters if the evolution does not completely extinguish the flames.

A temperature monitoring system consisting of interlocked temperature monitoring devices that measure the exact temperatures must be installed in each burn room at a level of 5 feet above the floor (NFPA 1402, 2019). The system in place is necessary for maintaining safety because once a burn room reaches a certain temperature, the devices will automatically activate a high-temperature shutdown which will shut off all burners into the space and force full ventilation of the training space. This ventilation will continue until the temperature returns to a safe number.

Both systems are required by NFPA code and therefore must be implemented in the design of the tower. A professional must be consulted to design the specific layout of these systems if they are included in the future tower.

4.3.6 Water Collection System

As stated, Costa Rica is a country extremely cautious about its carbon footprint and the conscious use of elements of the environment, one of those being water. In our initial conversations with the Bomberos, they expressed how it is important to them that they are not wasteful with their new tower, and communicated the need of a water collection system. This kind of system is not a requirement of NFPA code, and of the fire departments we interviewed, none of them have an advanced filtration system. It became clear that it is not a common element in firefighter training structures in the United States. Upon research online, there are very few reputable examples as the practice is so uncommon.

Due to the importance to the Bomberos', we recommend using a system involving recycled rainwater that was created in 2018 by another WPI IQP team (Boie et al., 2018). The recommended design is a collection tank next to the fire simulation area that collects rainwater through a gutter and piping system. The information and recommendations that the group completed could be built upon with our project so that we may integrate our needs into their technology. In order to collect the water from the tower, we believe that the base of the tower will need to be constructed of concrete and designed to slope the water flow into a series of underground drains. It would then lead the water to one of the chosen filtration tank designs the previous IQP group had offered. There, the water can be filtered and stored until it may be reused during future training evolutions in the tower.

4.4 FEASIBILITY OF TOWER IMPLEMENTATION

In order to make educated decisions during the modeling process, we decided to define three separate towers. Each of these had certain features that were necessary based on the Bomberos' needs and NFPA standards, but were unable to be compiled into a single tower without making sacrifices. Here are the elements included in each tower design:

Tower A

- 64 m^2 for base of the structure (8x8 m)
- Concrete with Rebar
- Each floor burn rooms
- LPG gas as fuel source
- 2-3 escape routes on each floor
- Half basement

Tower B

- 36 m^2 for base of the structure (6x6 m)
- Steel and Aluminum
- Burn room includes majority of each floor
- LPG gas as fuel source
- One main stairwell (no additional escape routes)
- Full basement- non burn room

Tower C

- More than 100 m^2 for base of the structure (larger layout with variety of room setups)
- Concrete with Rebar
- Individual burn rooms with safety zones on each floor
- Wooden pallets and hay are burned
- Multiple stairwells and escape routes
- No basement

As seen in Table 1, the criteria are assigned weights based on their importance. Since the Bomberos emphasized the need for a safe structure, safety received a score of five. Similar considerations were made for the other criteria. Performance and effectiveness were assigned scores of four because of their significance in the design. The visual appeal of the tower was not very meaningful for the Bomberos, so it received the lowest score of two.

The next part of the process involved giving scores to the three towers for each of the criteria listed. The scores were then multiplied by the weight in the corresponding row to determine the totals. For example, since effectiveness had a weight of four and Tower A was assigned a score of three for that criterion, Tower A received a total of twelve points for its effectiveness. After completing that procedure for each of the criteria, each of the towers' totals were summed in their respective columns. The tower that received the highest score was the best option for the Bomberos. As seen in Table 1, this was Tower A.

Criteria	Weight	Tower A		Tower B		Tower C	
		Score	Total	Score	Total	Score	Total
Cost	3	5	15	2	6	2	6
Performance	4	4	16	4	16	3	12
Safety	5	5	25	2	10	5	25
Visual Appeal	2	3	6	3	6	4	8
Eco-Friendliness	3	2	6	5	15	1	3
Effectiveness	4	3	12	3	12	5	20
	Total		80		65		74

Table 1: Weighted Pugh Matrix

Using the Pugh Matrix in Table 1 helped us prioritize each of the requests that the Bomberos made. By developing the list of general criteria, each of the three tower designs could be compared effectively. Since there were multiple considerations that needed to be made, the matrix was instrumental in establishing the team's rationale.

4.5 TOWER DESIGN ITERATIONS

The plan shown in Figure 7 was one of the first ideas that was proposed to the Bomberos. It offers a view from above the tower. An external stairwell is at the bottom of the image as well as an assortment of rooms within the main body of the building. The windows along the edges have annotations to depict shutters. Shutters must open outwards and are an important safety feature in case a firefighter is seeking an evacuation route. Similarly, it can be seen that all of the doors open outwards if an individual becomes trapped inside a room.

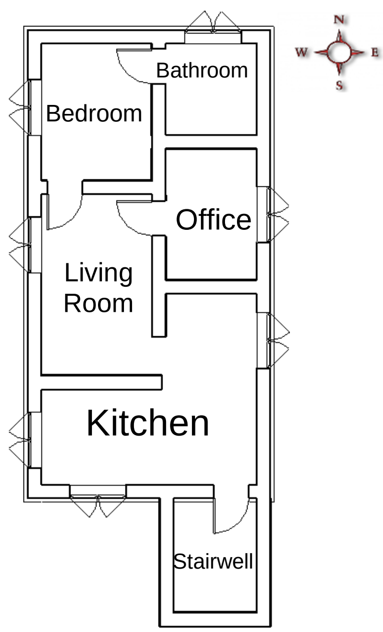

Figure 7: Example of Proposed Floor Plan

Following our presentation of this floor plan, the Bomberos had some constructive criticism. In this first design, we tried to simulate the layout of a house, with a few different rooms simulating bedrooms, a kitchen and a bathroom. The main issue our sponsors had was the congested interior layout of the tower. We originally visualized a small-scale house for this particular floor, but they were more interested in a training environment that mimicked an office building.

After that iteration, we decided that it was best to change the design so that each floor would have a specific theme, for example, the third floor simulating an office space. Despite this minor miscommunication, the plan in Figure 7 also would have been impractical due to the size of the rooms.

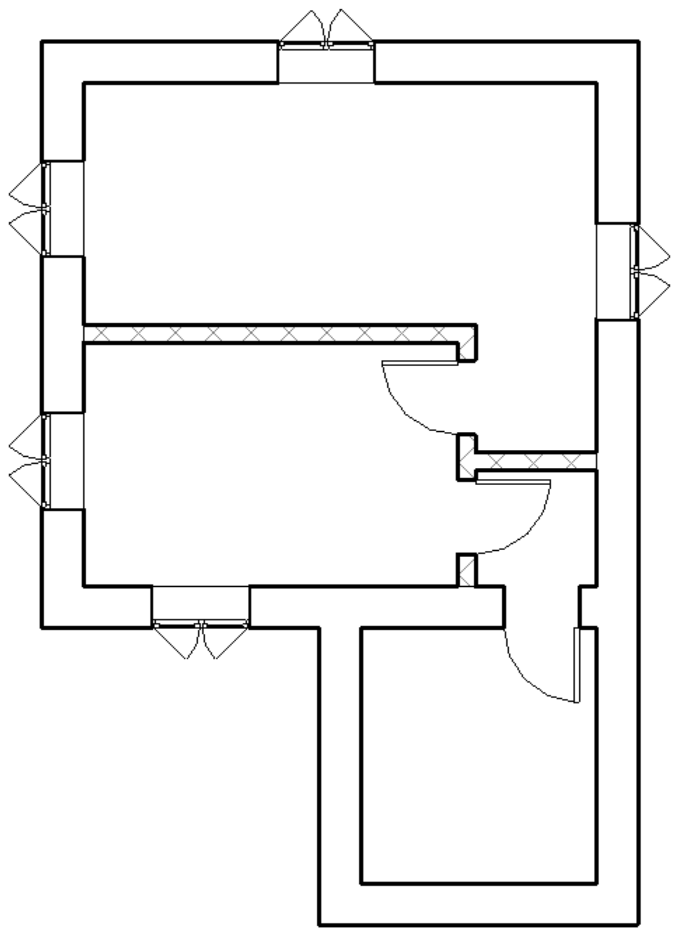

Figure 8: Second Iteration of Floor Plan

The Bomberos expressed that an office-oriented layout could make the design more appropriate given its simplicity. Less space would be needed due to a reduction in the number of rooms. Figure 8 depicts one of the modified floor plans that was created after consulting with the Bomberos. There was a noticeable reduction in the amount of rooms, and they were pleased to see something that offered simplicity. One of the main features that was altered from the floor plan in Figure 7 was the square footage of the tower itself. Our initial thought was that the rectangular layout would provide more space for additional rooms, but the Bomberos clarified that they were interested in a square layout. Constructing a tower with a square, eight-by-eight meter area was sufficient for their specific needs and space that was available.

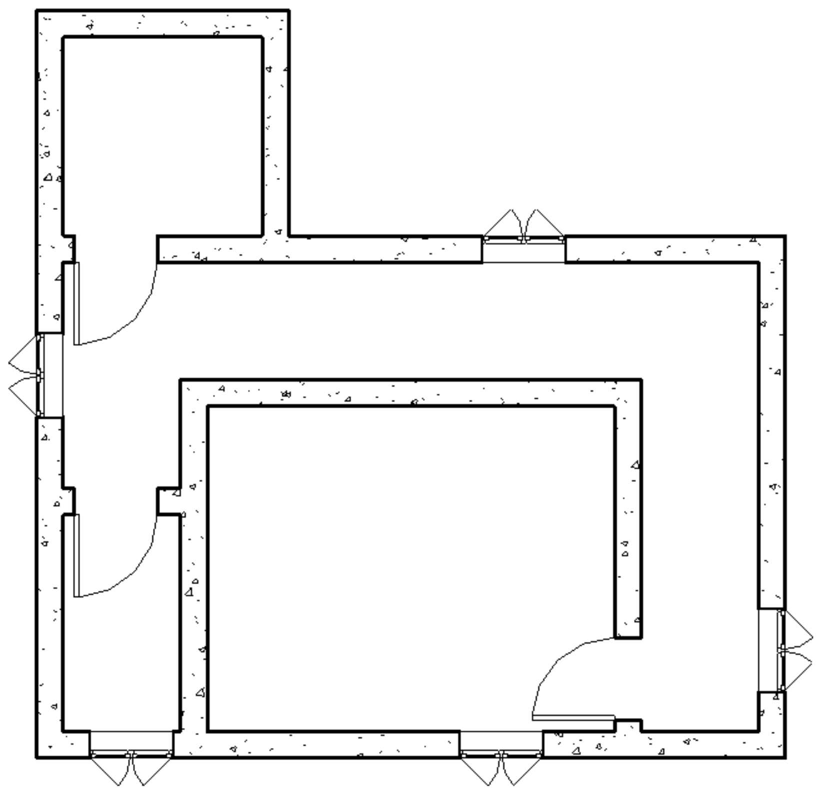

Figure 9: Final Iteration of the Fourth Floor of the Tower

Figure 9 shown above is one of the final floor plans determined for our structure. Upon receiving feedback regarding room size and layout, four other floor plans similar to this one were drawn and can be found in Appendix A. In order to vary the evolutions the Bomberos are capable of conducting, each floor plan is different. Additionally, the overall orientation of the building was rotated in order to better fit within the available area the Bomberos outlined.

After receiving feedback from the sponsors, the final floor plan arrangements were compiled. A 3D model was created in Revit, as shown in Figure 10. It provides a better understanding of the exterior view of the structure, as well as a view of the roof. This model does not incorporate the half-basement because the Bomberos would need to consult with a licensed professional regarding its implementation. We believe that the structure that was modeled is suitable for the scope of this project.

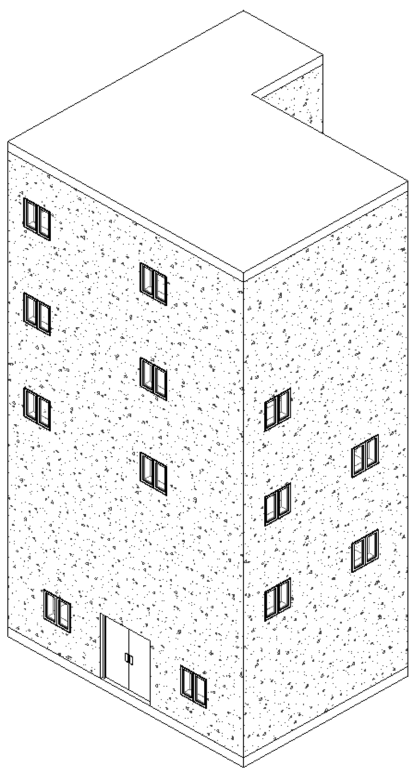

Figure 10: 3D Model of Fire Training Structure

4.6 COST ANALYSIS

Below is a table with a general overview of approximated material costs associated with Tower A, along with the supporting rationales. This was done by our team to provide more data since the Bomberos have limited funding. Thermal imaging cameras were also included in this analysis since it was an explicit request by the Bomberos. The prices of all items were based on U.S. costs and is subject to vary based on availability in Costa Rica. A more thorough table with calculations is in Appendix B.

Cement	51361.43
Rebar	24299.46
Tie Wire	520.93
Pipes	12894.34
Padgenite	65600
2 Cameras	6490
Total (USD)	161166.16
Total (CRC)	98582116.75

Table 2: Tower Material Cost Summary

The tower's main component is concrete, and accounts for the majority of the cost of the structure. The tower model has a height of nine feet (2.7432 meters) per floor, as well as an eight by eight meter base, with a staircase attached on the corner. The thickness of the walls and floors are one foot (0.3048 meters). From this, we found the overall volume of the tower in terms of necessary concrete, which ended up being 347.53 cubic meters. To estimate a price for the concrete, we researched prices online and found that a cubic meter of ready-mix concrete would cost approximately $147.79 (Concrete Network, 2021). Ready-mix concrete was chosen because it simulates the labor cost of wetting and laying the concrete, achieving a more accurate overall estimate. By multiplying the volume by price, we found a final price of approximately $51,361.43 for all of the concrete in the tower. It should be noted that this price is a liberal approximation, which does not take into account the volume subtracted for windows, drainage systems, rebar, and stirrups in the walls and ceilings.

As mentioned, rebar and stirrups are recommended in the walls to increase the strength and longevity of the tower. It is recommended that #4 steel rebar be used for optimal reinforcement. For our estimates, we placed rebar approximately every six inches in the building (Razorback Concrete, 2020). Since the building is approximately 45 meters tall, the total vertical length of rebar in exterior walls would be 10,890 meters. The rebar for each floor should go across in both directions, which comes to a total of 832 meters per floor for a total of 4,992 meters for the basement, four floors, and roof. The cumulative cost for all 15,882 meters of rebar would be $24,299.46 (The Home Depot, 2021a). The stirrups can be put as often as requested, and if it's assumed that two feet of 16.5 gauge rebar tie wire is used every two meters in the structure, the wire would end up costing $520.93 (The Home Depot, 2021b).

Since the tower is meant to be on fire, an LPG pipe system would need to be routed throughout the tower. Our pipe cost estimates were based on corrugated stainless steel tubing, a commonly used mode of transfer for liquid propane gas. Assuming that 1-1/2 inch pipes are necessary for enough gas transmission throughout the tower, we examined where the pipe system in the tower should be, shown in Appendix B. We found that the approximate length of pipe necessary in the tower would be 160 meters (~525 feet), making sure to account for piping up to higher floors. Multiplying by a bulk cost for 1-1/2 inch pipes (Ward Manufacturing, 2021), we found a final price of $12,894.34.

To protect and extend the lifespan of the concrete in the tower, we learned from our interview with the Worcester Fire Department that fire resistant tiles are often employed. One type of tile is called Padgenite, and is a thermally protective lining for fire training towers (WHP

Trainingtowers, 2020). Based on the tower design, our team believed it would be most practical to install Padgenite I tiles, since they are significantly less expensive than Super Padgenite HD panels and are still practical for the Bomberos' needs. We estimated that tiles would be placed around the interior perimeter and ceiling around the areas where gas pipes would be, as illustrated in Appendix B. Our group found we would need approximately 200 tiles, which would cost a total of $65,600 (WHP Trainingtowers, 2017).

One of the Bomberos' initial requests was a thermal imaging camera. The FLIR K33 is a handheld high performance TIC made for firefighting (Flir Systems, 2021). It is capable of scanning a large range of temperatures and employs a high-quality visual display. The camera can resist being dropped onto the concrete floor, being exposed to high temperatures, and the high humidity that is normal in Costa Rica. It is also a fairly affordable solution, costing $3,245.00 per camera.

Other considerations include the costs of labor associated with constructing the tower, along with the lesser costs of installing gas pipes, drainage system, proper burners, ignition system for the burners, windows, and doors. While we cannot provide estimates for these costs, it is important that they are considered when planning the tower's construction.

The sum of all costs gives an approximate price of tower materials of $161,166.15 in United States Dollars, or ₡98,582,111.43 in Costa Rican Colones.

5. RECOMMENDATIONS

In this section we present recommendations for the Bomberos of Costa Rica. Due to the NFPA code, design professionals are required for the ultimate design of all included elements within a live-fire training structure. Therefore, all future outlined objectives are recommendations the Bomberos must present to professionals in the event the structure comes to fruition. In this section we discuss our proposed design and what the team believes is the best course of action for the construction of a live-fire training structure. These recommendations are followed by future actions the Bomberos can follow in order to implement our ideas or potential future projects.

5.1 PROPOSED DESIGN RECOMMENDATIONS

Recommendation One: Concrete Structure

In communications with professionals and in research, we found concrete is the better choice for the fire training tower because of its greater resistance to repeated exposure to extreme temperatures. Additionally, a concrete tower is more resistant to high winds and earthquakes, and would be more cost effective. One negative about concrete is that it will suffer from spalling over time, which can lead to future maintenance costs. There are a few things to keep in mind when constructing the tower. First, rebar and stirrups should be installed while laying each segment of the tower to increase the overall strength of the tower. Additionally, drains, scuppers, and gutters must be installed on each floor to allow for water to flow out of the tower. We recommend that corrugated steel pipes be installed through the tower for transmission of liquid propane gas.

Recommendation Two: LPG Gas System

The liquid petroleum gas system was the system initially requested by the Bomberos. During our research and interviews, our group confirmed that it is the most ideal for the Bomberos' needs. This system is more environmentally friendly; it allows a clean burn in comparison to other types of fire ignition systems that produce more harmful emissions. HEPA filters could be used to significantly decrease emissions from the fires, but our team decided that they would be too expensive based on the available budget. While speaking with fire professionals, we concluded that the LPG system is easier and safer to control indirectly due to the detached control center where the fire is monitored by adjusting valves and regulating the gas flow.

Recommendation Three: Half-Basement

During our discussions with various professionals from fire departments and consulting NFPA code, there was broad support that implementing a full below-grade basement into the tower design would be dangerous if equipped with gas-fuel. The team concluded that the best alternative would be for the Bomberos to construct a half below-ground basement. This layout offers many features of a traditional basement, but also ensures that firefighters will have more than one route of egress. By building the tower into an inclined surface, one of the basement walls can be under ground while the opposite side is open to grade-level. The open side has a large door and windows which can be open or closed depending on how the floor is used. Although this may not simulate the exact conditions found in the basement of a building, the Bomberos would be able to enhance their skills while ensuring safety of everyone involved in the evolutions.

Recommendation Four: Interior Layout

The detailed floor plans that are recommended for the final design are shown in Appendix A. These floor plans were developed upon several iterations of feedback from the Bomberos. Each of the floors has a unique layout so that the Bomberos would be able to engage in a variety of different training exercises. It is important for firefighters to be exposed to a diverse assortment of layouts so that they do not become accustomed to a certain arrangement. The set of floor plans that we recommend were designed to offer both unconventional and traditional building layouts so that the Bomberos can train effectively without excessive repetition.

Recommendation Five: Water Collection System

Due to the extensive use of water that is needed when fighting fires, we understood the importance of incorporating a system for collecting water. Runoff water will be directed to scuppers which channel the water into drains located on the ground. The drains would be connected to a network of pipes and eventually lead to the tanks where the water would remain until it is needed in the future. Including a filtration system is another possibility, but we believed that it would be better to focus on the tower's overall design before considering additional components. A water filtration system was designed by a previous group of WPI students with the Bomberos therefore in the event the Bomberos' wish to include such a system, the previous IQP designs may be consulted. Despite the simplicity of the arrangement, this would help the Bomberos continue to uphold standards with respect to conservation efforts in Costa Rica. We conclude a water filtration system would add significant value to the tower.

5.2 RECOMMENDATIONS FOR FUTURE PROJECTS

The scope of this project was broad and aspects of the design and structure can be developed further, therefore we have defined potential future projects to build upon the work we have completed with the Bomberos.

The addition of an air filtration system would also be valuable for the Bomberos to help reduce harmful emissions during training exercises. The available budget does not support the inclusion of HEPA filters into the tower. Therefore we recommend future IQP research for a more cost-effective form of air filtration within live-fire training structures.

6. CONCLUSION

The goal of this project was to define the requirements of a live-fire training structure and recommend a design for the National Firefighter Training Academy in San José. We achieved this goal by researching, conducting interviews and consulting NFPA codes which enabled us to better understand what needed to go into the tower design.

Our primary consideration was to understand current professional firefighter training in various countries, and how these trainings are benefitted through use of a live-fire training structure. By conducting interviews with various professionals in fire-related fields, it became clear that some of the original requests made by the Bomberos would not be feasible for their tower. The information we collected helped us categorize which aspects of a new tower would be essential and which aspects would be considered supplemental. Three different tower designs were developed in order to help the Bomberos visualize the necessary inclusions and potential options they could implement. Upon analyzing the three designs in regards to various considerations, the final tower design was chosen. We were able to further enhance this set of recommendations by developing floor plans and 3-D modeling the tower for a better visualization. This ultimately led to a comprehensive cost analysis of the final design. The construction of a live-fire training structure would not only improve the skills and knowledge of the Bomberos to help safeguard property and lives, but has the potential to revolutionize fire training across Latin America.

REFERENCES

Agudelo, G. (2019, August 8). Why Natural Resources Are an Economic Potential For Costa Rica ⋆ The Costa Rica News. *The Costa Rica News.* https://thecostaricanews.com/why-natural-resources-are-an-economic-potencial-for-costa-rica/.

Avsec, R. (2018, October 31). Training Day: Ventilation basics. *FireRescue1*. https://www.firerescue1.com/fire-products/ventilation/articles/training-day-ventilation-basics-VIK1qVJK7OPxZoBC/

Boie, T., Muenchow, K., Vangos, T., & Vodola, K. (2018). *Designing a Sustainable Water Supply Network for El Cuerpo de Bomberos Training Practices.* [Undergraduate interactive qualifying project, Worcester Polytechnic Institute]. Digital WPI.

Ciolfi, J., Nippert, K., Picho, K., Spalding, L. (2020). *Exploration of A Robot Development Program for the Costa Rican Fire Department.* [Undergraduate interactive qualifying project, Worcester Polytechnic Institute]. Digital WPI.

Cole, Anthony. (2005, March 10). Fire Protection for Liquefied Petroleum Gas (LPG) Installations: The Basics. *Firehouse.* https://www.firehouse.com/rescue/article/10508099/fire-protection-for-liquefied-petroleum-gas-lpg-installations-the-basics

Concrete Network. (2021, February 15). Concrete Prices 2021 - How Much Does Concrete Cost? *The Concrete Network.* https://www.concretenetwork.com/concrete-prices.html.

Costa Rica. Costa Rica | *Climate Action Tracker.* (2020). https://climateactiontracker.org/countries/costa-rica/.

Costa Rica's Constitutional Abolition. futurepolicy.org. (2020, April 15). http://www.futurepolicy.org/peace-and-security/military-spending/costa-ricas-abolition-of-the-army/.

Ezekoye, O. A., Hurley, M. J., Torero, J. L., & McGrattan, K. B. (2012, October 31). *Applications of Heat Transfer Fundamentals to Fire Modeling*. https://cefrc.princeton.edu/sites/cefrc/files/reading-3.pdf.

Fire Facilities Staff. (2020, April 16). *About Our Towers*. https://www.firefacilities.com/fire-training-towers/about-our-towers/.

FLIR Systems. (2021). *FLIR K33*. FLIR. https://www.flir.com/products/k33/.

Food and Agriculture Organization of the United Nations. (2009, April 22). *FAO.org*. FAO.org : http://www.fao.org/faolex/results/details/en/c/LEX-FAOC003004.

Global Petrol Prices. (2021, March 8). *LPG prices around the world, 08-Mar-2021*. GlobalPetrolPrices.com. https://www.globalpetrolprices.com/lpg_prices/.

Greaser, A. (2018, February 15). *Costa Rican "bomberos" and their BMW Firexpress motorcycles*. RevZilla. http://www.revzilla.com/common-tread/costa-rican-bomberos-and-their-bmw-firexpress-motorcycles.

Guevara Arce, S. M. (2020, March). Analysis of the existing information of La Carpio informal settlement, Roble Norte sector, to create the basis for future research in fire safety. Retrieved 2020, from https://repositoriotec.tec.ac.cr/bitstream/handle/2238/11353/TFG_Sara_Guevara_Arce.pdf?sequence=1&isAllowed=y

Hamlett, L., Peterson, S., Sifuentes, K., Lopez, J. (2019) Plan for the Improvement of Water Treatment in Emergencies for El Cuerpo de Bomberos. Worcester; Worcester Polytechnic Institute.

Kidde Fire Systems (2021). *P&ID, KFS LPCO2 Master & Selector W/CO2 Delay* [blueprint].

Koonce, A. L., & González-Cabán, A. (1992). *Fire Management in Central America*. U.S. Forest Service. https://www.fs.fed.us/psw/publications/documents/psw_gtr129/psw_gtr129_koonce.pdf.

Madsen, J. J. (Ed.). (2005, June 1). Which is the better building material? Concrete or steel? *Buildings*. https://www.buildings.com/articles/36029/which-better-building-material-concrete-or-steel.

Massachusetts Firefighting Academy (2021). *Burn Building* [blueprint].

Mason, Mike. (2006, July 10). Live Fire Training - Part 2. *Firehouse.* https://www.firehouse.com/operations-training/article/10505079/live-fire-training-part-2

National Fire Protection Association. (2021). *NFPA: International.* https://www.nfpa.org/international

National Fire Protection Association. (2021). *NFPA: Overview.* https://www.nfpa.org/overview

NFPA 1001: Standard for Fire Fighter Professional Qualifications, 2019 Edition. In *NFPA National Fire Codes Online.* Retrieved from https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1001

NFPA 1402: Standard on Facilities for Fire Training and Associated Props, 2019 Edition. In *NFPA National Fire Codes Online.* Retrieved from https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1402

O'Donnell, R. (2015) Global Trends in Fire Training Facilities. *Firehouse.* https://www.firehouse.com/home/article/12092033/firefighter-training-trends-in-fire-training-facilities-around-the-world

Organización de las Naciones Unidas para la Alimentación y la Agricultura. (2006, December 22). *FAO.org*. FAO.org : http://www.fao.org/faolex/results/details/es/c/LEX-FAOC069651.

Press, A. (2009, November 18). Radiometric Temperature Measurements: II. Applications. Retrieved November 12, 2020, from https://books.google.com/books?id=OQLMldVUjD8C

Razorback Concrete. (2020, July 31). Does Concrete Always Need Rebar? *Razorback Concrete.* https://razorbackconcrete.com/does-concrete-always-need-rebar/.

RGB. (2008, May). *Rhode Island Fire Academy-Training Facility* [blueprint].

Skyciv. (2020, August 26). Steel, Wood and Concrete: A comparison. *SkyCiv Cloud Structural Analysis Software.* https://skyciv.com/technical/commonely-used-materials-in-structural-engineering/#:~:text=Steel%20is%20very%20strong%20in,(58%20%E2%80%93%2072.5%20ksi).&text=Concrete%20is%20extremely%20strong%20in,of%20about%2017MPa%20to%2028MPa.

Sturkol, S. (2018, June 5). Firefighters learn rope, rapelling skills during technical rescue training at Fort McCoy. *The U.S. Army.* https://www.army.mil/article/206472/firefighters_learn_rope_rappelling_skills_during_technical_rescue_training_at_fort_mccoy.

Spell, J. (2020, October 19). A firefighter's guide to fireground search and rescue- part 2. *FireRescue1.* https://www.firerescue1.com/fire-products/rescue-equipment/articles/a-firefighters-guide-to-fireground-search-and-rescue-part-2-TRLszcH6HvQpBhlJ/

Swanton Welding. (2016, September 7). Steel vs. Concrete: Which Comes Out on Top. *Swanton Welding.* https://blog.swantonweld.com/steel-vs.-concrete-which-comes-out-on-top.

TCRN Staff. (2019, March 25). New Fire Stations Will Keep Rainwater and Generate Their Own Electricity ⋆ The Costa Rica News. *The Costa Rica News.* https://thecostaricanews.com/new-fire-stations-will-keep-rainwater-and-generate-their-own-electricity/.

The Home Depot. (2021a, March). *1/2 in. x 20 ft. #4 Rebar-REB/4/615G4/20. The Home Depot.* https://www.homedepot.com/p/1-2-in-x-20-ft-4-Rebar-REB-4-615G4-20/202532809.

The Home Depot. (2021b, March). Weyerhaeuser 400 ft. 16.5-Gauge Rebar Tie Wire-05337. *The Home Depot.* https://www.homedepot.com/p/Weyerhaeuser-400-ft-16-5-Gauge-Rebar-Tie-Wire-05337/202094311.

Volunteer BaseCamp Staff. Volunteer Abroad: Emergency Services: Costa Rica: Fire and Rescue Volunteer: Fire Department of Costa Rica: Goicoechea. *Volunteer BaseCamp.* http://www.volunteerbasecamp.com/Volunteer-Abroad-Placements/Fire-and-Rescue-Volunteer/Costa-Rica/Fire-Department-of-Costa-Rica/Goicoechea/744.

Ward Manufacturing. (2021, March). Price Sheet. *WARDMFG.* https://www.wardmfg.com/price-sheet/.

Weintraub, E. (2020, April 15). Spalling: What It Is, What It Does, and How to Fix It. *The Balance.* https://www.thebalance.com/what-is-spalling-1798631.

WHP Trainingtowers. (2017, January). Padgenite Prices. *PDFfiller.* https://www.pdffiller.com/405669343-PDF_AccessoryOrderForm_2017v2pdf-order-form-pdf-WHP-Training-Towers-.

WHP Trainingtowers. (2020, August 5). Padgenite™ vs Other Liners. *WHP Trainingtowers.* https://trainingtowers.com/burn-rooms/padgenite-vs-other-liners/.

WHP Trainingtowers (2015). *Custom 1st Alarm - Four Story Rope Tower* [blueprint].

World LPG Association (WLPGA). What is LPG? (2020, September 21). https://www.wlpga.org/about-lpg/what-is-lpg/

Www.mrrabbit.cr. (2020). Bomberos Costa Rica. http://www.bomberos.go.cr/.

X. Cheng and Y. Zhang. (2019). Study on Explosion Safety Distance in LPG Tank Fire. *2019 International Conference on Intelligent Transportation, Big Data & Smart City* (ICITBS), Changsha, China, pp. 682-686, doi: 10.1109/ICITBS.2019.00169.

APPENDIX A: Floor Plans

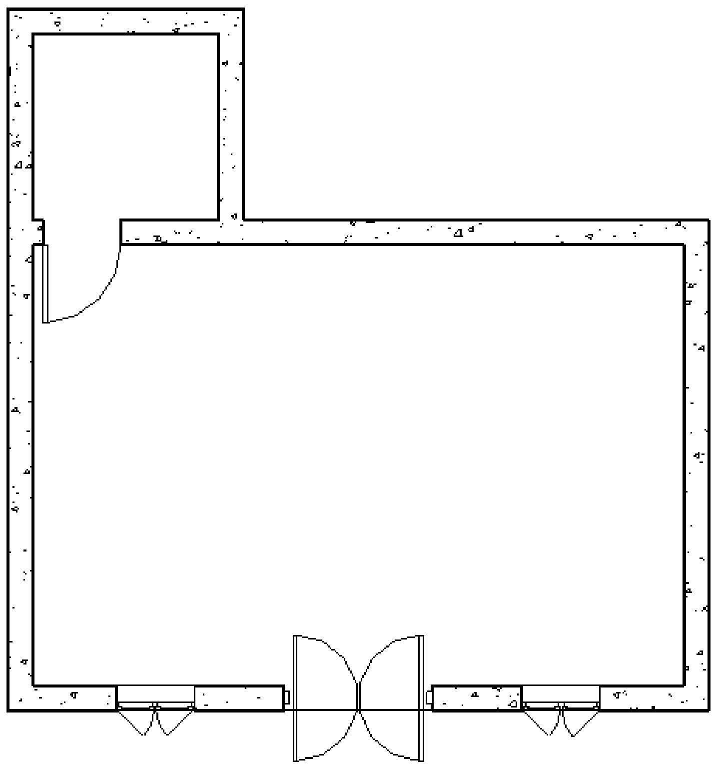

Figure 11: Floor plan of the basement of the tower

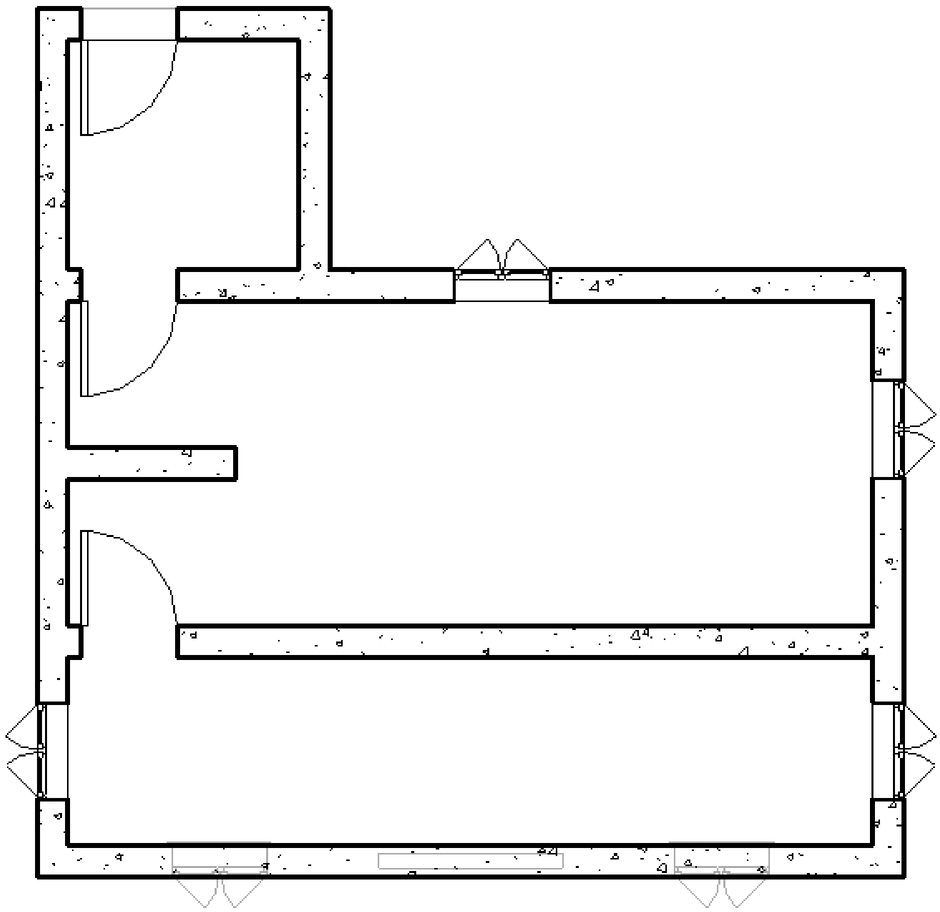

Figure 12: Floor plan of the first floor of the tower.

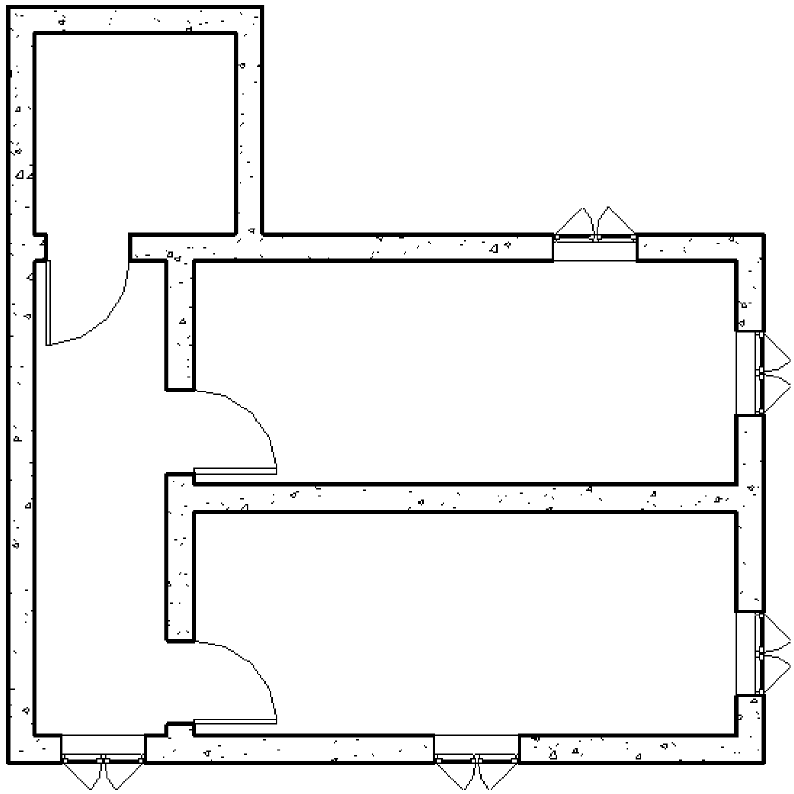

Figure 13: Floor plan of the second floor of the tower.

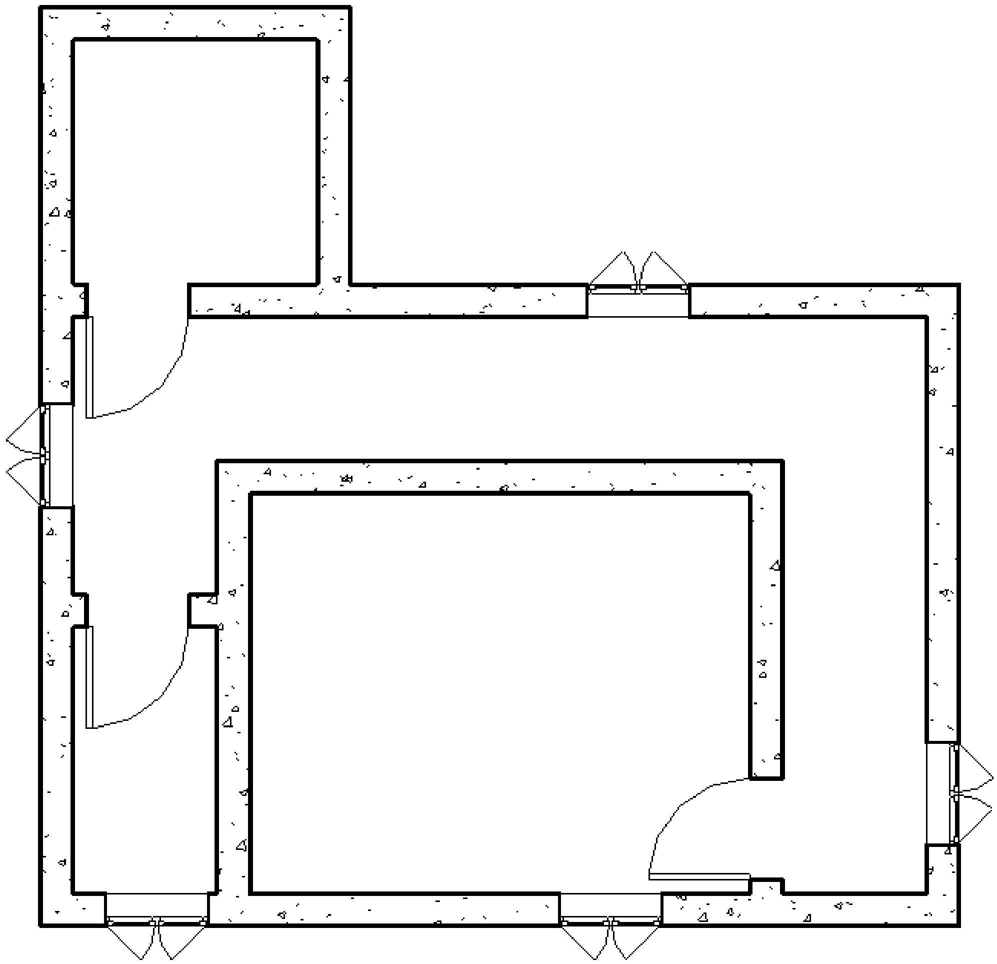

Figure 14: Floor plan of the third floor of the tower.

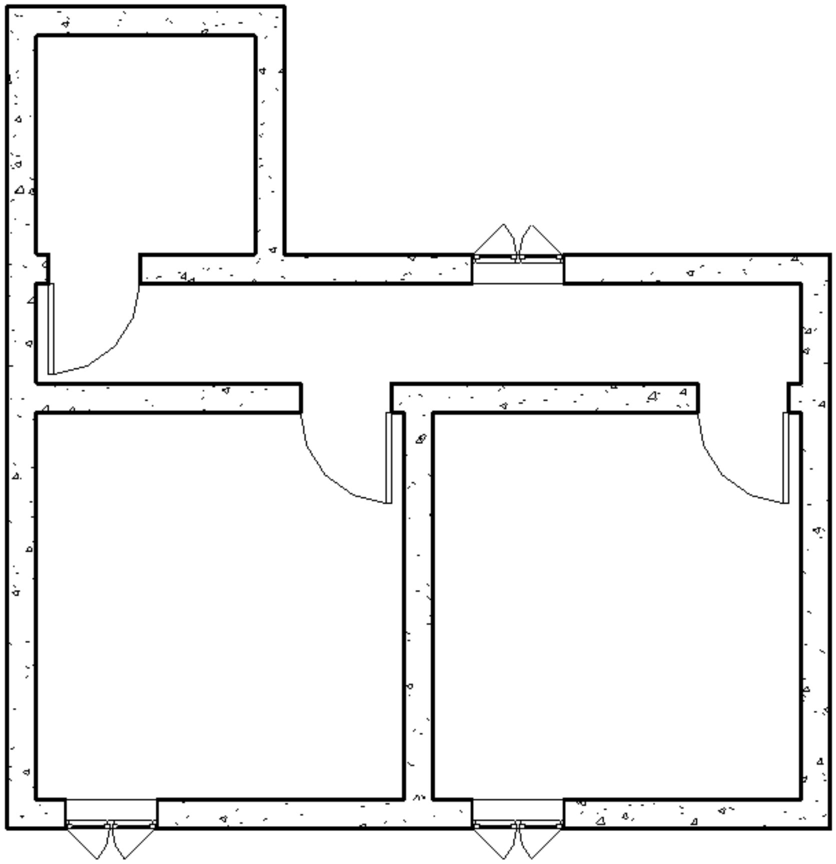

Figure 15: Floor plan of the fourth floor of the tower.

APPENDIX B: Cost Analysis

TOWER A								
Cement	USD price per volume (m3):	147.79				Pipes	USD price per le	80.5896
	Volume Calculations	Floors/Ceilings:	117.0432				Approximate len	160
		Ext. Walls:	154.6835616				Total:	12894.336
		Int. Walls:	Basement:	1.0451592				
			Floor 1:	7.73417808		Padgenite	USD price per 4'	328
			Floor 2:	10.24256016			Approximate sur	200
			Floor 3:	10.451592			Total:	65600
			Floor 4:	11.32952573				
		Stairwell Approximation:	35					
	Total volume (m3):	347.5297768				Cameras	USD Price per c	3245
	Total (USD):	51361.42571					Cameras:	2
							Total:	6490
Rebar	USD price per length (m):	1.53						
	Approximate length (m):	15882				Tie Wire	USD price per le	0.0656
	Total:	24299.46					Approximate len	7941
							Total:	520.9296
Total (USD):	161166.1513							
Total (CRC):	98582111.43							

Table 3: Cost Analysis

Below are the illustrations of the gas pipe system pricing rationale. The red rectangles represent a pipe along the floor, and the red circle represents a vertical pipe going from ground level to the other floors.

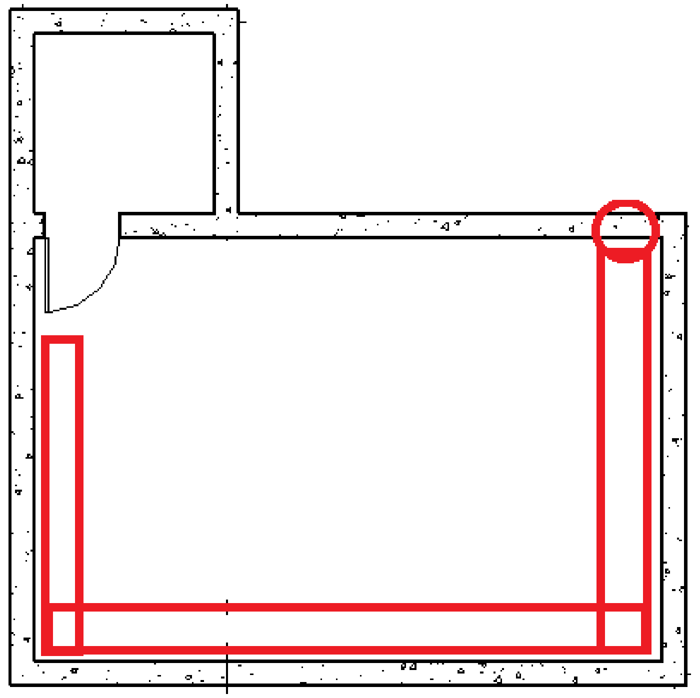

Figure 16: Mock up of gas pipes for the basement.

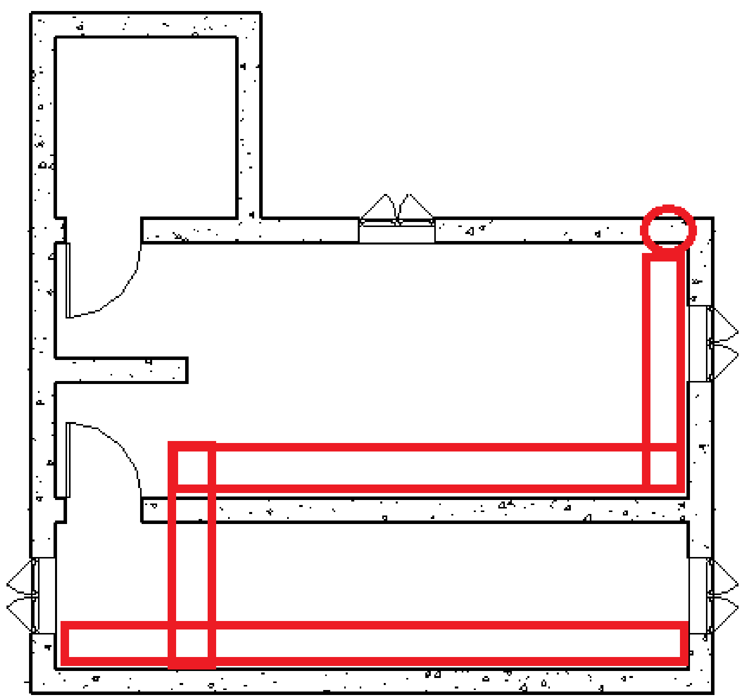

Figure 17: Mock up of gas pipes for the first floor.

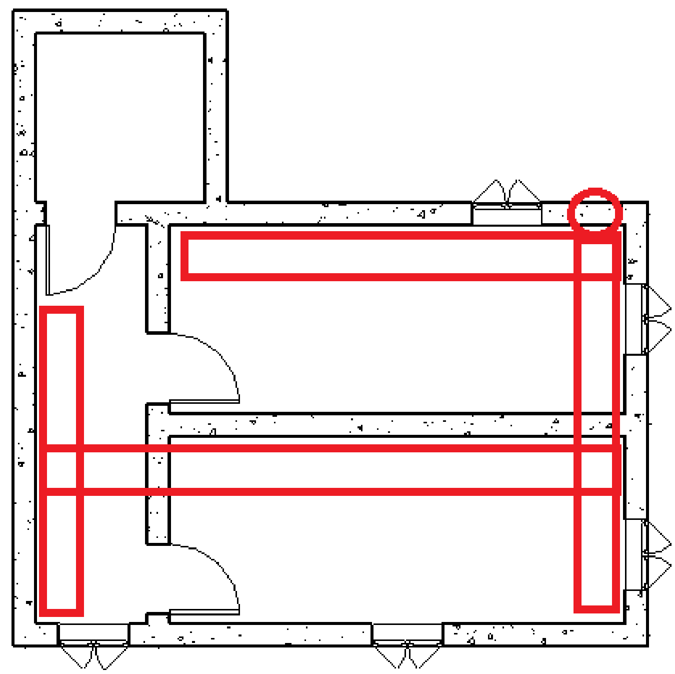

Figure 18: Mock up of gas pipes for the second floor.

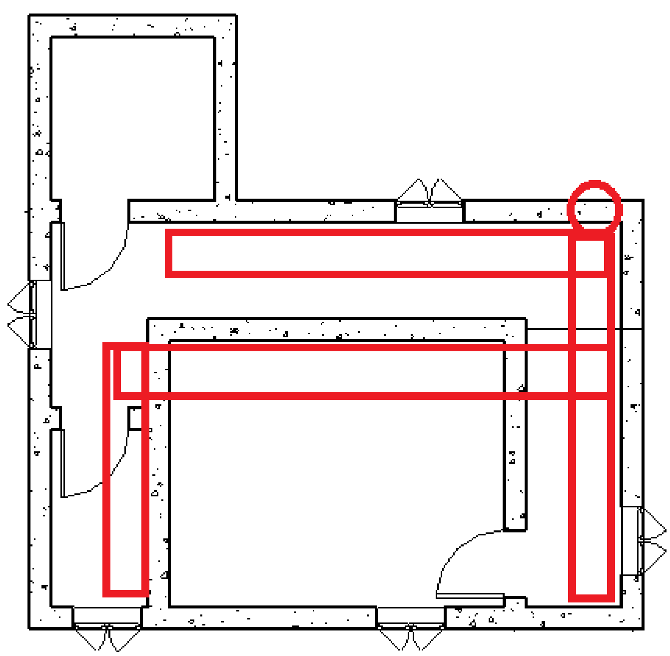

Figure 19: Mock up of gas pipes for the third floor.

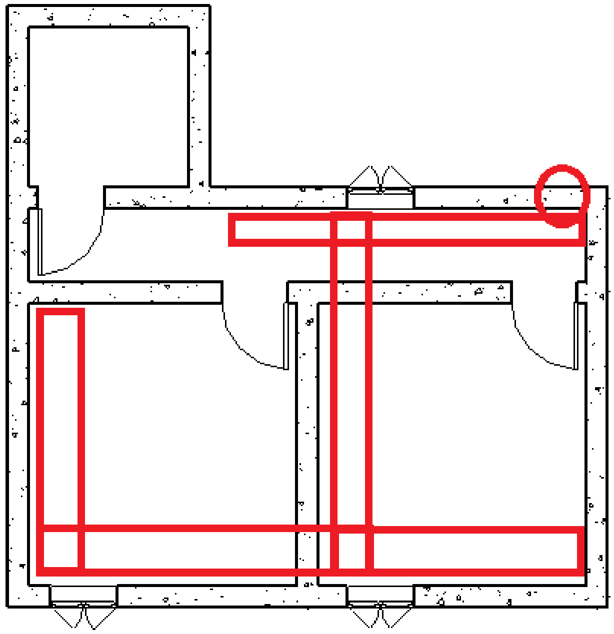

Figure 20: Mock up of gas pipes for the fourth floor.

APPENDIX C: Existing Schematics

An important component of our investigative efforts involved speaking with companies about existing projects they had been involved in. Whether we spoke with a fire department about the design of their training tower or were seeking advice from a professional company, the schematics that were offered to us helped with the visualization of this project. Some of the documentation that we acquired throughout the course of our research is included below.

WHP Trainingtowers

Figures 21-23 were provided courtesy of WHP, a company located in Overland Park, Kansas. They specialize in building fire training towers and built the one that is currently used by the Worcester Fire Department. A representative provided us with valuable information related to padgenite panels, the critical material needed to effectively fireproof a burn room. The building plans below were used for one of the towers they built in College Station, Texas. It has similar features to the tower design we were pursuing. Although an additional stairwell is located on the inside of the structure, the tower has a square cross-sectional area like the Bomberos requested. Since these plans shrank to fit the page, some of the annotations may be illegible. However, there are details pertaining to protective plating, OSHA standards, and various measurements that supported some of our decisions during the design process.

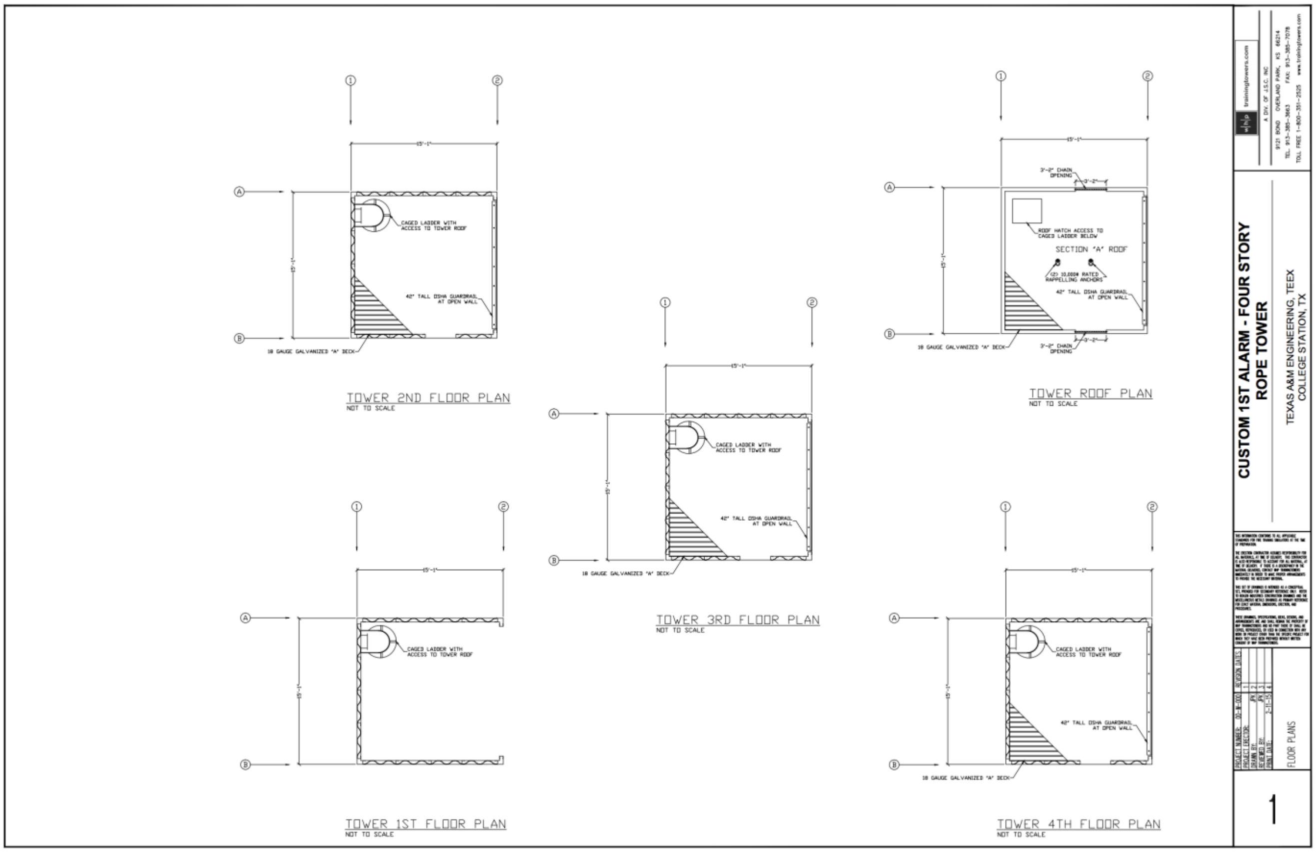

Figure 21: WHP Tower Schematic Page 1 (WHP, 2015)

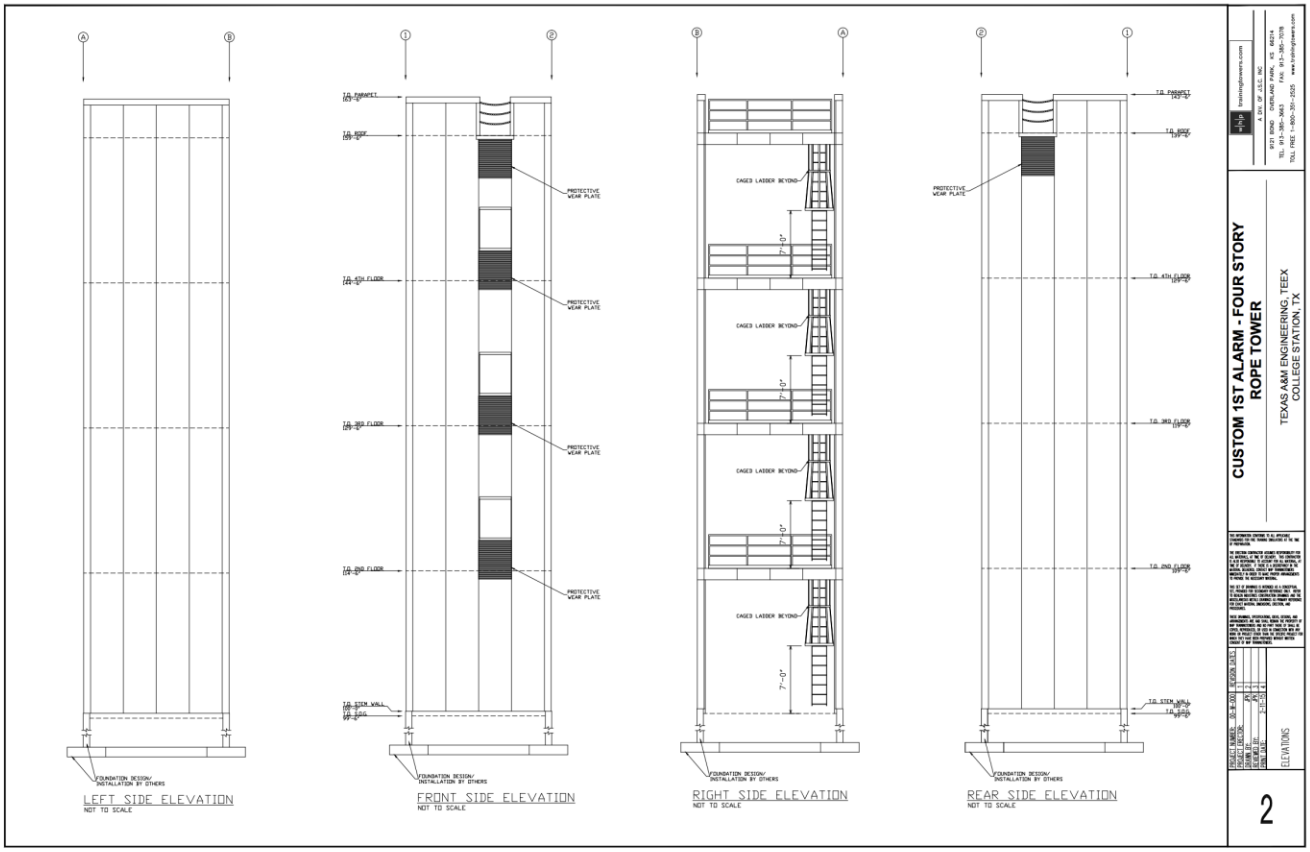

Figure 22: WHP Tower Schematic Page 2 (WHP, 2015)

Figure 23: Image of WHP Tower - College Station, TX (WHP, 2015)

Massachusetts Firefighting Academy

While meeting with the Massachusetts Firefighting Academy, the team learned about specific ways in which fire departments use their training towers. Figures 24-30 depict the structure that is currently in use in Stow, Massachusetts. An official from the Academy was able to provide us with the schematics of the on-site tower. The figures do not contain information with respect to the dimensions of the tower, but they are a good representation of the interior layout. Some pictures of the tower are included immediately following the schematics.

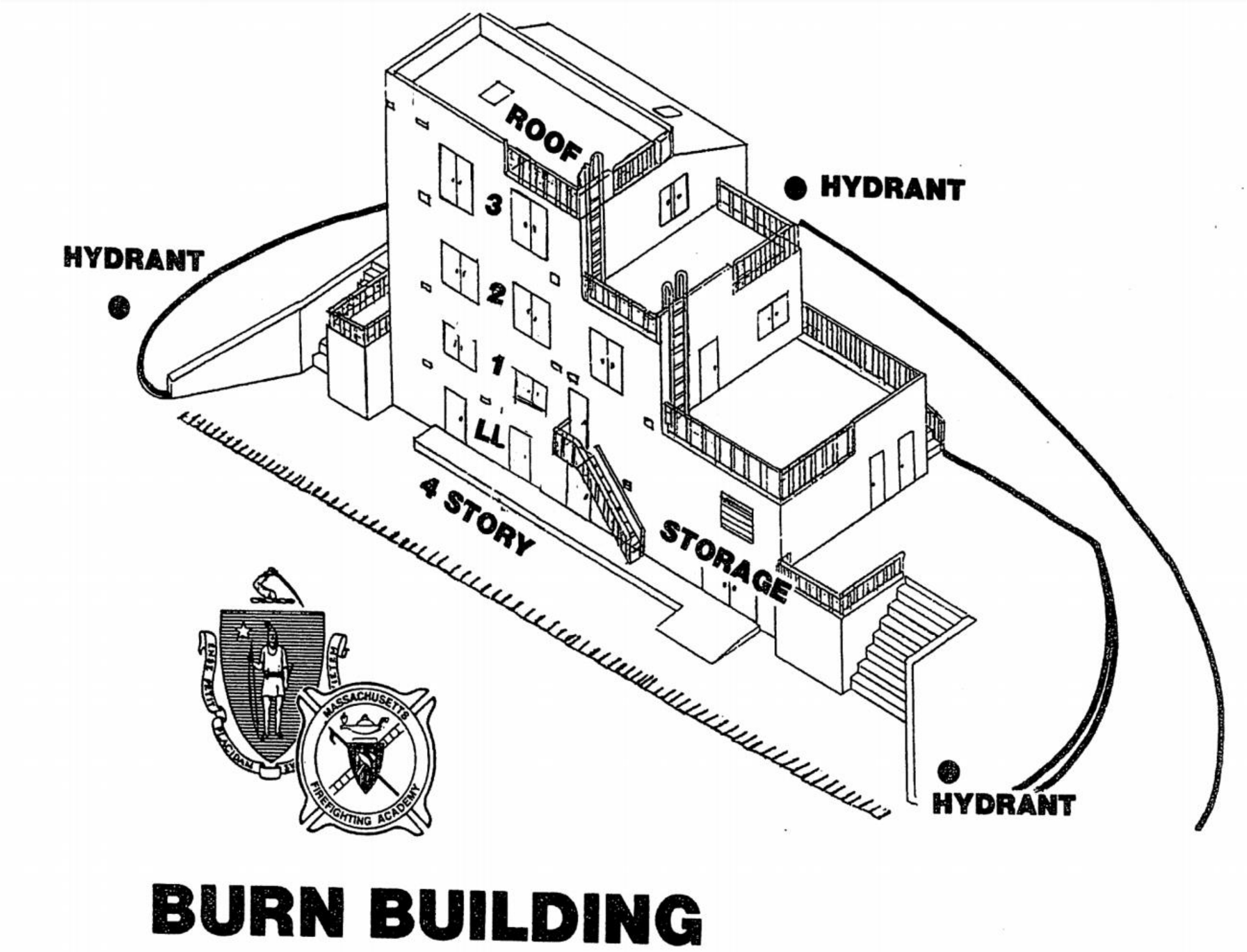

Figure 24: MA Firefighting Academy Burn Building (MAFA, 2021)

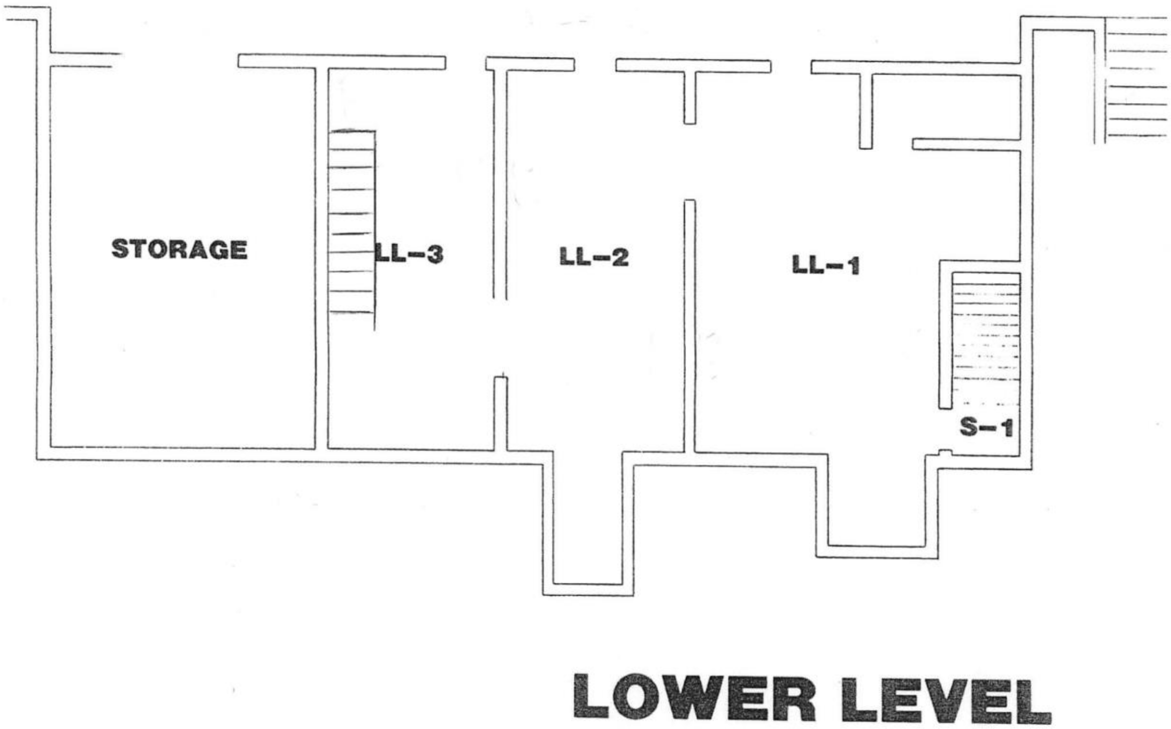

Figure 25: MA Firefighting Academy Lower Level (MAFA, 2021)

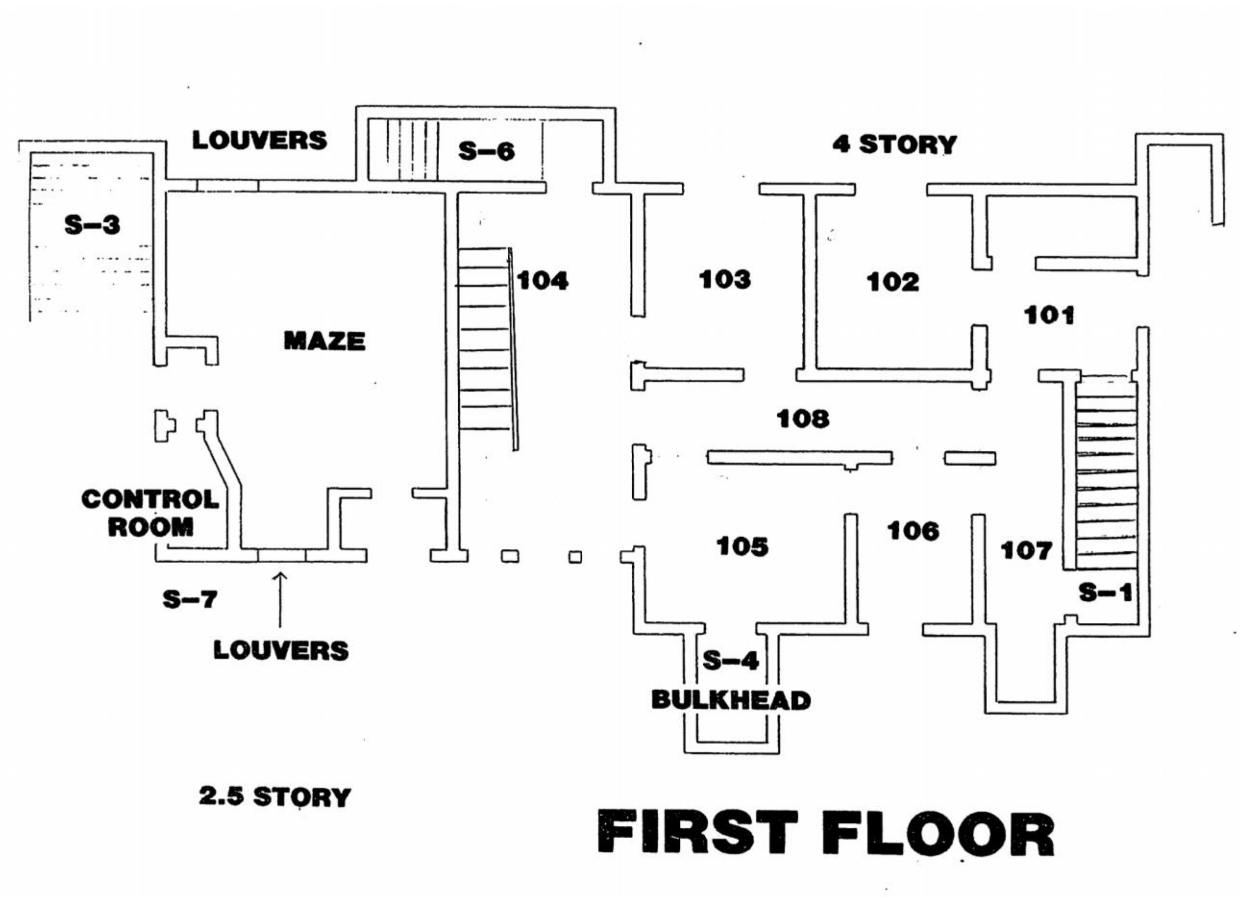

Figure 26: MA Firefighting Academy First Floor (MAFA, 2021)

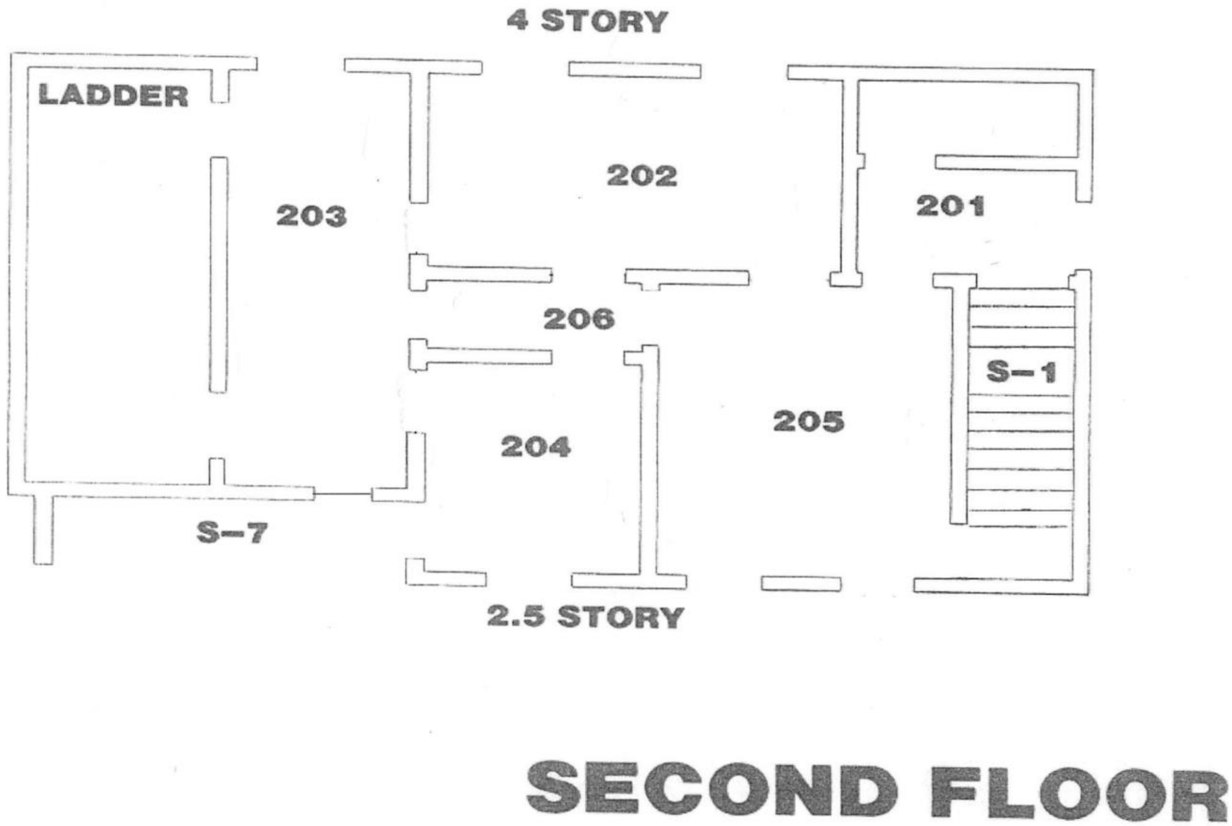

Figure 27: MA Firefighting Academy Second Floor (MAFA, 2021)

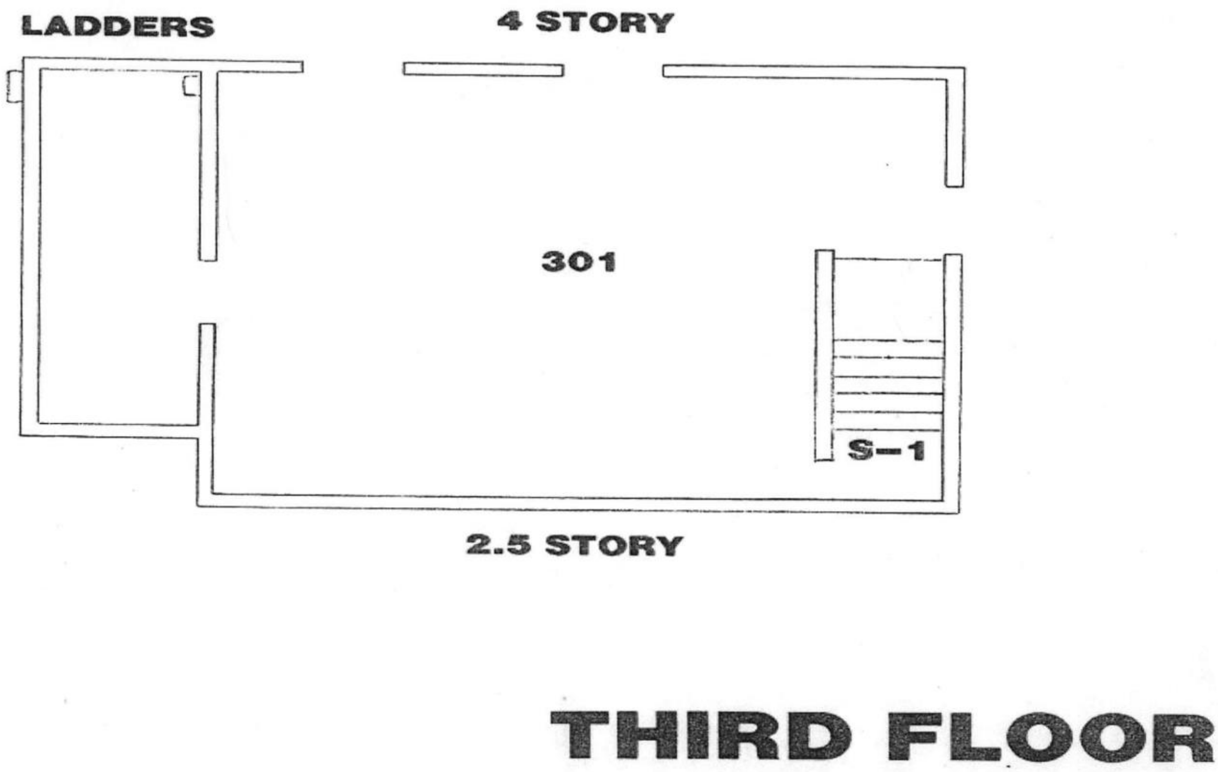

Figure 28: MA Firefighting Academy Third Floor (MAFA, 2021)

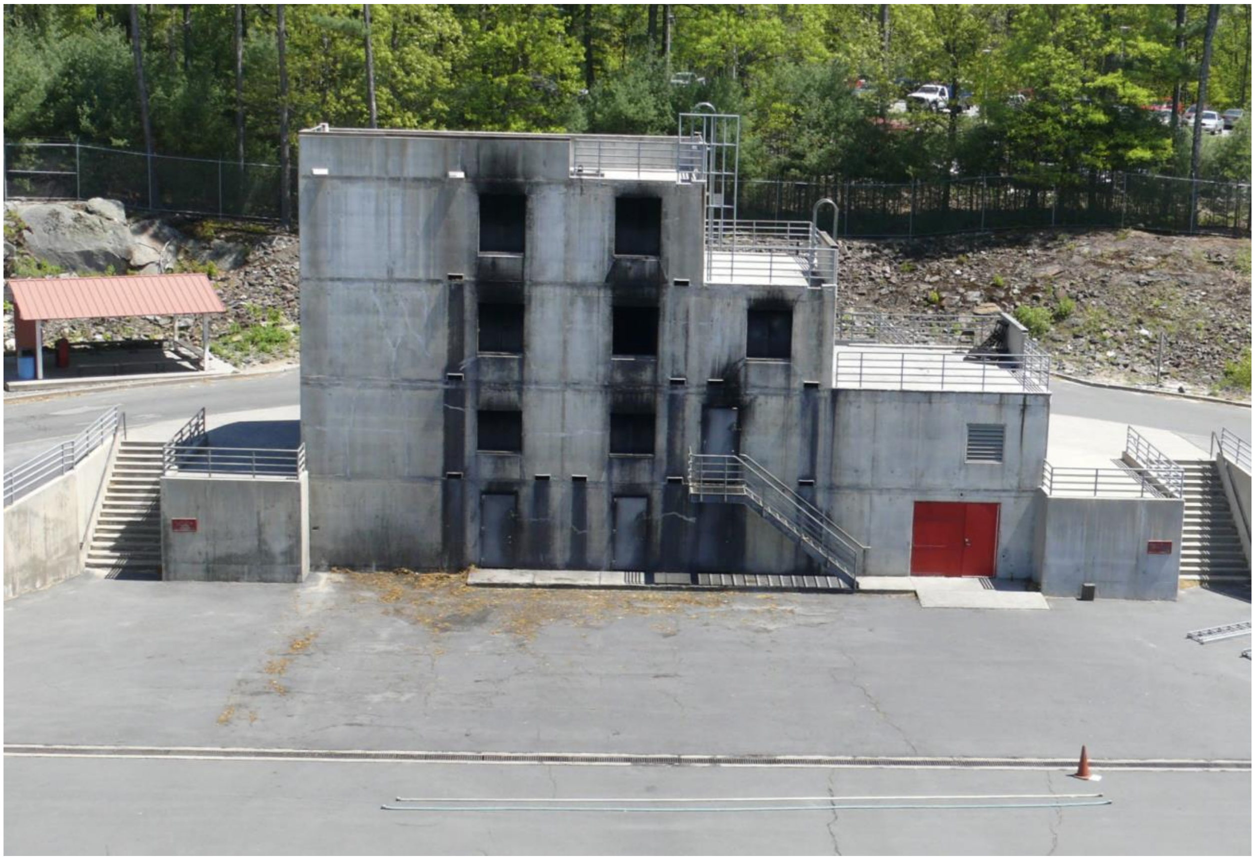

Figure 29: Image of MA Firefighting Academy Burn Building (MAFA, 2021)

Figure 30: MA Firefighting Academy Burn Building in Use (MAFA, 2021)

Rhode Island Fire Academy

During our interview with the Massachusetts Firefighting Academy (MAFA), we briefly learned about a training facility at the Rhode Island Fire Academy (RIFA). Their tower is a class B burn building rather than MAFA's class A burn tower. This means that the fires in Rhode Island are produced by igniting gas rather than using wood and hay. The tower is shown in greater detail in Figures 31-33.

The team spoke with an instructor from RIFA, and the discussion concentrated on the aspects of their gas system. While we understood early on that the specific piping layout would need to be determined by a licensed professional, the team wanted to gain more insight about how the system is set up. By explaining some of the exercises that are conducted in the tower and how conditions are constantly monitored, the instructor helped us see how each component of the system has a specific purpose. Whether it's the thermocouples that activate the fans at a certain temperature or the control boxes outside of each burn room, it was fascinating to acquire more knowledge about advanced firefighting technology.

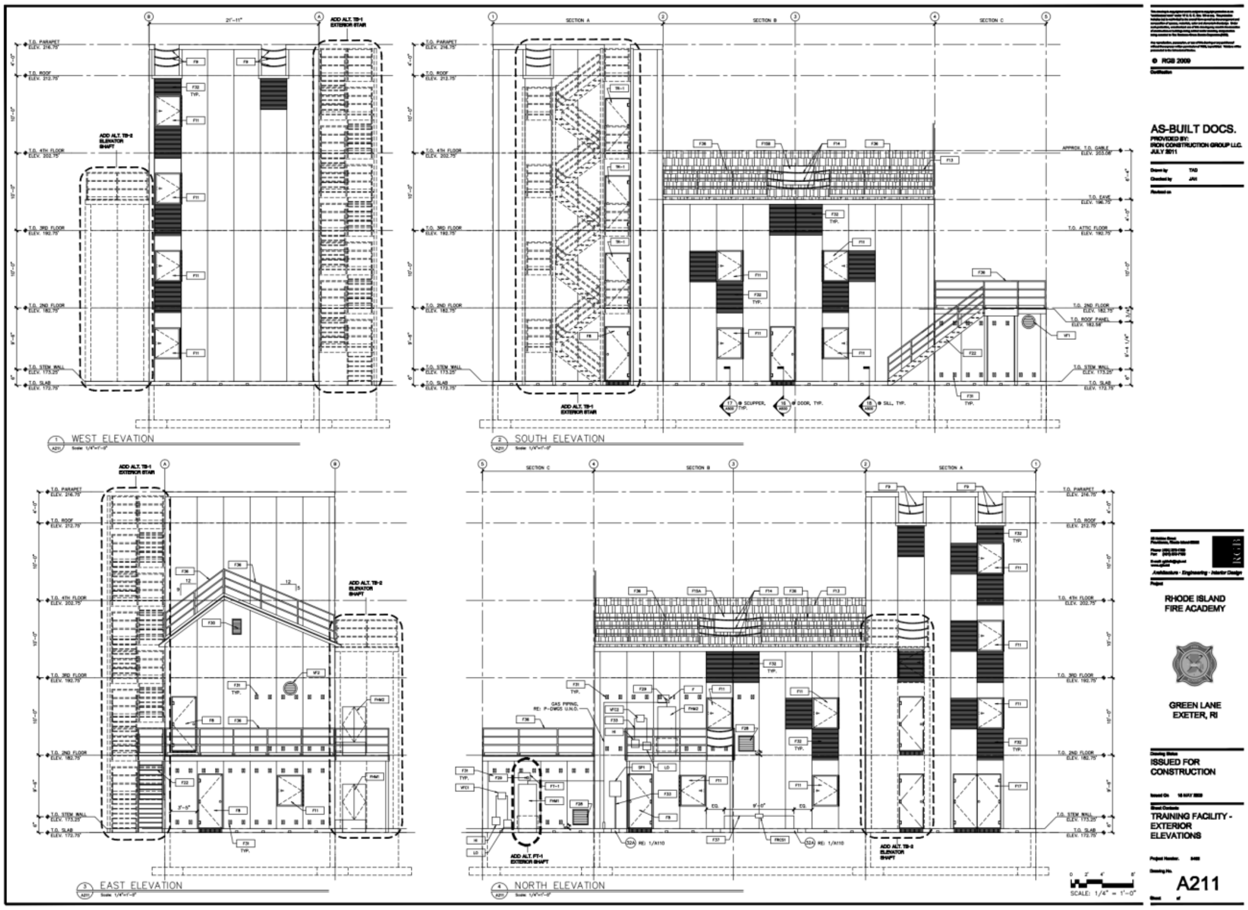

Figure 31: RI Fire Academy Burn Tower Schematic (RIFA, 2021)

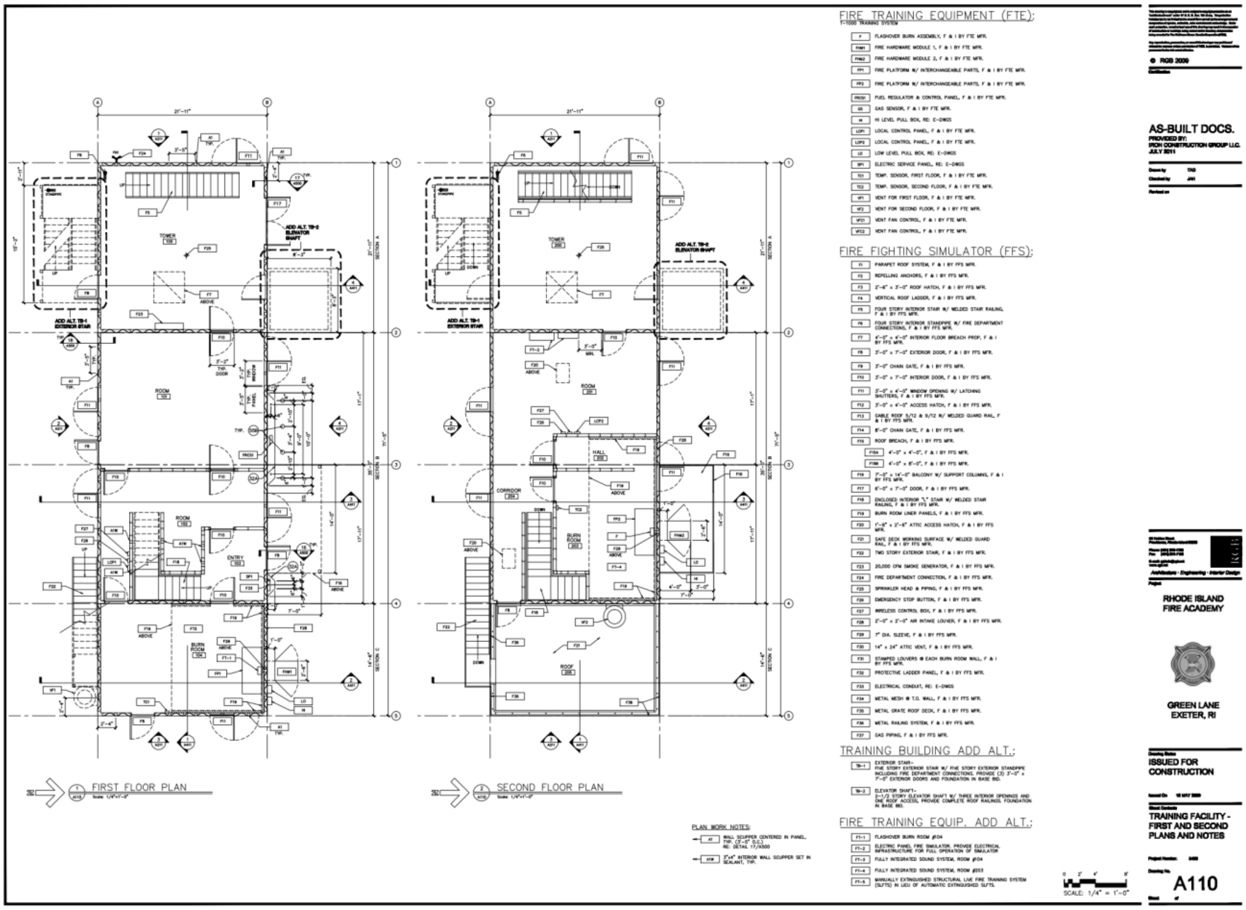

Figure 32: RI Fire Academy Floor Plans 1-2 (RIFA, 2021)

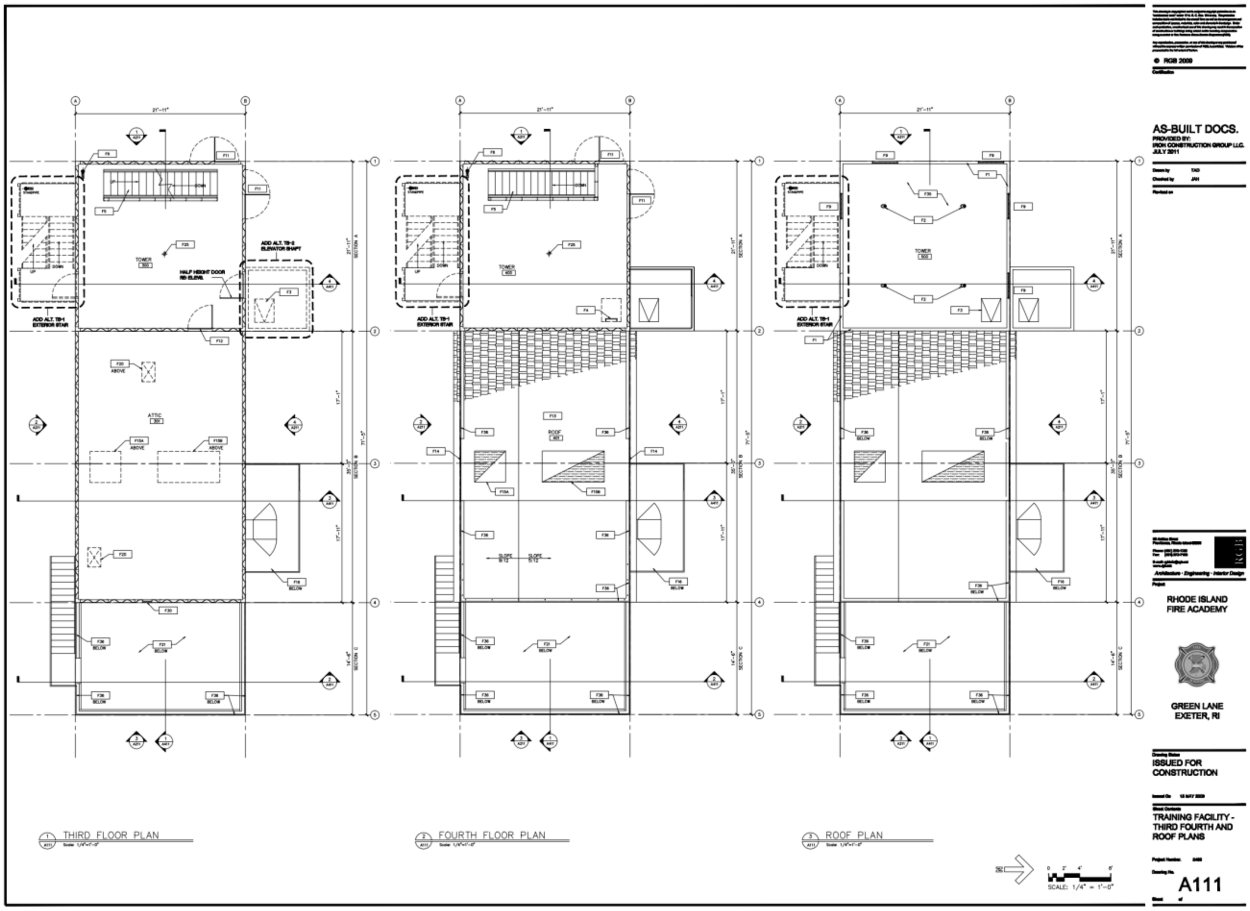

Figure 33: RI Fire Academy Floor Plans 3-Roof (RIFA, 2021)

Kidde Fire Systems

Although the main focus of this project involved the design of the tower itself, the team thought that it would be beneficial to research some of the other systems that are used in the fire protection industry. It should be noted that the schematics shown below represent the typical requirements of a fire suppression system. This would not be something incorporated into the design of a training tower due to the use of carbon dioxide. Carbon dioxide is effective for extinguishing fires since it removes the oxygen and stops the reaction. This is undoubtedly dangerous for any human because of the suffocation risks associated with asphyxiation. Carbon dioxide suppression systems are not used in locations with lots of human activity. They are primarily used in places such as machinery spaces, where they can help control accidental fires and people can seal off the area when dangerous situations arise.

The diagrams in Figures 34-35 were provided courtesy of Kidde Fire Systems. Our team was interested in the layout of an LPG gas system, but the representative stated how similarities can be found between suppression and gas systems. Although the diagram does not show the proper arrangement for a gas system, it offered a great model of what would need to be considered when the Bomberos go to incorporate the gas tanks into the overall design. By reverse engineering the schematic, a properly functioning system can be designed. If we had additional time to work on this project, our attention would have been directed to the performance, capacity, and ratings of pumps. Determining the diameter needed for piping and the different types of valves would also have been an important consideration.

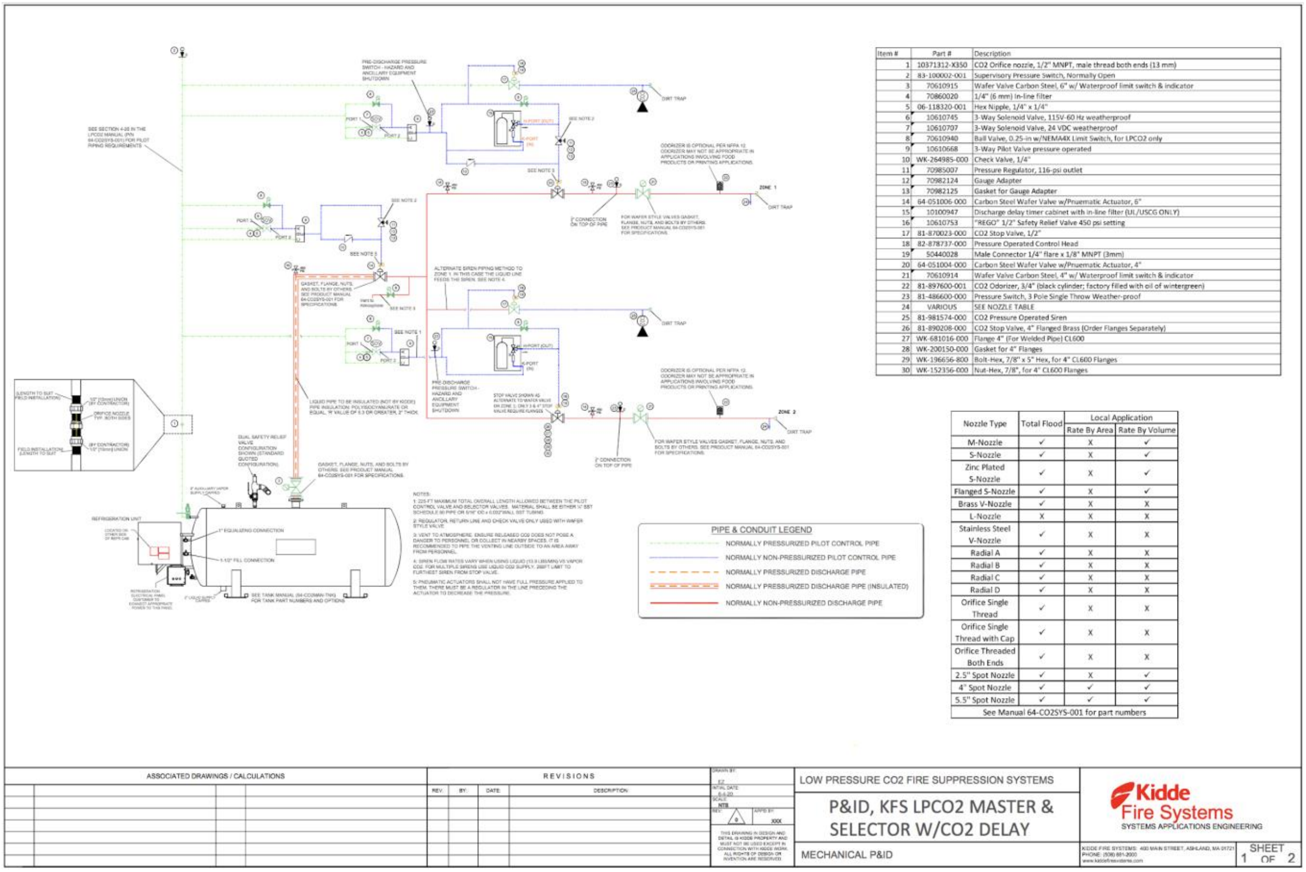

Figure 34: Kidde Fire Systems Pressure and Instrumentation Diagram Page 1 (Kidde Fire Systems, 2021)

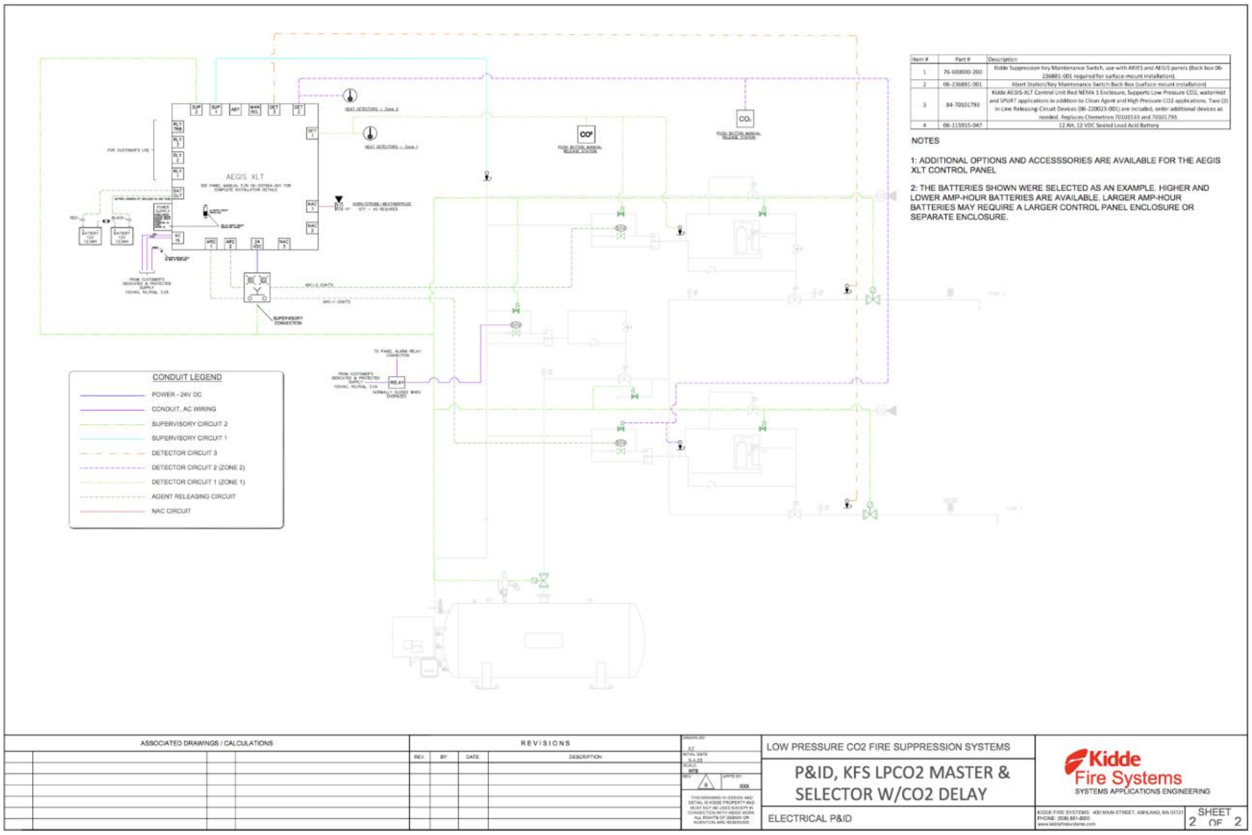

Figure 35: Kidde Fire Systems Pressure and Instrumentation Diagram Page 2 (Kidde Fire Systems, 2021)

APPENDIX D: Interview Question Sets

This appendix includes some of the questions that were asked during the interview process. Since we spoke with a variety of individuals who work with fire (e.g. firefighters, professors, contractors, etc.) we tailored the questions to each specific interview.

Set 1: Questions Regarding Training Towers

1. Does the city have a variety of different towers, or are the designs fairly similar to each other?
2. What are some elements of your training tower that you would like to modify if possible? (i.e. how to improve it/make it more effective for training exercises)
3. What do you wish the tower could offer? Are there basements?
4. If your towers incorporate the use of fire, what serves as the catalyst to ignite the flames? (e.g. LPG gas, flammable materials in a burn room, etc.)
5. Do you have specific burn rooms or is everything lit on fire?
6. General overview of what takes place/how they go about burn drills?
7. Are there any measures in place to help prevent carbon emissions such as a smoke suppression system?
8. Do you have the option of rearranging the floor layout with the use of movable walls?
9. Is thermal imaging used? If so, what does it primarily help with?
10. Is there a system to help recycle the water that's used during simulations?
11. Do you have windows that can open and close? If so, is there room for trucks to park in order to access them via ladders?
12. Are there additional escape routes other than the primary stairwell?
13. Would you be able to provide us with any pictures of your training tower(s)?
14. Do you have any information available with respect to the dimensions? Is there a company that we can reach out to?
15. What are some things to avoid, or some features of towers that have proven to be impractical for your training efforts?

Set 2: Questions Related to Materials Selection and Gas Systems

1. Is there any type of material that you would recommend when building a training tower? What are some specific applications where brick, metal, or concrete would be the most effective?
2. With respect to concrete, do you know what type of panels would be the most effective? We've heard that pagenite is commonly used.
3. Do steel towers usually require the same type of panels?
4. Even though concrete can spall due to the water being used, would you still recommend it?
5. Is it typical for the windows to be oversized for ventilation purposes? Should we avoid making them traditional?
6. Could you explain what some important considerations are to avoid issues with flashovers and any type of explosion? Window placement? Vent size?
7. The Bomberos are requesting a basement level. Is there any way to do this without putting them in serious danger? (e.g. explosions and suffocation from gas)
8. If you are familiar with an LPG gas system, how is it set up for a fire training tower? (i.e. where the control center goes, piping layout)
9. What is the ignition source? Pilot flame or something like a striker? Is it controlled from the control center?
10. Do you have any advice for determining gas quantities/size of tank needed?
11. Could you describe how a typical ventilation system works? Have you ever heard of a system that is used with HEPA filters?
12. We've heard that there are thermal sensors inside towers with LPG capabilities. Are they typically like thermocouples or actual thermal imaging cameras?
13. With regards to conservation, do you know of any system that can help suppress carbon emissions? (If at all)

APPENDIX E: Interview Summaries

The information that we acquired from our interviews are included below. Note that some questions were asked in addition to those shown in Appendix A based on the topics that were being discussed.

Worcester Fire Department

1. Does the city of Worcester have a variety of different towers, or are the designs fairly similar to each other?
    - No, just one in Worcester (on Grove St)
2. What are some elements of your training tower that you would like to modify if possible? (i.e. how to improve it/make it more effective for training exercises)
    - Metal-clad tower is hard to maintain - could use concrete but provides difficulties as well
    - Need windows that are smaller to be realistic (they are oversized)
    - Padgenite tiles used for fireproofing - material is expensive to replace
3. What do you wish the tower could offer? Are there basements?
    - No basements - wish that they had better basement capabilities
    - Simulate by entering on the second floor and going down to first floor
    - Would make new structure completely different (preferably a modular setup to "switch things up")
    - Concrete (like the tower in Stow) allows easy changing of compartments
    - Grade changes to simulate the typical infrastructure of Worcester (region with lots of hills)
        - Tower needs to address specific fire problems of the community
        - Example: Triple-decker apartments are common off-campus housing around WPI, so part of the tower is modeled as a triple-decker
4. If your towers incorporate the use of fire, what serves as the catalyst to ignite the flames? (e.g. LPG gas, flammable materials in a burn room, etc.)
    - Straw and pallets (more labor intensive than gas system)
    - Cannot create a realistic scenario without black out conditions (fake smoke)
    - Teepee is made then built up with straw, let it burn to make heat and smoke
5. Are there any measures in place to help prevent carbon emissions such as a smoke suppression system?
    - Nothing in place currently

- LPG doesn't produce as much smoke (gas burns cleaner than class A fires since there isn't any residue from material decomposition)
- The issue is Costa Rica is so environmentally conscious, pallets may not be an option in their opinion
- Balance of realism vs environmental concerns is important

6. Do you have the option of rearranging the floor layout with the use of movable walls?
    - Not currently - utilize places like WPI during the summer for exposure to new environments/floor layouts
7. Is thermal imaging used? If so, what does it primarily help with?
    - Hand held cameras are used
    - Safety staff inside will monitor the situation
    - Doesn't really add much value to training, but helps for safety
8. Is there a system to help recycle the water that's used during simulations?
    - No, but Mass Fire Academy does
9. Do you have windows that can open and close? If so, is there room for trucks to park in order to access them via ladders?
    - Windows with metal shutters
    - Wide for firefighters to enter from outside
    - Have to open from inside for safety purposes - emergency evacuation
    - Must have window open to feed the fire with oxygen
    - Close to increase smoke density for training
10. Would you be able to provide us with any pictures of your training tower(s)?
    - Will send out pictures
11. Do you have any information available with respect to the dimensions?
    - Unfortunately not - WHP is the company that built their tower
12. What are some things to avoid, or some features of towers that have proven to be impractical for your training efforts?
    - Thermal imaging hasn't provided much in terms of enhancing training procedures
13. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - Would use concrete instead of metal clad since it involves less maintenance
    - Depends on the environment - cold weather poses risk to concrete since water can freeze inside walls and cause damage when it expands
    - Concrete may be better option since Costa Rica doesn't get too cold
14. Accessibility of the tower
    - 360 access - very important to give trucks room on most (if not all) sides
    - Could be challenging based on the space that's available
15. Roof
    - Rappelling exercises are conducted (lowering to ground with ropes attached to anchor points on roof)

    - They have flat roof but peaks on the side to practice roof rescues
    - Roof props to replicate different pitched roofs/practice different scenarios

Bonus notes:

- Their tower went into service in 2004 (used to be the traditional "open air" design)
- We need to collect more info on what their residential areas look like to understand how their trucks and equipment would function in a real situation
- If they don't have sub basements in Costa Rica, then you don't need to go with them
- Safety officer on each floor (one person in charge of each crew)
- Looks if people are operating safely, they'll follow in the tower to make sure that people aren't panicking
- Building must offer places for ladders below the windows (some type of material that won't let the ladder slide since flat steel can be slippery)
- New recruits watch the entrance operation to understand how to go inside
- They hide and watch what goes on to see what the heat feels like
- If you get low enough visibility is okay, don't go without thermal imaging

Massachusetts Firefighting Academy

1. Does the city of Stow have multiple towers, or is the main tower the primary/only one that is used for training?
    - Only one tower exclusively used as a burn building
    - They have a ladder tower as well
2. Facilities in Stow
    - **Burn tower** for search and rescue, burns, and ventilation (no lights in there)
    - Front side (A side) is 2 stories (looks residential)
    - Back side (C side) is 4 story building (looks commercial)
    - **Six story ladder tower** (practice for using ground ladders, aerial ladder to access roof, practice going in and out of buildings, how to get into windows)
    - Ladder tower inside also search and rescue-old furniture, portable partition walls, few sprinkler heads, fire dept connections (FDC) to put water through standpipes
    - Simulates fire scenario but they do not flow water inside to avoid ruining the steel and concrete that has wooden partitions
    - Tower serves as a place to practice maneuvering with a full, live hose
    - Rappelling system for bailout if provided with rope (only from second floor)
    - **1.5 story wood search and rescue tower** (on concrete slab) which is separated into bedrooms, kitchens, living room etc.
    - Floor is on hinges to show different types of floor conditions: Put cement blocks under for a strong floor, tires go under for weaker floor (showing differences)

- Deck with hatch in the case of falling through a basement: Practice pulling someone up
- Breakaway panels: break through to escape through 18 inches between studs (go into “low profile configuration” and take air pack off their back to fit through)
- Small window to simulate entering/exiting through a basement window
- **Flashover simulator** (CONEX box) simulate flashover but only to observe
- Box is four feet above ground so that people can go under it (without going in to extinguish it)
- **Mini gas school** with car prop, dumpster
- **Gas school (one of few in the country)** burn propane to show relief valve, burn natural gas (w/o ignition source) to show how to control vapors, put out burning pit of natural gas
- They teach the private gas industry how to control a leak in their containers (for bobcats/small petroleum vehicles)
- **Maze** series of cages 2-3 tiers high for confidence building/ practice navigating with all the gear on while crawling in the dark (no fires or smoke)
- **2 other campuses:** Stow is most advanced, Bridgewater (brand new), Springfield as well

3. What are some elements of your training tower that you would like to modify if possible? (i.e. how to improve it/make it more effective for training exercises)
    - Need to have the steel and concrete well kept in order to prevent anything breaking down/decaying
    - Need to make sure that heat shields/tiles are always in place (to prevent concrete from spalling)
    - Have to throw the straw in just before the simulation in order to prevent the smoke from dying out (it burns quickly and is not that realistic to smoke in a building fire)
4. What do you wish the tower could offer? Are there basements?
    - Wish there could be propane (Class B fires) to compliment the Class A capabilities
    - They have a half-basement. Using the residential side located on an incline, people go in and can go downstairs two levels with an emergency escape located on the other side (lower part of the incline)
    - Training is safer without a true basement, it is best to have failsafe scenario if someone gets trapped
5. If your towers incorporate the use of fire, what serves as the catalyst to ignite the flames? (e.g. LPG gas, flammable materials in a burn room, etc.)
    - Mostly use straw/pallets.
    - Class A fires: Clean, food-grade wood pallets w/o pesticides etc.

6. Are there any measures in place to help prevent carbon emissions such as a smoke suppression system?
    - No. For the class B trailer, there’s an exhaust fan for ventilation only.
    - In RI, there are exhaust fans running constantly when the fire hits a certain temp.
7. Do you have the option of rearranging the floor layout with the use of movable walls?
    - Not in the burn tower
    - Portable wall partitions can be moved in the search and rescue building (ladder tower) due to open floor plan
8. Is thermal imaging used? If so, what does it primarily help with?
    - Handheld imaging is cheaper
    - Safety officers use those to take anywhere (used for safety)
    - If applying to the inside of the structure, need to be careful because it would be easy to damage (with water, axes, etc.)
9. Could you describe your system that helps recycle water that’s used during simulations?
    - Not necessarily complete recycling, more of a filtration system
    - Tries to screen the straw from going down the drains
    - 40,000 gallon tanks collect used water for reuse
    - The water isn’t purified at all
    - Capture about 75% of water used - some evaporates, some escapes into grass/nearby areas
10. Do you have windows that can open and close? If so, are they oversized or to scale for a standard building/home?
    - Yes, windows open in the burn tower
    - The windows are residential sized, metal plated, roof prop exists for cutting with axes (plywood & shingles)
    - Also a big door-sized hatch on the top
    - Burn tower windows can be opened. They’re not air-tight. Opening them is to practice hydraulic/power venting with a fog line
11. Is there room for trucks to park in order to access the tower via ladders?
    - Yes, left and right sides are on inclines
    - There is a driveway around the tower
    - Flat walkways with railings around it so there’s access to enter on each side in multiple different locations
12. Would you be able to provide us with any pictures of your training tower(s)?
    - Yes
13. Do you have any information available with respect to the dimensions? A company that we can reach out to?
    - Will be sending them over soon
14. What are some things to avoid, or some features of towers that have proven to be impractical for your training efforts?

- Don’t let the water get behind the fireproof tiles. It can freeze, expand, and cause major damage
- The water will fall to the floor and drain out the sides of a steel building since there’s no concrete that could absorb some of the water
- Need drains/scuppers for water runoff (could have a pitched floor)

15. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - Steel + Concrete
    - All fireproof tiles have to be in place or the concrete can spall (break off/fragment)
16. Accessibility of the tower
    - Driveway which wraps around
    - There is truck access on all four sides of the tower
17. Roof
    - Flat roof to learn how to use saws etc.
    - There is the option of having firefighters rappel down the side
    - Double-door with metal hatch can be opened for ventilation purposes

Bonus Notes:

- Water drains and is filtered out before it returns to the tanks.
- Separate support staff build and man the fires.
- LPG is easy to set up, Stow has it in a mobile prop, Class B burn buildings.
- Fire resistant panels (in burn chambers) change the rate of fire spreading
- Need to make sure that anything exposed will be protected (with tiles)
- The Academy mostly deals with class A and B fires, not C due to environmental standards, and no class D burns either (burning metals)
- No foam extinguishing agents are used on live-fires. They use dish detergent in an open field to mimic the scenario (sometimes run a foam program, but it hasn’t been done in a while)

Rhode Island Fire Academy

1. General overview of their tower
    - Their first floor is a burn room - they have an exterior door and two interior doors (one coming from corridor and other coming from the cove)
    - They have a set of stairs outside: once you go up a certain amount of stairs, you turn 90 degrees, and go up another set
    - A set of stairs inside goes from first to second floor

- When it's dark and smoky the distinctive stair pattern helps to keep track of orientation (not get lost in building)
- Little limitations with their tower (capable of running through various scenarios)

2. Training practices (ladders, rappelling, etc.)
    - Introduce laypeople to the fire, teach them the skills needed to handle, and then help them practice the skills
    - Search and rescue drills
    - Line management
    - Rapid intervention training
    - Live-fire training
    - Cold smoke drills
    - Confined space training
    - Elevator shaft/silo: space used for plastic drainline which hooks to the roof and allows for confined space training (e.g. if a firefighter is in a well)
    - Exterior tower doesn't have landing between floors (two escape routes in every room)
    - Theatrical smoke - not created by the fire
    - Have a room with 12 sides for search practices
    - Training in a room with some walls and doors that can trick the firefighters to help them practice being lost in a building
3. General overview of what takes place/how they go about burn drills
    - Lots of practice with making a series of turns
    - Emphasis on knowing your bearings/where you are in the building
    - Practice of backdraft with various pressures
    - Practice with smoke of different temperatures to understand levels of heat
4. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - Their walls are steel and the floor slabs are concrete
    - Be careful with concrete: Cement tower 5 or 6 stories high in Kingston started cracking and ceramic tiles had to be installed for protection
5. With respect to concrete, do you know what type of panels would be the most effective? (We've heard that Worcester Fire uses pagenite…)
    - Ceramic tiles are sometimes used
    - White, 1"x 2.5"x4," $600 per tile, replaced after 7 years
    - Tiles exposed for 9-10 hours a day for multiple days straight
    - Burn rooms in use 3-4 days of the week 10-11 months of year
    - Do preventative maintenance and they will last!
        i. Back wall isn't tiled in the first room
        ii. Second story room the back wall is halfway tiled and they suffer no damage - depends on how much heat is output by the system

6. Even though concrete can spall due to the water being used, would you still recommend it? Is it probably the cheapest option?
    - Their tower is steel
    - Get more time out of a metal/cement building like theirs
    - Cement is fine as long as you don't use it very frequently at extreme high temps
7. Is it typical for the windows to be oversized for ventilation purposes? Should we avoid making them traditional?
    - Need to avoid wind tunnels so you can open the windows
8. The Bomberos are requesting a (real) basement level… Is there any way to do this without putting them in danger? (e.g. explosions and suffocation from gas)
    - Don't have a basement
    - Simulate a basement, when the second floor becomes the first floor. Only way to get into the basement is the interior stairs (difficult exercise)
    - Can practice getting out of small basement windows
    - Buildings should have minimum of 3 ways out for safety
9. How can the roof end up being so expensive?
    - Ventilation props
    - Lots of different ways to practice with inclines (not necessary for Bomberos)
10. Could you explain how the LPG gas system works in your fire training tower? (i.e. where the control center goes, amount of burners based on volume of room, etc.)
    - Make sure to have a good structure to support the system
    - Have a prop for a fireplace that is certain amount deep, gas has to bubble through water and then ignites a pallet
    - Ceiling reach temperatures of 1500-1800 degrees Fahrenheit
    - Have a 45 ft long trailer that has panels. Burn room is equipped having hay and pallets that are lit up
    - Gas is better for longer practices because regardless of the amount of water put onto a class A fire, it won't burn out
    - Class B involves an easier cleanup - Class A fires can reignite unintentionally
    - For gas systems, when done just shut the system down, water puts the fire out completely
11. How is the control center set up? (Does it provide anything other than a way to monitor valves and temperature?)
    - The system relies on combustion fans. Once the temperature reaches a certain number, the gas immediately shuts off. Steel frames, walls, concrete, and panels soak up the heat so it takes a while for temperature to increase.
    - The material holds the heat and radiates it out
    - Control box setup outside of each burn room - interlock safety features, two burn props in each room, combustion fan that feeds the pilot flame

    - Flashover equipment (simulates a flashover by running fire across the ceiling) - runs for 12-15 seconds and increases the heat immediately
12. We've heard that there are thermal sensors inside towers with LPG capabilities. Are they typically like thermocouples or actual thermal imaging cameras?
    - They are thermocouples
    - Activates the fans in the burn rooms
    - TICs - thermal imaging cameras, students use it to learn. If gets to 500-700 degrees they shut off automatically
    - The walls and floor suck up the heat so it takes long for the heat to rise
    - Fans run ¼ speed the whole time, run full speed before the fire is lit to vent gases from rooms for safety
    - Full speed commences if 700 degrees Fahrenheit is reached
    - High speed if 10% LEL to 15%
    - Prop uses propane as a vapor state only at 500 BTU
13. How do you determine gas quantities/size of tank needed?
    - 2 tanks that feed the building and props
    - They have 1000 gallon tanks - pure vapor in props and pilots are liquid
14. Could you describe the ventilation system that is used?
    - Windows swing out
    - Thermocouple system activates ventilation to control heat & smoke
    - Hydraulic ventilation also incorporated on lower floors
    - Where the tower is placed produces a natural wind tunnel as well
15. Do you know of/have any contacts for companies that build fire towers?
    - Kidde Fire Systems in New Jersey (used to be called KFT)
16. Would you be able to provide us with plans or pictures of your facility and the control center? We're looking for blueprints to use as guidance.
    - Sending over building plans but nothing is available in terms of the gas system

Bonus Notes:

- LEL - lower exposure limits
- Their roof is expensive due to the framing (shingles on 1-inch exterior plywood anchored with steel joists and rafters) becomes an issue for replacements
- Their flat roof has anchors (lightweight concrete) for rappelling

Troy Fire Department

1. What are some elements of your training tower that you would like to modify if possible? (i.e. how to improve it/make it more effective for training exercises)
    - They have a tower in Latham, NY
    - It is metal with four stories and has rappelling capabilities

    - City of Troy does not have a tower. Rensselaer county does but that is being rebuilt at the moment.
    - Their tower weakens with constant heat exposure
    - They perform egress and ingress drills
2. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - Concrete is good, but it can be difficult to preserve against repeated live-fire/high temps. Spalling occurs (cold water on certain locations of heat stresses and starts eroding the concrete)
    - Use lining materials with sacrificial panels to increase tower lifespan (called pagenite)
    - Concrete poured with rebar makes the structure more stable
3. What do you wish the tower could offer? Are there basements?
    - Basement is available but no live fires are lit in it
    - Basements have increased danger with fire fighting
    - Use doors to simulate basement conditions
    - FAST (fire assistance and search teams) evolutions are to practice options for getting someone out of the building
4. If your towers incorporate the use of fire, what serves as the catalyst to ignite the flames? (e.g. LPG gas, flammable materials in a burn room, etc.)
    - Propane
5. Do you have specific burn rooms or is everything lit on fire?
    - Specific burn rooms
    - 4 story central section is open and one room in north side is a burn room (10x12ft and locked down)
    - 1 story additional burn room - open the door to let heat get into the building to simulate going into a building with fire.
    - Need to protect structure from fire, so whole thing can’t be a burn room
6. Do you have windows that can open and close? If so, are they oversized?
    - BILCO doors that can hold in smoke, reduce light
    - They help simulate “open as you go” to ventilate the tower
7. Is there room for trucks to park in order to access them via ladders?
    - Yes, there is room around all sides for access with trucks
8. Are there additional escape routes other than the primary stairwell?
    - Exterior fire escape
9. Is the stairwell located inside the main body of the structure or outside (i.e. fire escape)?
    - Both are available
10. Is thermal imaging used? If so, what does it primarily help with?
    - Yes, live-fire training instructors must watch inside the burn room. They use thermal imagers and there's additional thermal imaging training.

- Handheld, 6x6in block camera, detects quarter degree Fahrenheit increments when temperature increases
- Effective in specific situations
- The equipment is around $6,000
- FLIR - Forward-looking infrared camera

11. Are there any measures in place to help prevent carbon emissions such as a smoke suppression system?
    - No. They are not allowed to use anything that has toxic smoke anymore, so they use wood stacks and hay.
    - When it hits 1000 degrees Fahrenheit, turn on the sprinklers to cool the room down.
    - Wood should not be terrible for the environment.
    - Putting fire out creates more smoke and steam, full burn to fully extinguished involves going through a complete combustion cycle.
12. Is there a system to help recycle the water that's used during simulations?
    - Newer tower collects and filters the water
13. Would you be able to provide us with any pictures of your training tower(s)?
    - Can reach out to get us a contact
14. Do you have any information available with respect to the dimensions? A company that we can reach out to?
    - 30x40 ft on the bottom floor
    - No additional schematics available
15. What are some things to avoid, or some features of towers that have proven to be impractical for your training efforts?
    - You should have access on all four sides, with a paved area around the tower
    - It is beneficial to be able to do many training activities at once (ladder, live-fire, stand pipe evolutions, etc.)
    - Have to talk to the end user to see what is the need of the particular department
    - Have to be able to do live-fire training, rescue training, get in from different sides, how to get out of the building, rappelling training, ladder operations, truck access around the whole building, FAST training, egress/ingress, use the building smoky without fire and with fire as well
    - They have had a net outside before for firefighters to jump in, not very helpful
16. Are there any other facilities/props that you use with your training efforts?
    - Fake smoke is used during the simulations (not live fires)
    - Fake TV set used to create the smoke (machine that creates smoke without hazardous chemicals and doesn't have heat either)
    - Someone is manning a sprinkler system to make sure the temperature doesn't get too hot
17. How does the water sprinkler system work?

- It’s just in the burn room, water is piped in from underground
- Tanks exterior to the building with a control box for water supply
- One person outside is in control, he has temperature sensors from in the room and he controls when water goes out.
- Basically open and close the valves. Deflector on bottom to create shower effect.
- Propane buildings have temperature sensors built into the burn rooms inside trailers which tell the control people when to activate sprinklers
- Similar to a thermocouple - basic and not too expensive

18. Do you ever have thermal imaging cameras get damaged?
    - They are very resistant, however they are electronic and can have failures
    - Can be thousands of dollars to replace them

WPI Fire Protection Engineering Department

1. What issues does the Bomberos’ location for the tower have, if any?
    - Doesn’t think that the nearby buildings will be an issue
2. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - Usually concrete or steel so that burners are only things providing the heat
3. With respect to concrete, do you know what type of panels would be the most effective?
    - No - familiar with galvanized steel towers but every story needs to be reinforced
    - Specific burn rooms are cheaper regardless
    - If you have fire on each story you must isolate each story from another, must be insulated more effectively
4. Even though concrete can spall due to the water being used, would you still recommend it? Is it probably the cheapest option?
    - Depends on the humidity - if we can find affordable metallic material it could be a better option
5. Is it typical for the windows to be oversized for ventilation purposes? Should we avoid making them traditional?
    - Most facilities he has seen have slits and no windows
    - Slits within the walls for ventilation: intake oxygen from slits low to ground, smoke/heat escapes from slits up high
6. The Bomberos are requesting a (real) basement level… Is there any way to do this without putting them in danger? (e.g. explosions and suffocation from gas)
    - Instead, use a sloped basement and have a large double door (one large enough for two firefighters to walk through) to exit in case of panic/emergency
    - Be careful that we don’t have any flashovers (radiation issues)

- Also make sure that the oxygen levels are under control

7. If you are familiar with an LPG gas system, how is it set up for a fire training tower? (i.e. where the control center goes, piping layout)
    - Contact the fire protection lab instead- WPI has a large propane system
    - Standards of gas are very important-it will have to be extremely specific based on the tower
8. How do you determine gas quantities/size of tank needed?
    - Need to discuss with someone who is more qualified
9. Could you describe the ventilation system that is needed?
    - Ventilation slits on top to avoid accumulation of gases
    - Try to avoid lots of fans so that there is still some smoke (for training purposes)
10. With regards to conservation, do you know of any system that can help suppress carbon emissions? (If at all)
    - Simplest way is to burn as clean as possible, other than that collect smoke and filter it
    - Otherwise HEPA filters are used (very expensive: up to millions of dollars in industrial applications)
    - Chemical processes are available, but are costly to install
    - Filters are still less expensive but require maintenance
    - Slots in the floor- emissions shouldn't be terrible if the Bomberos use the tower for a maximum of two hours each day
11. We've heard that there are thermal sensors inside towers with LPG capabilities. Are they typically like thermocouples or actual thermal imaging cameras?
    - Consult with the lab
12. Do you know of/have any contacts for companies that build fire towers?
    - Yes, knows of some people from Sweden (sending contact information)
13. Does the FPE Dept. have any types of plans or pictures that could help us/that we could use?
    - Need to ask people from the lab instead

Bonus Notes:

- Ask Bomberos how often they plan to use the tower
- How high are the flames they hope for? If they want them to go to the ceiling we need to reinforce the concrete on top too
- Learn more about slits versus actual windows (smoke emissions will not change regardless of the size)
- Slits do help in terms of "feeding the fire" versus windows because windows run the risk of flashovers where too much oxygen at once could cause explosions

WPI Fire Protection Engineering Laboratory

1. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - BULLEX is a possibility
    - Cost: concrete usually cheaper than steel
    - Worcester has steel to deal with the cold weather
    - MFA has concrete
    - Longevity is better with concrete but it needs to be protected
2. With respect to concrete, do you know what type of panels would be the most effective? (We've heard that Worcester Fire uses pagenite…)
    - Can't find that info online-need to call some companies
    - Thermal tiles help avoid flashover damage
    - Flashover can be avoided with gas system being able to be controlled from the outside
3. For towers made of steel, would you expect that the same type of tiles would be needed? Seems like the main concern is heat inside rather than the steel being damaged.
    - Same tiles needed, but flashover could still happen
4. Is it typical for the windows to be oversized for ventilation purposes? Should we avoid making them traditional
    - Depends on the wind and location of the tower
    - Wouldn't necessarily avoid traditional sized windows
5. The Bomberos are requesting a (real) basement level… Is there any way to do this without putting them in danger? (e.g. explosions and suffocation from gas)
    - Have design elements of a basement without a true basement
    - Try a bulkhead to an underground basement with one side of the floor opened to grade
    - Basement fires are notably lethal, probably do something like leaving a side open for egress
6. If you are familiar with an LPG gas system, how is it set up for a fire training tower? (i.e. where the control center goes, amount of burners based on volume of room, etc.)
    - Able to turn off the gas to prevent room from getting too hot and flashover occurring
    - Need to speak with a professional for more information
7. WPI FPE Propane system
    - Outside there is a 500 gallon liquid propane tank
    - Propane will vaporize to help create the fires
    - Draw liquid propane from the tank and use vaporizers at elevated temperatures that then go to mass flow controllers on the way to the building
    - Avoid condensation if possible
    - Vaporizers by torrex (ALGAS-SDI TX-320)
    - System costs at least $200,000-300,000

    - Control system valves inside the building offer people full control of the gas
    - They can set and control flows at a safe distance from the burn hood
    - They have +/- 1% accuracy of 3,500 liters per minute
8. What is the ignition source? Pilot flame or something like a striker? Is it controlled from the control center?
    - Somebody with a torch
    - Remote ignition with hotwire is possible but not always necessary
    - In a fire tower, a propane torch can serve the purpose
9. How do you determine gas quantities/size of tank needed?
    - Needs to be done by a professional engineer/outside company
    - Could try and send them an email with a quick email with questions
    - Probably at least 500 gallons since the lab's building is similar to 6x6m
10. Could you describe the ventilation system that is used at WPI with HEPA filters?
    - If it shuts down it shuts down the propane feed as well
    - Very powerful system, but also expensive to implement
11. We've heard that there are thermal sensors inside towers with LPG capabilities. Are they typically like thermocouples or actual thermal imaging cameras?
    - Seems somewhat unnecessary based on how general we're keeping the tower
12. Do you know of/have any contacts for companies that build fire towers?
    - BULLEX
13. Does the FPE Dept. have any types of plans or pictures that could help us/that we could use?
    - He'll ask for permission and then might be able to share them with us

Bonus notes:

- Make calls to figure out costs (manufacturers, fire depts.)
- Materials: ask fire departments for who built the tower- call those companies
- Potentially look into historic line of duty deaths to justify a walkout basement (last 10 years or so of an officer dying in a training tower basement)
- Really understand who builds them, what do they cost and what makes them so useful
- Look into departments and what they exactly use their towers for
- Research the Back Bay fire in 2016

WHP Training Towers

1. Is there any type of material that you would recommend when building a training tower? Brick, metals, concrete?
    - In cold weather, water can seep in and freeze to make the concrete pop
    - Heat can create steam and increase the pressure

2. With respect to concrete, do you know what type of panels would be the most effective?
    - Ceramic is used but padgenite is put behind as insulation
    - Set on grid of hatches for air space and insulation
    - Tiles are bolted through the supports on the walls
    - They use Super Padgenite HD: 1 inch thick, 2x4ft, weighs 55lbs
    - Per square foot the price is $48.50 (w/o labor)
3. Even though concrete can spall due to the water being used, would you still recommend it? Is it probably the cheapest option?
    - Probably the easiest for Costa Rica - would need the metal tower to be shipped
4. Does steel usually require the same type of panels? Did Worcester express particular interest in steel over concrete?
    - Yes, same panels are used
5. Can you refer us to a supplier/anywhere we can get info on costs?
    - Yes, will send some information
6. Is it typical for the windows to be oversized for ventilation purposes? Should we avoid making them traditional?
    - They can be, but depends on the size of the burn room
    - Probably don't need oversized for our scenario as long as people can get in and out
7. Could you explain what some important considerations are to avoid issues with flashovers and any type of explosion? Window placement? Vent size?
    - Generally there isn't a universal ventilation system
    - Just open the windows up
    - Highest portion will have a fan to suck all the smoke out
    - Gas props usually vent smoke from the burn room
    - Some use artificial smoke
8. Do you ever use LPG gas systems, and if so, how is it set up for a fire training tower? (i.e. where the control center goes, amount of burners based on volume of room, etc.)
    - Towers come as class A buildings (no LPG)
    - Gas prop can cost $165,000 with all the sensors and shut offs
    - $140,000 for the second installation
9. We've heard that there are thermal sensors inside towers with LPG capabilities. Are they typically like thermocouples or actual thermal imaging cameras?
    - Steel liner for burn rooms won't allow thermal imaging cameras due to the heat/radiation distortion (wouldn't be able to see what's going on inside)
10. Are you able to provide us with any blueprints of simple towers/gas systems? (We'll cite the info.)
    - Sending something over (talk to KFT for gas system)

Bonus notes:

- They actually make their own containers that appear as shipping containers

- Containers are more like hallways rather than rooms
- Theirs don't need more interior walls for support
- Need to line windows and doors so they can be burned too
- Gas fires won’t be as hot as a class A fire