Design, Construction, and Verification of an Apparatus Capable of Testing Fire Attack Hoses at Realistic Fire Ground Conditions

Major Qualifying Project Report

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Abstract

Modern day fires are burning hotter and faster than ever before. As a result, fire attack hoses are subjected to more intense conditions and are more likely to fail on the fire ground. Currently, the only test for thermal performance of a fire hose is a conduction test. This project designed, built, validated, and verified a prototype apparatus useful for assessing the performance of a fire attack hose charged with water and exposed to a convective and radiative environment reflecting pre-flashover conditions. Each system of the apparatus was designed and tested to meet set performance criteria. The apparatus was then tested to verify that the results would be repeatable and withstand future testing. The team also determined a matrix of hoses to be tested within the prototype apparatus.

Acknowledgements

Our team would like to thank everyone that helped us complete this project, especially our advisor Professor Notarianni and the WPI FPE Lab Director Raymond Ranellone. We would also like to acknowledge the Fire Protection Engineering Department, Mechanical Engineering Department, and Chemical Engineering Department for their support in this project. Lastly, we would like to thank Statia Canning and Diane Porier for their administrative assistance throughout.

1.0 Introduction

In recent decades, fires have been burning hotter and faster due to changes in materials, fuel loads per unit area, and floorplan layouts. As a result of these conditions, the firefighters on the ground are put at greater risk when attempting to extinguish a fire. Recently, fire attack hoses have been failing at a higher rate due to these conditions. Firefighters need hoses capable of performing under these more intense fire ground conditions to protect themselves, as well as to safely rescue occupants and to protect property.

The large majority of fire attack hoses in use by the U.S. fire service are manufactured in accordance with *NFPA 1961: The Standard on Fire Hose*. NFPA documents state that: "this standard defines the design and construction requirements for new fire hose, the testing required to verify the design and construction, and the inspection and testing required of all new fire hoses [1]." Although, NFPA 1961 mandates multiple tests for various performance criteria of a fire attack hose, NFPA 1961 includes only one test for thermal performance of a fire attack hose [1]. This is a conductive heat test that is not representative of fire ground conditions in duration or magnitude. Another team at WPI has developed a more rigorous conduction test [2]. However, conduction is only one of three modes of heat transfer found on the fire ground. There are no standardized tests to determine performance of a fire attack hose exposed to convective and/or radiative heat stresses.

The goal of our project was to design, construct, and validate a prototype of the first ever apparatus capable of testing and documenting the performance of modern day fire attack hoses charged with water and subjected to convective and radiative heat stresses representative of conditions on the fire ground. A Standard Operating Procedure (SOP) to test fire attack hoses at consistent and repeatable conditions was created and executed. The design, verification, validation, and SOP are all documented within this report. In addition to the design and construction of the prototype apparatus, a path forward was developed to show how the apparatus could be used to provide useful data to help in the manufacturing of a next generation fire attack hose. This path takes the form of a matrix of hoses, which are paired by similarities and differences between their four key components. The results from testing these hoses within the apparatus could determine how each of these components affect the performance of fire attack hoses within these environments.

2.0 Background

Fire attack hoses serve as a tool for fire suppression and are vital to the life safety of firefighters and occupants in emergency situations. It is thus imperative that a fire attack hose can withstand modern day fire ground conditions a firefighter would be subjected to. The following background section will: describe the modern-day fire ground; detail the construction of fire attack hoses; and review thermal performance tests specified in national and international codes for fire attack hoses.

2.1 The Modern Day Fire Ground

Fires have been burning hotter and faster in recent years due to changes in materials and building layouts present on the fire ground. As a result of these more hostile conditions, fire attack hoses are failing more frequently. This section outlines the effects of the construction methods, fuel loads, and floorplan layouts of buildings on the fire ground, modes of heat transfer, and real world examples of hose failures due to convection and radiation.

2.1.1 A More Dangerous Environment

Fire ground conditions have evolved in recent years because of changes in materials of construction, fuel loads present in buildings, and the architectural floor plans in new construction. New materials, as well as increases in fuel loads per unit area, such as new furniture comprised of synthetic materials, have caused compartments to reach flashover conditions at a much faster rate. A study conducted by Underwriters Laboratories (UL) compared the rate of development of a fire in a typical living room of the mid-twentieth century (consisting of wood, cotton, wool, and fur materials), to that of a modern day living room, consisting of both natural and synthetic materials in a larger quantity [3]. The study demonstrated that modern day living rooms can reach flashover conditions up to eight times faster than a typical living room fifty years ago, as shown in Figure 1 below [4]. Thus, changes in fuels and fuel loads drastically impact the rate of development of compartment fires.

Figure 1: Comparison of Room Furnishings (UL Study)

In addition to changes in fuel loads, architectural floor plans have changed in recent years. Open floor plans are now common in new construction, allowing for increased airflow (oxygen) to a fire. Based on the fire tetrahedron, increased oxygen leads to fire propagation. Additionally, buildings with open concept layouts lack passive fire containment because of the decrease in the number of walls within the building [3]. Changing the layouts, fuel loads, and building materials, have led to more intense fire conditions in recent years resulting. This means temperatures within compartments increase quicker than ever before from the point of ignition, requiring a fire hose that is both more heat resistant and durable.

2.1.2 Modes of Heat Transfer Present on the Fire Ground

On the fire ground, all three modes of heat transfer occur: conduction, convection, and radiation. Each mode of heat transfer contributes to fire propagation in a different way, each of which is described below.

Conduction is the diffusion of heat from a warmer to a cooler body (object) that are in contact with each other. The rate of conduction is dependent upon the surface area and difference in temperature of the bodies. Figure 2 below displays conduction between a warmer and a cooler body in contact.

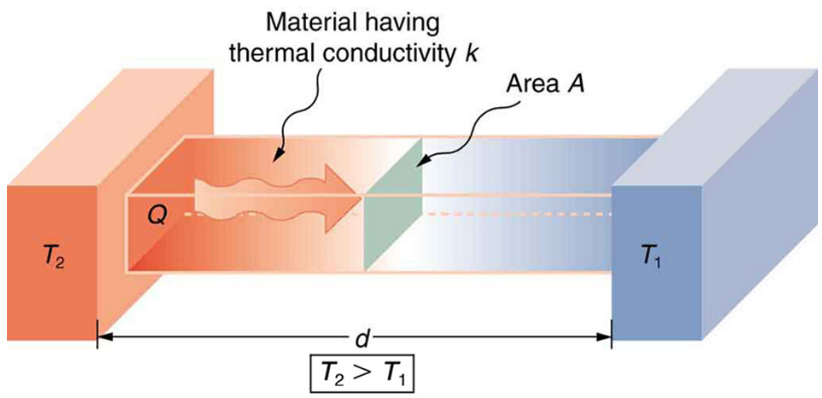


Figure 2: Conduction Through a Plane Wall

Conduction occurs on the fire ground when a hot object such as smoldering wood or molten metal that comes in contact with an initially cooler object such as a fire attack hose or other equipment. Prior to fire suppression being activated, the surface temperature of the floor can reach up to 260 °C [5].

Convection is the exchange of heat between a gas, liquid, or solid, involving the movement of a fluid medium, as seen in Figure 3.

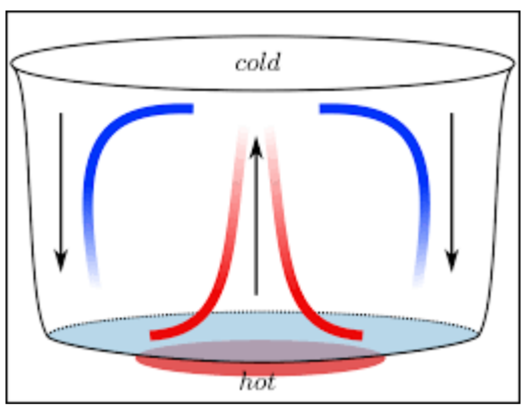


Figure 3: Common Convective Heat Transfer

Airflow velocities and lower layer gas temperatures contribute to the existence of convective heat transfer in a compartment fire. These velocities range from 1.0 to 1.4 m/s throughout a compartment during pre-flashover conditions, and can increase to up to 8.0 m/s during flashover [6]. The flow of hot air as it passes over the hose can cause hose failure, due to convection. Additionally, the high temperatures in the lower gas layer not only affect the performance of the fire hose, but expose the fire service members to dangerous air temperatures. The gas temperature in the lower region of a compartment ranges between 100 and 300 °C prior to flashover [7].

The third mode of heat transfer is radiation, which is defined as the emission of heat energy from a body in all directions. Unlike other modes of heat transfer, radiation does not require direct contact between a heat source and an object. A simple example of radiation is shown below in Figure 4.

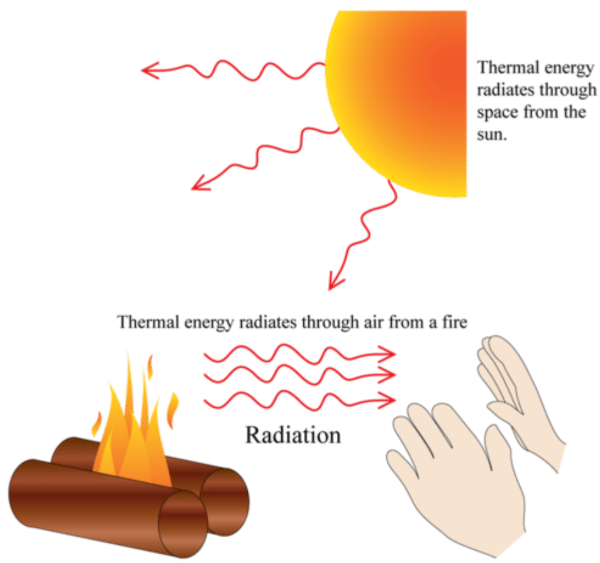


Figure 4: Energy Transfer Through Radiation

Radiative heat transfer to fire attack hoses occurs from both the fire itself and from the upper smoke layer within a compartment. Radiation enables compartments to reach dangerously high temperatures, often up to 1200 °C [3]. However, when the upper layer reaches a temperature of 600 °C, the compartment is considered to have reached flashover conditions and firefighters are advised against entering the compartment for safety purposes. Firefighters work during pre-flashover conditions, which typically range between temperatures of 100 to 300 °C in the lower layer [7].

2.1.3 Real World Examples of Hose Failures

A significant percentage of hose failures on the fire ground, 10%, were primarily the result of convective and radiative heat transfer, according to the database of recent hose failures in the United States [8]. Thus, hose failures due to these two modes of heat transfer cannot be ignored. One example of radiation causing a hose failure on the fire ground was found during a residential fire in Hull, Massachusetts on December 16, 2014. A fire attack hose on the front lawn near the residential structure was exposed to intense thermal radiation, causing a burn through failure. Other examples of convection or radiation causing hose failures include hot air flow in the structure, direct contact with flames, and heat radiating from the fire [8].

2.2 Construction of Modern Municipal Fire Attack Hoses

As materials and manufacturing practices continue to develop, fire attack hoses have been engineered to be lighter and stronger [9], specifically within the jacket and liner components. Manufacturers make use of synthetic fibers to provide strength and abrasion resistance, while still allowing for a lightweight and flexible hose. The majority of hoses in the industry are composed of two layers of woven fabric called the "jacket". The two most common jacket materials are Polyester $(C_{10}H_8O_4)_x$ and Nylon 6.6 $(C_{12}H_{22}N_2O_2)_x$. Polyester has a melting point of 260 °C [10] and Nylon 6.6 can melt at temperatures as low as 220 °C, although it has a higher ignition temperature than Polyester [11]. It can be seen from the melting/autoignition points that both Polyester and Nylon 6.6 hoses are subject to failure at conditions well below those of a pre-flashover fire. Properties of these two materials are shown in Table 1.

Table 1: Polyester Compared to Nylon 6.6 [10, 11]

Jacket Type	Melting Point (°C)	Autoignition Temperature (°C)	Hazardous Decomposition Products
Polyester	260	500	CO, ethylene glycol, aldehydes
Nylon 6.6	220 - 250	>700	Ammonia, CO, hydrogen cyanide, aldehydes

Nylon 6.6 is a stronger thread, but often requires heat and abrasion coatings to protect the jacket material from burn-throughs. This additional coating increases the hose cost. Polyester jacket material is more durable and affordable, and thus is often manufactured or purchased without a coating [12].

Jacketed hoses are typically lined with a thin-walled rubber material bonded to the inside of the jacket [9]. There are three common materials used for internal liners: TPU (Thermoplastic Urethane), EPDM (Ethylene Propylene Diene Monomer (M-class) rubber), and Nitrile/PVC Through the Weave. EPDM is the most affordable liner material; however, it is applied using an adhesive application method, which causes the liner to be prone to delamination failures, thus disrupting the water flow through the fire attack hose [12]. TPU liner material is typically more lightweight than EPDM and less prone to delamination. This lightweight material's rigidity often leads to a higher friction loss, which decreases the performance [12]. Lastly, while Nitrile/PVC Through the Weave liners offer "a more hydraulically efficient waterway" [12], this liner encounters the same friction loss issues as the TPU liners. Table 2 below compares the various hose liners, as described in the section.

Table 2: TPU, EPDM, Nitrile/PVC Comparison [12]

Liner Type	Benefits	Drawbacks	Hazardous Decomposition Products
TPU	Lightweight, less prone to delamination	High friction loss, more expensive	CO, CO_2, dense smoke, other toxic vapors
EPDM	Most affordable, less friction loss	Prone to delamination	Carbon oxides, nitrous oxides, other hydrocarbons
Nitrile/PVC Through the Weave	Improved flow qualities, very lightweight	High friction loss	Phenolics, CO, CO_2

Fire attack hoses are manufactured and sold with multiple coating types and diameters, in addition to consisting of multiple jacket and liner materials. Manufactures list coatings that are for additional abrasion and heat resistance. Hoses made with Polyester or Nylon can vary by weight per unit length, jacket thickness, and/or coatings. The most common fire attack hoses have diameters of 1.5", 1.75", and 2", however large diameter hoses (LDH), such as 4" diameter hoses are also used in the industry [12]. The differences between the performance of fire attack hoses as few of the jacket material, liner material, and coatings, as well as the weight differences between hoses could be explored through hose testing within the prototype apparatus, as described in Section 6.0.

2.3 Description of Existing Fire Hose Standards

To understand why hose failures are occurring on the fire ground, it is important to research both domestic and international standards that describe the thermal performance tests for fire attack hoses. This section below details the relevant standards for fire attack hoses.

2.3.1 National Fire Protection Association (NFPA) Standard 1961

Fire attack hoses used in the United States typically must be compliant with *NFPA 1961: Standard on Fire Hose*. NFPA 1961 outlines the design requirements for attack hoses, supply hoses, occupant uses hoses, forestry hoses, and suction hoses. This standard also outlines all hose construction requirements including diameter, linings and jackets, and other hose characteristics. Chapter 6 of NFPA 1961 focuses on the hose testing for manufacturers' hose certifications. These tests include heat resistance tests, twisting and kinking tests, burst tests, adhesion tests, among others. Chapter 7 outlines sampling, inspection, and testing to assure quality control of hose products [1].

One test in particular, the heat resistance test, could be improved to ensure higher quality fire attack hoses in the industry. Currently, the heat resistance test consists of only a conduction test. A 2.5" by 1.5" by 8" steel block is heated to 260 °C and stamped on the fire attack hose for 60 seconds. Following the stamp, the hose is pressurized to three times its service test pressure. If the hose does not leak, it passes the NFPA 1961 heat resistance test [1]. Since this is the only thermal performance test, it will not be further tested for thermal stresses. The current heat resistance test is not representative of actual conditions fire attack hoses will be subjected to on the fire ground. The heat resistance test does not utilize convective or radiative testing methods, both of which have a major impact on the fire ground. Although these hoses are inspected thoroughly and meet several requirements, hose failures still occur frequently in the field [8].

2.3.2 Relevant International Standards for Fire Hose Testing

While NFPA 1961 is widely adopted in the United States, code bodies in other nations have similar standards for thermal performance tests of fire attack hoses. The most relevant international fire attack hose standard is the Deutsches Institut fur Normung (DIN) 14811. *DIN 14811: Fire-fighting hoses – Non-percolating lay flat delivery hoses and hose assemblies for pumps and vehicles* is a fire hose performance standard developed by the German Institute for Standardization. The most relevant section of this standard pertaining to this project is the "flame resistance test," which is the only flame resistance test of fire attack hoses in the world. The object of the test is to analyze hose performance against flame impingement as well as the self-extinguishing capabilities of the hose. This test entails pressurizing a fire attack hose to 70 psi and exposing a portion of the hose to an open flame, impinging the hose for ten seconds. If the hose does not burst and the after-flame/after-glow time is three seconds or less, the hose passes the trial. This test is repeated four more times. If the hose passes four out of five tests, it is approved according to the standard [13]. This test is more comprehensive than NFPA 1961 because it incorporates multiple modes of heat transfer, as opposed to just a conduction test.

2.4 Review of Existing Alternative Testing Methods

Other groups have recognized the need for thermal performance test of a fire attack hose test where thermal conditions are more representative of the fire ground. The Bureau of Alcohol, Tobacco, Firearms, & Explosives (ATF) conducted full-scale scoping tests and bench-scale laboratory tests exposing fire attack hoses charged with water to radiant heat fluxes representative of pre-flashover and flashover conditions [14]. In addition to these tests, a previous WPI project group developed an apparatus capable of testing fire attack hoses charged with air at convective and radiative pre-flashover conditions [15]. Our project was designed to fill the void between the ATF and WPI testing methods by creating an apparatus capable of testing fire attack hoses charged with water at both convective and radiative conditions simulating pre-flashover.

3.0 Project Scope and Methods

3.1 Mission Statement

Our mission was to design, build, validate, and verify the first ever apparatus capable of assessing the performance of a water-charged fire attack hose subjected to radiative and convective conditions simulating a pre-flashover fire. Our team researched various studies that have documented temperatures and heat fluxes on the fire ground. These values were used to develop criteria for the creation and validation of a prototype test apparatus, which allows for performance testing of both commercially available and future fire attack hoses. Each component of the prototype apparatus was validated to ensure that it could achieve and maintain the performance criteria. The system's ability to test water-charged modern day fire attack hoses was verified at pre-flashover fire ground conditions. The data gathered from testing hoses using the prototype apparatus will provide knowledge useful to: fire departments in selecting a fire attack hose; manufacturers in designing a next generation (i.e. more heat resistant) hose; and the relevant code bodies, in establishing more meaningful thermal performance tests.

3.2 Methodology

To accomplish the project mission, the team utilized the following methods:

1. Development of Performance Criteria Useful in Apparatus Design
2. Design of the Apparatus
3. Construction of a Prototype of the Apparatus
4. Development of Verification Methodologies of Each Individual Component
5. Development of Hose Testing Procedure for Validation of the Apparatus
6. Confirmation of Accuracy and Consistency of Test Results
7. Construction of a Matrix of Hoses to Test

Methods 1-3 involved the research, design, and construction of the testing apparatus, Methods 4-6 involved verification and validation of the testing apparatus, and Method 7 involved research and preparation for future convective and radiative hose tests within the constructed apparatus. Sections 4 through 6 below detail the execution of the methods and present the project results.

4.0 Design and Construction of the Prototype Apparatus

The prototype apparatus was designed and constructed to provide testing capabilities necessary to assess water-charged fire attack hoses at pre-flashover conditions; the following section details the apparatus design and construction.

4.1 Development of Performance Criteria Useful in Apparatus Design

The team established criteria to determine necessary operating parameters for the prototype apparatus. These were selected to ensure that the system generated conditions representative of the fire ground from ignition to just prior to flashover. The performance criteria consisted of five key areas, as follows:

1. Heat Flux and Temperature
2. Convective Airflow
3. Hose Pressurization
4. Test Duration
5. Determination of Hose Failure

4.1.1 Heat Flux and Temperature Performance Criteria

The prototype apparatus was designed to produce heat fluxes and temperatures representative of pre-flashover fire ground conditions.

At the point of flashover, the heat flux in a compartment at floor level was documented and determined to be approximately 20 kW/m^2 [16]. Studies conducted on firefighter PPE have shown that the heat fluxes on the pre-flashover fire ground range between 5 and 12 kW/m^2 [7]. In a separate study, fire tests were conducted at floor level, including a mattress fire, which produced a maximum heat flux of 13 kW/m^2 [7]. Therefore, a heat flux range of 5 - 18 kW/m^2 was chosen as representative of pre-flashover conditions on the fire ground.

These studies conducted on firefighter PPE have also found that the temperatures of the pre-flashover fire ground range from 100 °C and 300 °C [7]. Section 8.6.4.1 of NFPA 1971, *the Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* (2013), requires that all firefighter PPE must be tested in an oven where the temperature at the center of the oven is 260 +/- 6 °C, which is representative of a temperature that the materials are exposed to on the fire ground. Section 8.8.5.2 of NFPA 1971 (2013) stated that protective footwear, including the sewing thread (Section 7.10.3), is to be tested at temperature of 260 +/- 5 °C [5]. Protective footwear is exposed to the same fire ground conditions as fire attack hoses are. Thus, to accurately represent conditions that fire attack hoses would be exposed to on ground level, within the range of pre-flashover temperatures, the prototype apparatus was designed to produce a range of temperatures varying between 100 to 300 °C at hose level.

By designing the prototype apparatus to a large temperature and heat flux range, it will be able to simulate conditions at various stages of pre-flashover and provide versatility in fire attack hose testing capabilities.

4.1.2 Convective Velocity Performance Criteria

The prototype apparatus was designed to produce airflows representative of fire-induced convection.

A study was conducted at the National Institute of Standards and Technology (NIST) regarding airflows induced by a fire in a compartment setting. The study analyzed fifty-five full scale pool fires of varying sizes. Various mass flow rates of air were recorded through different sized openings [17]. These mass flow rates can be used to calculate velocity measurements [15]. These calculations showed that velocities vary between 1.0 - 1.2 m/s. In addition to this study, a NIST study researching the performance of SCBA masks on the fire ground utilized an air velocity of 1.4 m/s to simulate pre-flashover conditions [6].

To remain consistent with data observed in the pool fire study and criteria utilized in the SCBA mask study, a velocity range of 1.0 to 1.4 m/s was selected for use in the convective system of the apparatus.

4.1.3 Hose Pressure Performance Criteria

The testing apparatus was designed to test water-charged fire attack hoses at standard operating pressures representative of those used by the fire service.

Seventeen fire departments across the United States were contacted to determine the operating pressures of 1 ¾” hoses used on the fire ground. The pressure of the hose is dependent upon the nozzle utilized by the fire service; discharge pressures at the nozzle can range from 50 to 100 psi. To provide the desired pressure at the nozzle, the hose must be pressurized at a greater value to accommodate for the friction loss, which is dependent upon hose diameter, hose type, and length [18]. Based upon the average operating length and a smooth bore nozzle for a 1 ¾" line, hose pressure was calculated to be 140 psi with a standard deviation of 13.

The prototype apparatus was designed to accommodate a water-charged fire attack hose at 150 psi, a conservative number to account for the range of hose pressures used on the fire ground, over the test duration, as described in Section 5.1.5 below.

4.1.4 Test Duration Performance Criteria

The prototype apparatus was designed to achieve and maintain testing conditions over the duration of the test.

Protective footwear and fire attack hoses are exposed to the same conditions on the fire ground. Sections 8.8.5.2 and 8.8.7 of NFPA 1971 evaluate fire protection footwear by exposing them to a heat test for 20 minutes, at temperatures representative of lower level fire ground conditions [5]. Therefore, because protective equipment is designed to withstand exposure for at least 20 minutes, the fire attack hoses will also be tested for this period of time.

The prototype apparatus was designed to produce consistent and repeatable results. Such that if the same fire attack hose should be tested a number of times, the results will be within a 10 % tolerance.

4.1.5 Hose Failure Performance Criteria

Hose failure within the fire industry does not have standard criteria across all fire departments. Based upon seventeen conversations with fire service members, hose failure normally occurs abruptly, causing significant pressure loss. Conversations with several fire departments can be found within Appendix A. Based upon these conversations and research of testing standards, it was concluded that a pressure drop of greater than 5% significantly affects the performance of a fire attack hose. Since hoses will be charged to 150 psi, a pressure of 142.5 psi was selected as the minimum tolerable pressure during testing in the apparatus. Therefore, a failure was determined to be the time at which a hose drops below a pressure of 142.5 psi.

4.2 Design of the Apparatus

This apparatus was the first ever apparatus designed to test the performance of a fire attack hose when pressurized with water. The apparatus consisted of four main components:

1. Radiative Panel
2. Inline Fan
3. Duct Heater
4. PID System

The specifications for each of these components were limited by cost, as this is a prototype apparatus; for a final design, more rigorous components should be utilized to ensure the final apparatus can withstand multiple hose failures over time.

4.2.1 Selection of System Components

System components were selected to meet the performance criteria and objectives of our project. A previous WPI group designed and built a similar testing apparatus. The design objectives of our prototype apparatus exceed the objectives of the previous apparatus in some areas. Therefore, all system components of the previous apparatus were evaluated to determine if their performance was sufficient for our design. Some system components of the previous apparatus, such as the radiative panel and inline fan, were incorporated into our design. This section details the selection of system components, ensuring they fall within the designed performance criteria.

4.2.1.1 Radiative Panel

The team selected a radiative panel to produce a range of heat fluxes from 5 to 18 kW/m^2 and a temperature range between 100 and 300 °C; these ranges of temperatures and heat fluxes are representative of what is generally found within the lower layer of a compartment fire prior to flashover. To produce these conditions, the team selected the QF-061225 Infrared Panel Heater from Omega Engineering, which was capable of producing a maximum heat flux of 38.75 kW/m^2 and temperature of up to 870 °C in the apparatus [19]. See Figure 5 below for an image of this heater.

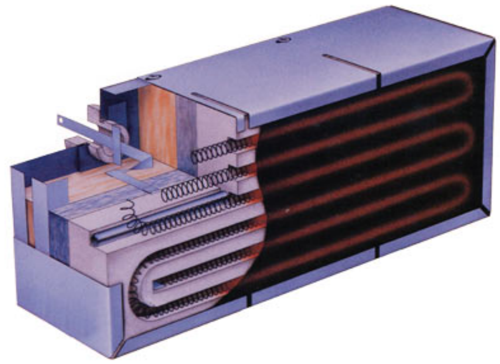


Figure 5: Omega QF-061225 Infrared Panel Heater

4.2.1.2 Inline Fan

An inline fan was selected to produce the necessary air velocity within the testing chamber to simulate convective airflow velocities on the fire ground. Inline duct fans are rated by their volumetric flow rate in cubic feet per minute (CFM). The following equations were used to calculate the fan rating, in CFM, needed to produce the desired airflow velocity [20].

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

The density of the air was assumed to remain constant as it passes throughout the fan, based upon standard operating conditions.

$$A_1 V_1 = A_2 V_2$$

The above equation was then used to calculate the required velocity that the fan needed to produce to provide sufficient airflow throughout the testing chamber, assuming no friction or head loss. A_1 and V_1 represent the area and velocity, respectively, of the inline fan. A_2 and V_2 represent the inlet area and velocity, respectively, into the testing chamber.

$$A_1 = \pi r^2 = \pi(3.0\ in)^2 = 28.27\ in^2 = 0.018\ m^2$$

$$V_1\ is\ unknown\ \left(\frac{m}{s}\right)$$

$$A_2 = \pi r^2 = \pi(1.5\ in)^2 = 7.07\ in^2 = 0.0046\ m^2$$

$$V_2 = 1.2\ \frac{m}{s}$$

To calculate V_1:

$$0.018\, m^2 * 1.2\, \frac{m}{2} = 0.0046\, m^2 * \ V_1$$

$$V_1 = 4.69\, \frac{m}{s}$$

The velocity units can then be converted to CFM by multiplying the velocity in $\left(\frac{m}{s}\right)$ by the area (m^2) of the inline fan.

$$4.69\, \frac{m}{s} * 0.018\, m^2 = 0.08\, \frac{m^3}{s} = \ 0.08\, \frac{m^3}{s} * \left|\frac{60\ s}{1\ min}\right| * \left|\frac{35.32\, ft^3}{1\ m^3}\right| = 178.52\ CFM$$

The above CFM represents a value calculated assuming no friction or head losses. To account for the additional losses, the following assumptions were made:

1. The flow is steady and incompressible
2. The entrance of the inline fan is negligible, thus the flow is fully developed
3. Air is an ideal gas
4. The flow is turbulent

Properties of air were determined based on the expected temperatures within the flexible tubing, and other important variables used within the calculations are shown in Table 3 below:

$$\rho = 0.566\ \ kg/m^3$$

$$\mu = 3.178\ x\ 10^{-5}\, kg/m * s$$

$$\nu = 5.505\ x\ 10^{-5}\ \ m^2/s$$

Table 3: Variables for Inline Fan Calculations

	Variable	Units
Average Velocity	V	m/s
Reynolds Number	Re	Dimensionless
Friction Factor	f	Dimensionless
Head Loss	D	m

Head loss was determined to be 20 m based upon bends within the flexible tubing, the entrance of the flexible tubing from the heating chamber, and the exit of flexible tubing into the testing chamber. The following equations were used to determine head loss within the system:

$$V = \frac{\dot{v}}{A} = \frac{\dot{v}}{\pi(0.038\,m)^2/4}$$

$$Re = \frac{VD}{\nu} = \frac{V(0.038\,m)}{5.505\,x\,10^{-5}\ m^2/s}$$

$$\frac{1}{\sqrt{f}} = -2.0log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$h_L = f\frac{L}{D}\frac{V^2}{2g}$$

This set of four equations and four unknowns was solved using an Excel Spreadsheet (shown in Appendix B), the calculated values solved are as follows:

$$\dot{v} = 24.78\,CFM \qquad f = 0.07 \qquad V = 10.32\ m/s \qquad R_e = 7{,}000$$

As shown above, a volumetric flow rate drop of 24.78 CFM was calculated, based on friction and head loss. Therefore, the total required volumetric flowrate of the system was calculated to be 203.3 CFM. A McMaster-Carr high output, direct drive fan with a maximum of a 240 CFM rating was selected. The selected fan required a 120 VAC power source, and produced a maximum velocity of 5.0 m/s [21]. To adjust the fan to the required velocity for testing, a variable speed potentiometer was added, which allowed for accurate and precise control of velocity. The fan was run on 85% of its maximum capacity, and produced the required velocity throughout the flexible tubing and within the testing chamber.

4.2.1.3 Duct Heater

A duct heater was specified in order to produce a range of temperatures within the convective airflow system that were representative of pre-flashover fire ground conditions. The duct heater worked in conjunction with the radiative panel to produce these temperatures. Duct heating coils are sized based upon manufacturer's data and specifications; each manufacturer provides correlations between volumetric airflow and heater capability for each model of heating coils. The Goodman brand of heating coils, which have been used successfully in similar projects, was selected and the correlation between volumetric airflow and heater capability is as follows:

$$kW = \frac{CFM * \Delta T}{3160}$$

kW corresponds to the heater capability, CFM corresponds to the volumetric airflow that the system produces, ΔT corresponds to the change in temperature between the system and the ambient conditions, and 3160 is a system coefficient [22]. To determine the appropriate sized heating coil for the prototype apparatus, the volumetric flow rate (CFM) was assumed to be the maximum flow of that of the inline fan (240 CFM), as described in Section 4.2.1.2 above. An ambient air temperature of 20 °C, and an average flow temperature of 200 °C were both assumed as well. The required heater capability was determined to be 13.7 kW, as shown below:

$$kW = \frac{240\ CFM * (200 - 20)°C}{3160} = 13.7\ kW$$

To ensure that these specifications could be easily met, a 20 kW Goodman HKS Heating Coil was chosen [23], as shown in Figure 6 below.

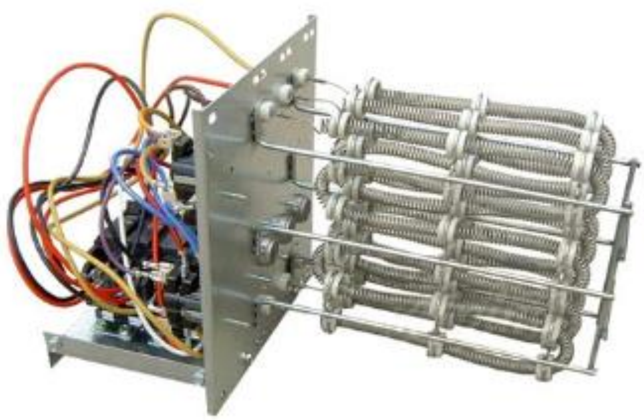


Figure 6: Goodman Heating Coil

4.2.1.4 Proportional-Integral-Derivative (PID) Controller

Proportional-Integral-Derivative (PID) controllers were utilized to control the temperature outputs of the radiative panel and duct heater. The team selected two different PID controllers based upon functionality and price. The first PID controller, the Omega CN32PT, as shown in Figure 7 below, was selected to control the radiative panel. The CN32PT controller is a more expensive PID that is capable of programming the radiative panel to a set temperature. This programming capability allows the PID to carefully control the increase in heat within the radiative panel to prevent thermal shock [24].

Figure 7: Omega CN32PT PID Controller

The second PID controller, Omega CN742, is a basic and inexpensive PID and was selected to control the duct heater, because thermal shock is not a concern within this component of the apparatus [25]. Figure 8 below shows this PID controller.

Figure 8: Omega CN742 PID Controller

The two selected PID controllers were capable of achieving and maintaining the temperatures within both the radiative panel and the duct heater.

4.2.2 Enhancements to Previous Apparatus Designs

Previously, a WPI project group created a convective and radiative fire attack hose testing apparatus which was capable of testing hoses pressurized with air. Our team modified the design of this apparatus to create the first ever apparatus capable of testing water-charged fire attack hoses. This apparatus was also designed to test fire attack hoses with a range of diameters and heat loss throughout the system was minimized. These improvements are detailed in the subsections below.

4.2.2.1 Protecting System Components to Test with Water-Charged Lines

The team first evaluated which system components needed to be protected to allow for water-charged hose testing, and concluded that the radiative panel and convective system required modifications. The radiative panel must be protected because exposure to water would cause it to crack, due to thermal shock, and therefore not function correctly. Thus, a protective panel is required to be placed between the hose and the radiative panel during testing. However, this panel must still allow the proper amount of heat flux to pass through. As a result, heat resistant, transparent materials were identified as options, as described in Section 5.1.2.

The convective system also needed to be designed to withstand a hose failure when testing with water, because any water that entered the system would permanently damage the system, rendering it unusable. Liquid trap systems, also known as P-Traps were utilized in the design of the convective system to prevent water from entering the convective chamber or coming in contact with the inline fan, causing a failure.

4.2.2.2 Minimizing Heat Loss and Allowing For Hose Diameter Versatility

Additional considerations were made to address heat loss concerns because the loss of heat from the apparatus during testing means that the system may not be operating at the desired pre-flashover conditions, thus decreasing the accuracy and introducing uncertainty into the data obtained from the tests. The testing chamber and all ductwork were designed to be fully sealed and insulated, minimizing heat loss. In addition, the team developed multiple designs for the method to load a hose into the apparatus. Three potential testing chamber designs were drafted, and potential positive and negative points for each design were identified. These initial design drafts are outlined in Appendix C. Following the initial design stage, the team selected the drawer design concept as the design to move forward with. Figures 9 and 10 below show the initial sketches for the drawer concept.

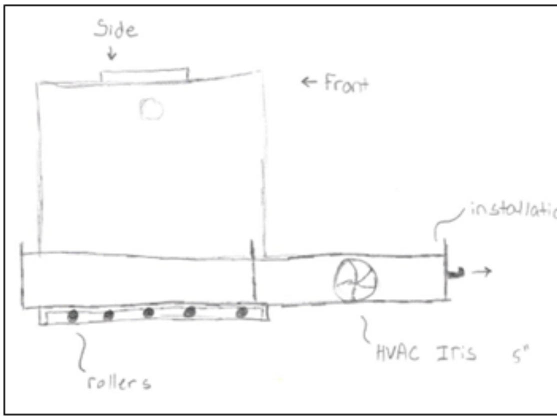


Figure 9: Drawing of Possible Drawer Concept

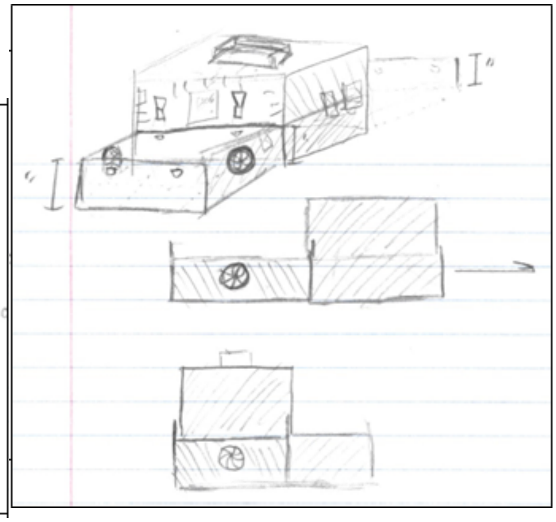


Figure 10: Drawing of Possible Drawer Concept

As shown in the figures, the drawer concept consisted of two separate pieces that make up the testing chamber. Figure 9 shows a more detailed side view of the drawer concept, while Figure 10 displays the full testing chamber with the sliding drawer. The drawer piece was a two-pocketed drawer that slides within the box section and latches to both the front and the back. The first pocket was empty and was used during the heating of the testing chamber. While the testing chamber reached its desired temperature, the front pocket was exposed to ambient air, allowing the team to load the fire attack hose and charge the line prior to seamless placement into the testing chamber. When the front pocket was slid within the testing chamber, the back pocket slid out of the back of the box. The transition between drawer pockets retained the heat of the testing chamber. To provide hose diameter testing versatility, HVAC irises were selected as the hose inlets providing a tight seal around the hose, limiting heat loss.

SolidWorks drawings were created to provide a digital representation of the new testing apparatus, as shown in Figure 11 below.

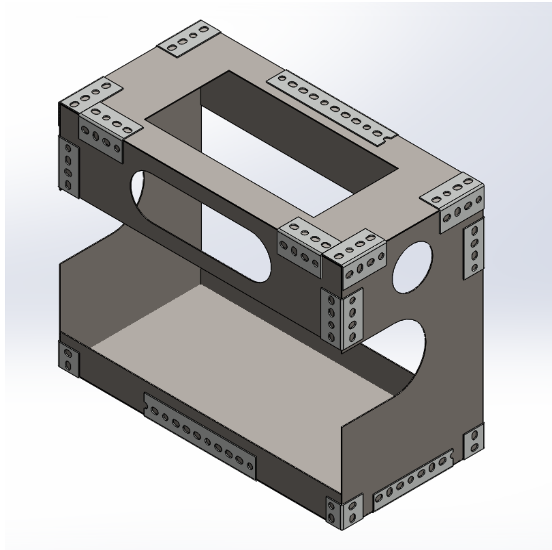


Figure 11: SolidWorks Assembly

4.3 Construction of a Prototype of the Apparatus

The testing apparatus was constructed utilizing the designs in the SolidWorks files, as shown in Figure 11 of Section 4.2.2.2 above. The apparatus was constructed in three stages: the testing box and drawer, data acquisition system, and the power system. The testing box and drawer were constructed to withstand thermal shock due to water and high temperatures. The data acquisition system consisted of Type-K thermocouples, a heat flux gauge, and two PID controllers. A power system including a 120V distribution rail and a 240V hardwire connection was added to provide sufficient power to the entire apparatus, as described in Section 4.3.3 below.

4.3.1 The Testing Box and Drawer

The testing box and drawer were the first pieces of the apparatus to be built. Both were constructed out of 0.064 inch thick zinc-galvanized sheets, which were chosen based upon durability and low cost, as the team had a fixed budget. The sheets were cut according to the SolidWorks drawings, utilizing a band saw and jigsaw within the WPI Fire Protection Laboratory machine room. Reinforcement brackets were then used to secure the testing box together. The drawer was secured utilizing J-B weld, a metal binding adhesive that chemically bound the metal together, so that the drawer could slide into the testing box smoothly. Additional J-B Weld was added to the testing box to provide rigidity to the testing chamber as a whole. The drawer was placed into the testing box atop five conveyer rollers that allowed for easy operation of the drawer.

The radiative panel chosen for the testing apparatus was the Omega Engineering QF-061225 Infrared Panel Heater, as described in Section 4.2.1.1. The heater was positioned atop the testing box, and stabilized with aluminum t-slotted extrusion frame supports (80/20). Below the face of the heater, a protective glass panel, as described in Section 4.2.1.1, was positioned on top of two metal hangers, so that the glass could easily be replaced if it fractured as a result of a hose rupture.

The convective heat transfer system of the apparatus was located below the testing box. An inline duct fan was placed directly before the heating element and provided flows and velocities that met performance criteria standards.

A glass viewing window was added to the testing box to allow visibility during testing. To decrease stress fractures during hose failure, the glass panel was cut into an oval shape and secured using J-B weld and insulation. An additional handle was added to the front face of the drawer to allow for easier hose exchanges during testing.

Images of the constructed testing box and drawer can be seen in Figures 12 and 13 below.

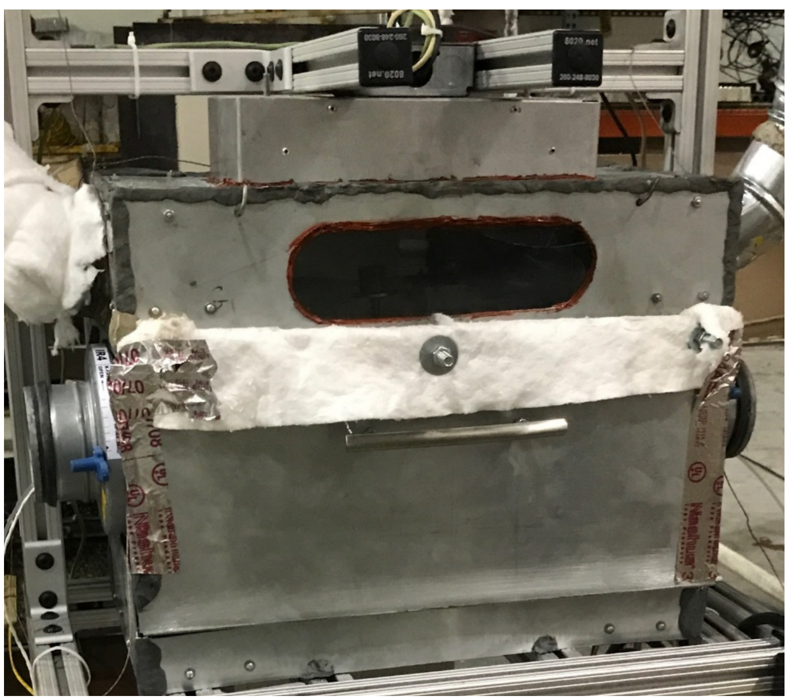


Figure 12: Completed Apparatus Testing Box and Drawer

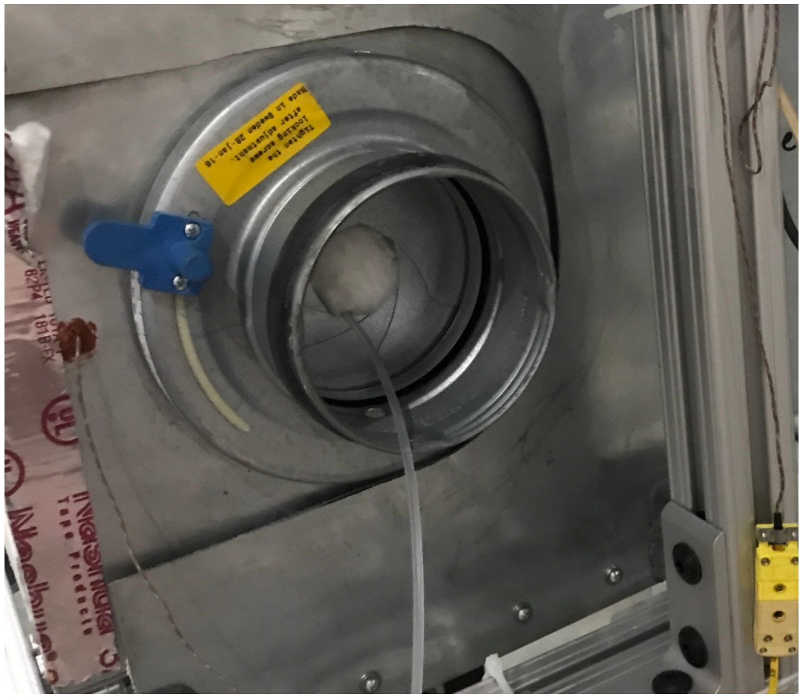


Figure 13: View of the Iris Damper on the Testing Apparatus

4.3.2 Data Acquisition

Throughout testing, temperatures at various locations within the apparatus were recorded to ensure that the apparatus was producing and maintaining conditions representative of pre-flashover. Type-K thermocouples were selected based upon their quick-response to changes in temperature and their high heat resistance. All data was recorded every one second through the use of National Instruments SignalExpress software, a DAQ chassis, and an NI 9213 cartridge. The exact location of each of the Thermocouples are shown in Figure 14.

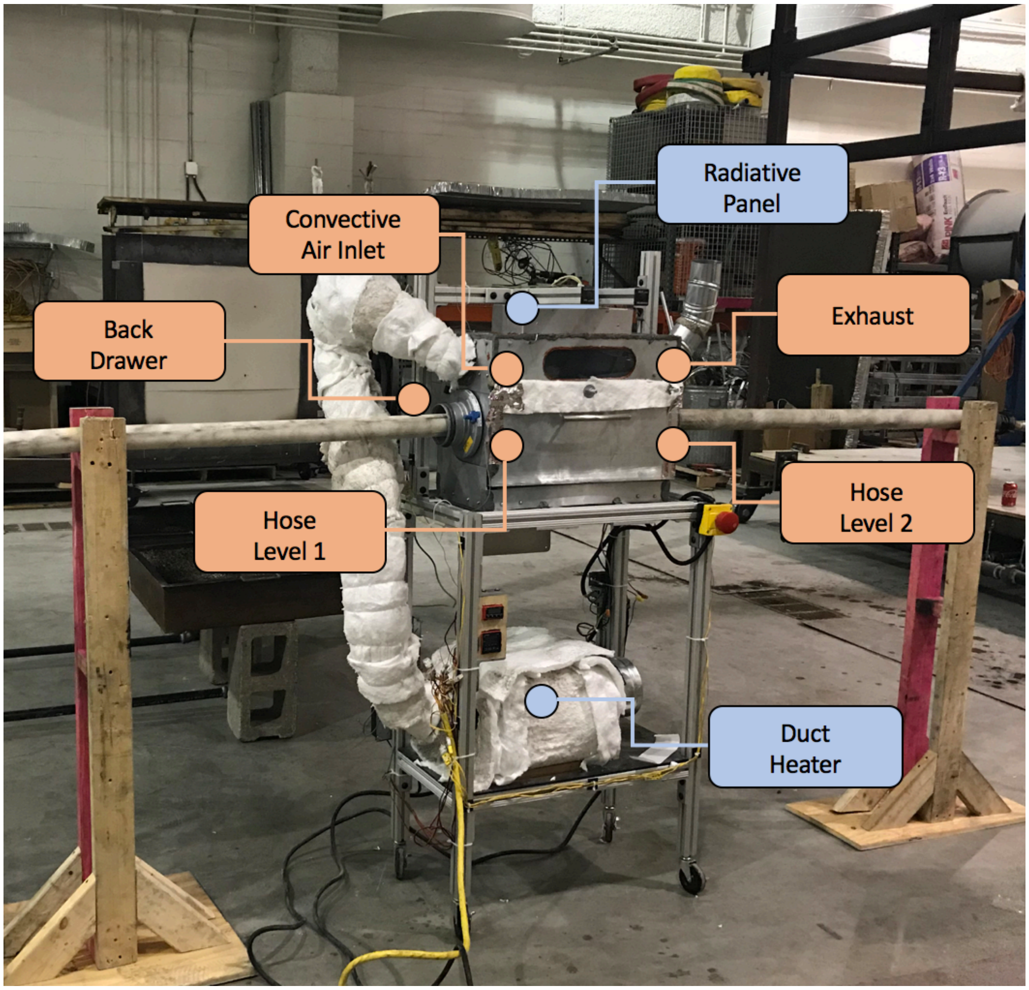


Figure 14: Thermocouple Diagram within the Apparatus

A total of seven thermocouples were used for data acquisition, as shown in Figure 14. Five thermocouples measured air temperatures at hose level and in the upper layer (Convective Air Inlet, Exhaust) of the testing chamber. Two additional thermocouples were placed at the radiative panel and duct heater, as shown in blue in Figure 14. The purpose of these thermocouples was to measure the temperature of the components to provide feedback to the PID controllers used to maintain the set temperature for the tests.

4.3.3. Power System

The testing apparatus consists of various components that require power. To provide sufficient power, a power distribution rail was constructed on the backside of the testing apparatus to provide 120V power connections. The following devices utilize 120V:

- PID Controllers
- Radiant Panel
- Duct Fan

Below is a schematic of the 120V power system.

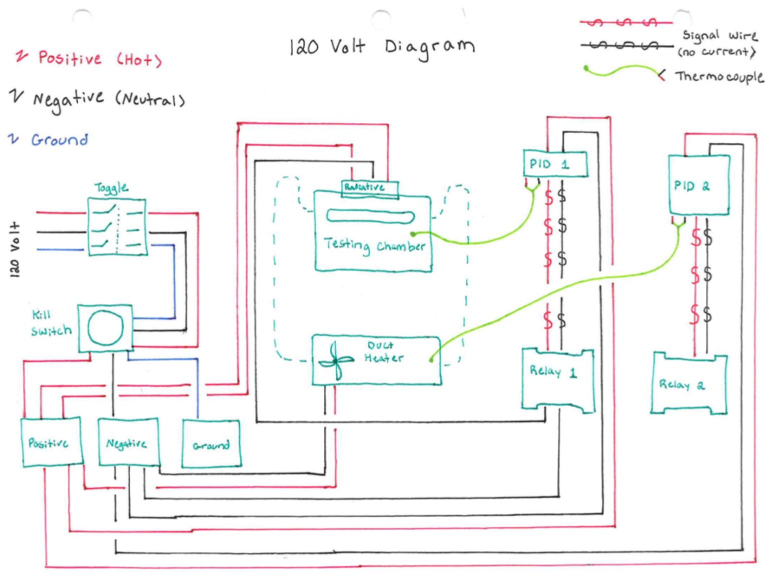


Figure 15: Schematic of 120V Power System

In accordance with manufacturer specifications, a 240V hardwire connection was wired to power the Goodman Heating Coils. Below is a schematic of the 240V power system.

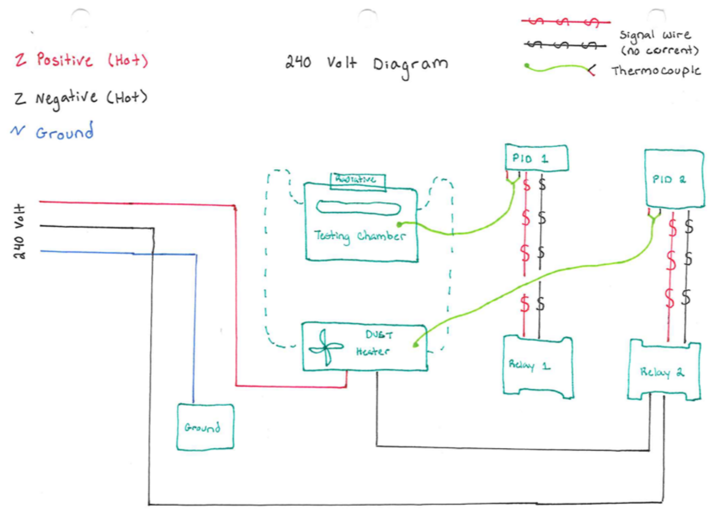


Figure 16: Schematic of 240 V Power System

The radiative panel and convective heater were connected to a 20A solid state relay, which acted as a switch to control the output temperature of both pieces of equipment. A Type-K thermocouple was placed within both the radiative panel and convective heating chamber and connected to the individual PID controllers. The PID Controllers processed the data collected through the thermocouples and turned on or off the solid state relay. The temperature within the testing apparatus was directly related to the temperature range set by the PID controllers. To ensure the PID controllers could maintain an accurate and precise temperature range, the system required validation and verification.

5.0 Verification and Validation of the Prototype Apparatus

5.1 Verification Methodologies of Each Individual Component

To ensure that the fire attack hose testing apparatus met the aforementioned performance criteria, the functionality of each component of the apparatus was verified. The verification of each individual system component was essential for the creation of a functional test apparatus. The testing methods below detail how each component was verified.

5.1.1 Convective Air Flow Testing Method

For the convective system to properly simulate the conditions of the fire ground, the airflow through the testing chamber was required to have a velocity of 1.0 to 1.4 m/s. A hose test, without failures, takes 20 minutes to be completed. Prior to the test, the apparatus takes roughly 15 minutes to reach testing temperature. Therefore, the airflow must be sustained for a minimum of 35 minutes.

To verify the capabilities of the inline fan, a hot wire anemometer was used in accordance with the following procedure:

1. Set the hot wire anemometer perpendicular to the airflow inlet within the testing chamber. (Note: it is important that the anemometer is perpendicular to the airflow inlet to read the proper velocity.)
2. Power on the hot wire anemometer and record the initial reading.
3. Power on the inline fan located at the bottom of the system.
4. Adjust the potentiometer, which is mounted to the back of the testing apparatus, to the desired airflow velocity range (1.0 to 1.4 m/s).
5. Record the hot wire anemometer velocity reading every 15 seconds for 35 minutes. A stopwatch was utilized to determine each of the recording intervals. Velocity values were read off the screen of the hot wire anemometer. The times and velocities were recorded in a Microsoft Excel data sheet.
6. Graph the results of the test on a velocity versus time chart.
7. If the desired range is sustained 100% of the time throughout the 20 minutes of testing, as well as the 15 minutes it takes for the system to heat up, the convective system, as built, meets the performance criteria.

Results from this verification test are detailed in Section 5.3.1.1 below.

5.1.2 Protective Glass Panel Testing Method

A glass sheet was installed between the radiative panel and the testing area to protect the radiative panel from water exposure during testing. With the addition of the glass sheet, verification was required to ensure that the pre-flashover heat flux and temperature ranges, set in the performance criteria section, were achievable. Three different glass panels were selected as options to protect the radiative panel, as described below:

Glass Option 1 - Tempered Glass: The tempered glass selected was rated for temperatures between 1300 and 1550 °C, though it shatters as a result of thermal stress.

Glass Option 2 - NeoCeram Glass: This glass was rated up to temperatures of 800 °C and has a high thermal shock resistance rating; it breaks into large pieces when exposed to thermal stress, as opposed to shattering.

Glass Option 3 - Typical Window Glass: This glass was rated to temperatures of up to 1400 °C; however, it shatters with rapid heat transfer.

Each glass panel was tested to determine if the glass could allow proper heat flux and temperature at hose level, while being able to withstand contact with water in the event of a hose failure. The following procedure was used to test each glass panel:

1. Place the glass panel to be tested on the glass mounting frames within the apparatus test chamber.
2. Connect the Type 173473 Heat Flux Gauge to a water source, maintaining constant flow throughout the gauge during testing. Plug the heat flux gauge wire into the DAQ 9213 module, along with all apparatus thermocouples.
3. Place the heat flux gauge perpendicular to the radiative panel with the gauge face placed just above hose level.
4. Power on the apparatus.
5. Adjust the potentiometer accordingly until the desired fan speed of 1.0-1.4 m/s is detected using a hot wire anemometer and sustained for one minute.

6. Begin recording SignalExpress temperature and millivolt readings using the DAQ 9213 module.
7. Set the bottom PID (controlling the convective heating system) to 200 °C initially, increasing the temperature by increments of 50 °C every five minutes until the temperature is set to 350 °C. The temperature must be increased in increments of 50 °C so that the convective system does not draw too much current and trip the breaker in the WPI FPE Performance Lab.
8. Set the top PID, which controls the radiative panel, to 350 °C.
9. Once temperature and millivolt readings plateau, record the temperature and use the millivolt readings and the Certificate of Calibration for the heat flux gauge (located in Appendix D) to determine the heat flux.
10. Increase the set temperature on the top PID to 400 °C until the criteria of step 9 is met.
11. Continue to increase the set temperature of the top PID in increments of 50 °C until it reaches 850 °C, recording temperature and millivolt readings at each set point and determining the corresponding heat flux.
12. Power off the apparatus and safely remove the glass panel.
13. If proper temperatures and heat fluxes are not achieved in the testing chamber, the glass sheet fails the verification test. If proper temperatures and heat fluxes are achieved, execute Step 14.
14. Utilize the discharge hose of the heat flux gauge to spray water on the hose-facing side of the glass panel for 5 minutes, which is the estimated maximum time it will take to remove a failed hose from the testing apparatus.

If the glass panel did not shatter, it passed the thermal shock test and can be considered as an option for protection of the radiative panel. If the glass panel shattered, it failed the thermal shock test and will no longer be considered as an option for protection of the radiative panel from thermal shock. Results from the radiative panel glass verification test are detailed in Section 5.3.1.2.

5.1.3. Hose Pressurizing Method

During testing, the fire attack hoses will be filled with water and charged to 150 psi. To pressurize a hose, follow the procedure below:

1. First, connect the yellow hose on the rig (seen in Figure 17 below) to the residual water connection within the performance lab.

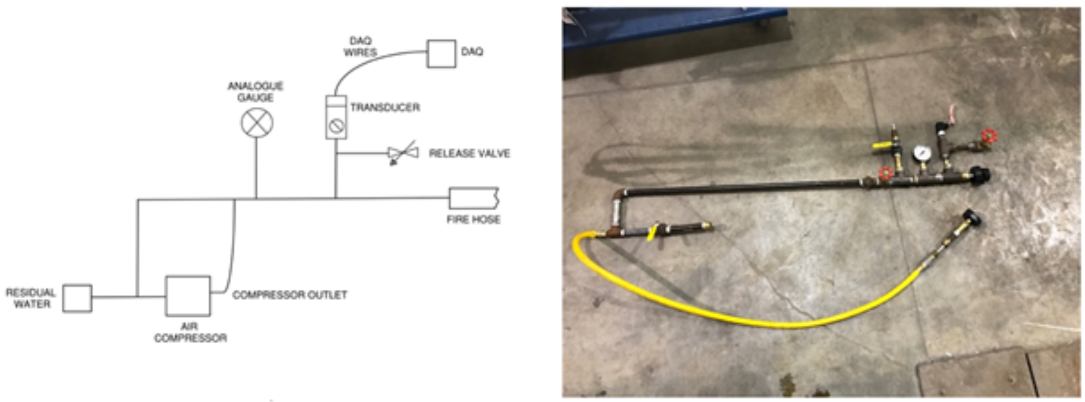


Figure 17: Hose Pressurizing System and Schematic

2. Once this connection is established, attach a pressure washer to the rig, using the connection immediately following the yellow ball valve.
3. Attach the hose of the pressure washer to the quick connect plug located on the pressure rig.
4. After the pressure washer is attached, close all valves on the pressure rig and open the residual water valve to allow water to flow into the rig.
5. Attach the female coupling of the fire attack hose to the end of the pressure rig.
6. Utilizing hose clamps, shorten the hose to only the length required for testing, which will also provide a quicker pressurizing time. After the hose is connected, pressurize it to 150 psi using the gauge to determine the pressure within the line.
7. If the pressure of the hose is maintained for a full 20 minutes, the hose pressurizing system is sufficient for testing.
8. After the test occurs, release the water within the rig, by using the red globe valve. For easier clean up, run a garden hose from the globe valve to the drain within the lab.

Results from this verification test are detailed in Section 5.3.1.3 below.

5.1.4 Hose Loading Method

The apparatus was designed to ensure that a fire attack hose could be loaded efficiently into the testing chamber. The drawer system was the key design component that allows fire hoses to be loaded quickly into the testing chamber, minimizing heat loss and increasing testing efficiency. To load a hose into the testing chamber, follow the procedure below:

1. Open the drawer so that the testing chamber is enclosed while still having access to both irises.
2. Open both irises, remove any water, confirm that the bricks are located correctly, and replace any damaged insulation within the drawer.
3. Once the drawer is prepared, slide a fire attack hose through both irises and charge the hose (refer to 'Hose Pressurizing Method').
4. Once the hose is located within both irises, clamp the irises onto the hose.
5. Slide the drawer back into the testing chamber quickly but carefully, so not to damage the apparatus.

5.1.5 Water Removal System Testing Method

If a fire hose failed during testing, water would then be discharged into the testing chamber, with the chance of entering the flexible tubing and traveling down the piping to the inline fan. Thus, to ensure that water did not damage the inline fan, and cause the apparatus as a whole to malfunction, the flexible tubing connecting the testing chamber and convective system was formed into an inverted P-trap design. In this inverted P-trap, the tubing curved up (instead of down) above the height of the testing chamber and dipped down to connect to the convective heating chamber, as shown in Figure 18 below.

Figure 18: P-Trap Design on the Apparatus

Since the water did not have enough momentum to reach the top of the inverted P-trap curve, the water stopped within the tubing and returned to the testing chamber. The water removal system required verification to ensure the convective system would not be damaged during testing. To conduct the convective system water removal method, utilize the following steps:

1. Disconnect the flexible tubing from the inline fan and convective heating chamber, located at the bottom of the testing apparatus, by removing the metal clamps which fasten the flexible tubing to the convective system.
2. Deposit water into the upper end of the flexible tubing.
3. If the water does not flow back into the testing chamber, the design fails and the height of the P-trap should be modified. If the water flows back into the testing chamber, the water removal method is verified.

Once it was confirmed that each individual component could perform as designed, the apparatus required validation as a whole. System validation requires that the apparatus as a whole can perform to ensure accurate, precise, and consistent results. To properly validate the apparatus, a standard operating procedure was developed.

5.2 Hose Testing Procedure for Validation of the Prototype Apparatus

To ensure repeatability of hose tests within the prototype apparatus, the team developed a standard operating procedure (SOP) for running these tests. The SOP details the necessary procedures for apparatus start-up, hose testing, and shutdown. The SOP must be followed during every hose test within the apparatus, regardless of whether data will be collected. Below is the hose testing SOP:

1. Plug in the 120V and 240V electrical cords into power sources to power on the apparatus, and turn on both PIDs.
2. Using the hot wire anemometer, complete the convective airflow testing method, as detailed in Section 5.1.1 above, to ensure that the convective system functions at a velocity of 1.0 to 1.4 m/s. Note: A 35 minute verification is not needed for each test, however measurements should be taken for 1 minute to ensure the fan is functioning properly between tests.
3. Pull the sliding drawer forward, so that the preparation chamber is being preheated, and the testing chamber is exposed to ambient conditions.
4. Power on the DAQ system, and SignalExpress, and begin recording temperature data.
5. Upon completion of the convective airflow test, set the PID that controls the convective system to 200 °C.
6. When the temperature reading on this PID stabilizes, increase the temperature by 50 °C. Repeat this step until the temperature reading on the PID is 350 °C. The temperature must be increased in increments of 50 °C so that the convective system does not draw too much current and trip the breaker in the WPI FPE Performance Lab.
7. The radiative panel is controlled by a set temperature entered into its respective PID. To reach the goal of a specific temperature at hose level, a specific heat flux is required. This heat flux-temperature relation must be calculated based upon a test (as shown in Section 5.3.1.2). Heat flux cannot be entered directly into the radiative panel PID, therefore a correlation curve relating the set temperature of the PID and the required heat flux must be generated. Set the PID to the set temperature required to achieve the desired heat flux. These correlation curves can be found in Section 5.3.1.2 Figures 20 and 21.

8. Slide an uncharged hose through the irises located in the testing chamber.
9. Attach the female coupling of the fire attack hose to the water supply.
10. Clamp the other end of the hose shut using a hose clamp.
11. Support both sides of the hose using hose stands.
12. Open the water supply located in the FPE Laboratory, and charge the hose with water to the residual pressure.
13. Once the hose is charged to residual pressure (about 60 psi), use the pressure washer to increase the pressure to 150 psi, purging all air, and securely clamp the hose using the iris dampers.
14. Slide the testing chamber into the apparatus, exposing the hose to pre-flashover conditions.
15. Assign one member of the team to gather data from the pressure gauge using a stopwatch, collecting data points every 5 seconds.
16. Continue testing for 20 minutes, or until a failure occurs (5% pressure loss).
    a. If failure occurs, use the release valve to drain the hose so that more water does not enter the testing chamber.
17. Upon completion of the test, slide the testing chamber out of the apparatus. If more tests will be completed, leave the power sources to the apparatus on. If this is the final test of the day, power down the apparatus.
18. Allow the preparation chamber to cool to ambient conditions.
19. Using the release valves located next to the pressure washer, as shown in Figure 16 above, drain the water from the hose.
20. If the hose will not be tested again, unclamp the hose and remove it from the testing chamber.

The SOP was executed to properly validate the testing apparatus after each individual component had been verified. The results from this verification and validation process are described in section 5.3.

5.3 Accuracy and Consistency of Test Results

The team verified and validated the system to ensure that the components of the prototype apparatus, and the apparatus as a whole, were capable of generating an environment representative of pre-flashover within the testing chamber. The results of the verification and validation procedures are detailed in each of the following subsections.

5.3.1 Component Verification Results

5.3.1.1 Results from the Convective Airflow System Testing Method

The team designed the convective system so that the inline fan produced an airflow velocity between 1.0 to 1.4 m/s. The convective system, including the inline fan, was tested in accordance with the convective system test method. The inline fan produced an average airflow velocity of 1.22 +/- 0.0663 m/s, over the test period of 35 minutes, as shown in Figure 19 below. The airflow velocity remained within the range of 1.0 to 1.4 m/s throughout the entire test duration.

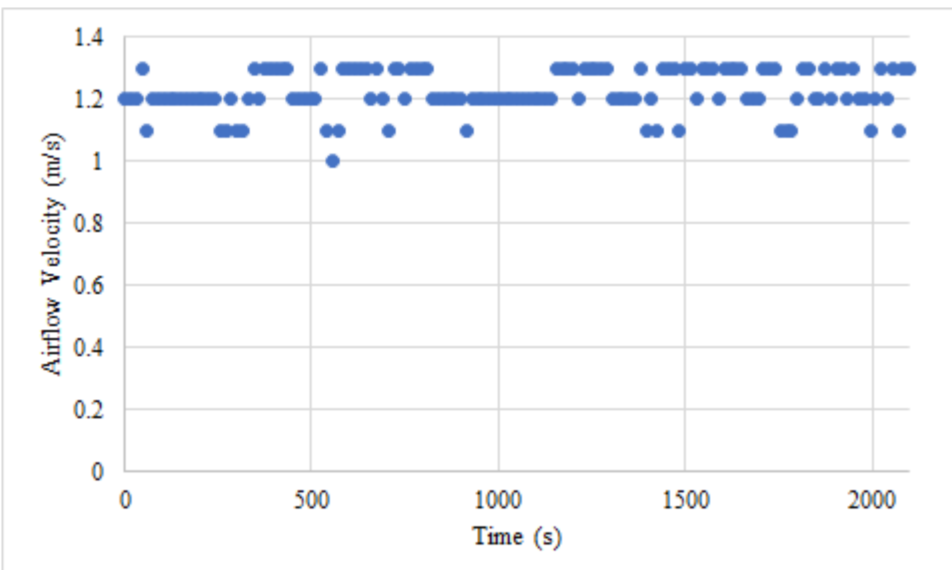


Figure 19: Results from the Convective System Test

5.3.1.2 Results from the Protective Glass Panel Testing Method

The team selected three different sheets of glass to potentially protect the radiative panel from water damage. Option 1 allowed the required heat flux to be applied to the hose area of the testing chamber. However, when sprayed with water during its thermal shock test, the tempered glass shattered, removing this panel from consideration. Option 3 shattered during the heat flux testing, and thus was not considered as a type of glass to be used to protect the radiative panel. Option 2 also allowed the required heat flux to reach the hose area of the testing chamber, and the glass did not crack or shatter when sprayed with water continuously for 5 minutes. Therefore, the team selected Option 2 to protect the radiative panel from water damage. Heat flux and temperature curves were generated utilizing the results from testing the system with Option 2 protecting the radiative panel, as shown below in Figures 20 and 21.

Figure 20 displays the correlation between the temperature setting of the radiative panel and the heat flux present at hose level that results from this setting. The prototype apparatus was designed to output a heat flux range of 5 - 18 kW/m^2, but produced a range of heat fluxes between approximately 3.5 kW/m^2 and 25 kW/m^2 in practice.

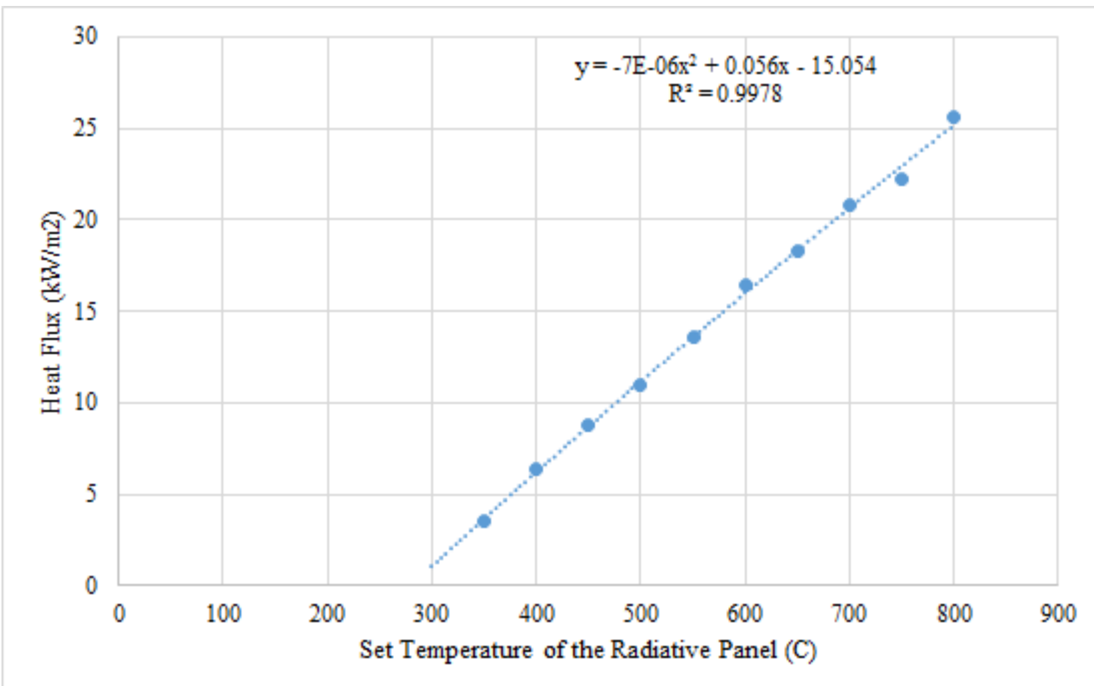


Figure 20: Heat Flux Calibration Curve

Figure 21 displays the correlation between heat flux at hose level and the temperature at hose level. The apparatus was designed to produce a range of heat fluxes between 5 to 18 kW/m^2, and a range of temperatures between 100 to 300 °C at the hose level within the apparatus. Thermocouples were placed at hose level in the testing chamber. Temperatures at each thermocouple were recorded at the same time as the voltage, which was converted to heat flux. Heat flux and temperature were correlated, as shown in Figure 22 below. The Temperature 1 curve below corresponds to the hose-level temperature on the left side of the testing chamber, and the Temperature 2 curve corresponds to the hose-level temperature on the right side of the testing chamber. The apparatus output a temperature range of 130 to 290 °C over the output heat flux range of 3.5 to 25 kW/m^2. Because the experimental temperature range fell within the designed range of the apparatus, the temperature output of the radiative panel was verified.

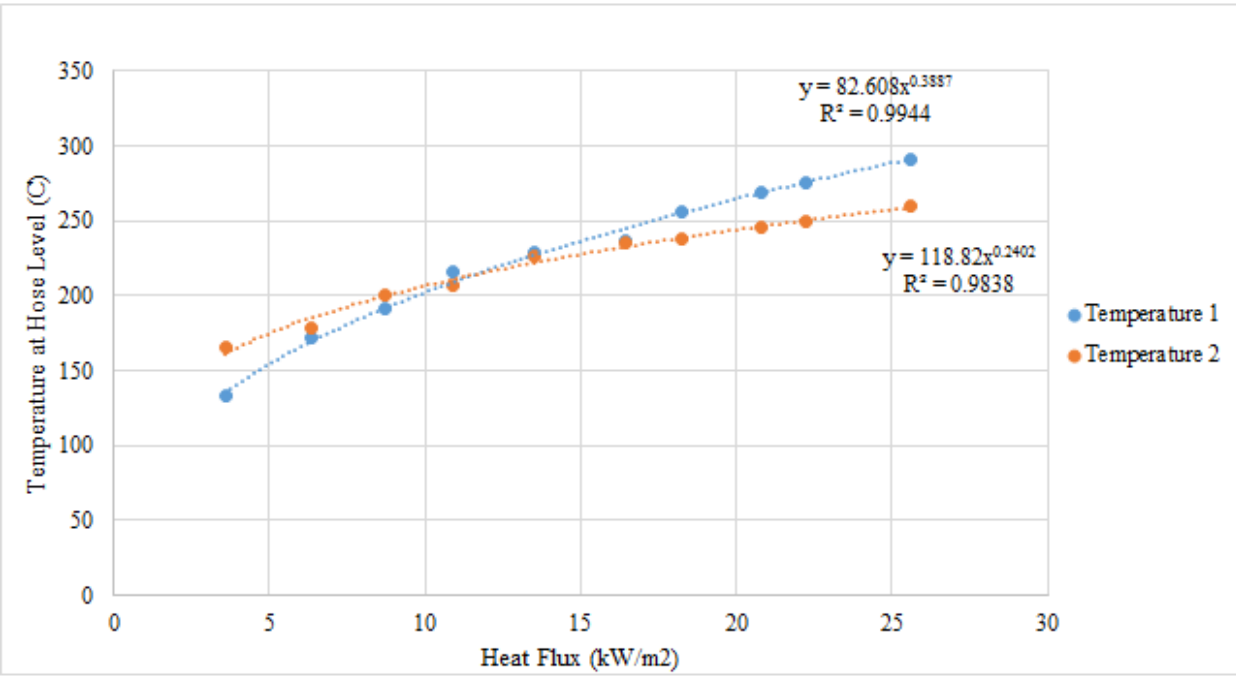


Figure 21: System Temperature Calibration Curve

5.3.1.3 Hose Pressurizing, Hose Loading, and Water Removal Test Results

The Hose Pressurizing, Hose Loading, and Water Removal Tests were all executed without errors. The test hose was pressurized to 150 psi, which is within the tolerance of the average operating pressure, and this pressure was sustained for 20 minutes. The hose was loaded with ease using the drawer mechanism, with negligible heat loss. Lastly, the inverted P-Trap design functioned properly, ensuring the convective system was not damaged during testing. Thus, each of these three components were verified to repeatedly perform as designed.

5.3.2 Validation of the Prototype Apparatus

To validate the performance of the prototype apparatus, the team executed fire attack hose tests following the SOP at a heat flux of 18 kW/m^2. The heat flux was chosen because it was representative of conditions at hose level just prior to flashover. From Figure 23, the temperature at hose level at a heat flux of 18 kW/m^2 was approximately 250 °C. The hose subjected to the validation tests had the following criteria:

Table 4: Properties of the Tested Hoses

Jacket Material	Polyester
Liner Material	EPDM
Weight	19 Pounds
Coating	None

The hose failed in less than 5 minutes during each of the three tests. Failures were dramatic bursts, and the hose pressure dropped significantly at the moment of failure during all three tests. Table 5 below shows the time to failure and pressure immediately after failure of all three tests. Appendix E shows photos of the hoses at and just after failure.

Table 5: Hose Failure Data

Test Number	Time to Failure (min:sec)	Pressure Immediately After Failure (psi)
1	4:08	127
2	3:52	124
3	4:33	126

The apparatus achieved and sustained the performance criteria during the three tests, and repeatedly withstood water discharge during hose failures. Each component was inspected following the completion of each test to verify that it withstood the test and did not sustain any damage. Following our inspection, the prototype design was validated; the apparatus is capable of consistently simulating pre-flashover conditions on the modern day fire ground.

This apparatus is the first ever verified and validated apparatus capable of testing hoses charged with water at conditions simulating pre-flashover.

6.0 Construction of a Matrix of Hoses to Test

In addition to testing to determine the overall performance of a fire attack hose, the apparatus can be used to repeatedly and consistently test hoses available to the industry to evaluate how each key component affects the overall performance of a fire attack hose. To properly assess the reliability and performance of key components of a fire attack hose, each component must be isolated and tested accordingly. The team evaluated all fire attack hoses available in the industry and paired relevant hoses together, isolating key components. This isolation matrix can be seen in Table 6.

Table 6: Hose Matrix

	Hose 1	Hose 2	Hose 3	Hose 4	Hose 5	
Jacket Material	Polyester	Nylon 6.6	Polyester	Polyester	Polyester	
Liner Material	EPDM	EPDM	EPDM	TPU	Nitrile	
Coating Type	None	None	None	None	None	
Hose Diameter	1.75"	1.75"	1.75"	1.75"	1.75"	
Weight Per 50 Feet	19 lb	18 lb	19 lb	16 lb	17 lb	
	Hose 6	**Hose 7**	**Hose 8**	**Hose 9**	**Hose 10**	**Hose 11**
Jacket Material	Polyester	Polyester	Polyester	Polyester	Polyester	Polyester
Liner Material	EPDM	EPDM	TPU	TPU	EPDM	EPDM
Coating Type	None	None	None	None	None	Heat & Abrasion
Hose Diameter	1.75"	1.75"	1.75"	1.75"	1.75"	1.75"
Weight Per 50 Feet	19 lb	24 lb	16 lb	21 lb	19 lb	19 lb

The hose matrix isolated each of the four key components of a fire attack hose for testing. Jacket material was first isolated, shown above as Hoses 1 and 2. As shown, all other components remained constant, while the jacket material varied between Polyester and Nylon 6.6. To properly assess the impact liner material has on the performance of a fire attack hose, hoses were selected with three different liner types, shown above as Hoses 3, 4, and 5. To determine the effects weight has on a fire attack hose, hoses with identical components, but a large variance in weight were selected. Two pairs of hoses were selected for weight testing to evaluate the impact across two different liner materials (EPDM and TPU), shown above as Hoses 6, 7, 8, and 9. Lastly, coatings were isolated for testing of hoses with heat and abrasion coatings versus hoses with no coating, shown above as Hoses 10 and 11.

The results from future testing of these hoses within the prototype apparatus will provide critical information about the performance of a fire attack hose as well as each of the hose components when subjected to pre-flashover fire ground conditions.

7.0 Conclusion

In conclusion, our team built the first ever prototype apparatus capable of testing water-charged fire attack hoses in a pre-flashover convective and radiative environment. The prototype apparatus was verified and validated, using the testing methods described in this report, thus proving that each system component and the apparatus as a whole is capable of producing accurate and repeatable conditions. This apparatus should be used to test hoses available to the fire service industry to analyze their performance because the apparatus provides a simulation of fire ground conditions that the current NFPA 1961 standard is unable to provide.

8.0 Recommendations

The test apparatus met the performance criteria and is capable of completing reliable and repeatable convective and radiative tests on water-charged fire attack hoses. The following recommendations are offered for the further refinement of the testing apparatus:

8.1 Incorporate a Pressure Transducer into the Data Acquisition System

For more precise pressure data collection, a pressure transducer should be used in conjunction with the analog pressure gauge. Analog gauges require manual recording of data, as data readings must be taken by the operator of the equipment. This form of data collection is not the most precise and accurate method, due to user error, which cannot be avoided. To increase both precision and accuracy within the data collection system, a pressure transducer should be wired into a DAQ cartridge, allowing for instantaneous and more frequent pressure readings via SignalExpress or LabVIEW programs.

8.2 Transition from SignalExpress to LabVIEW to Record Data

Our team used SignalExpress to collect temperature data within the testing chamber. SignalExpress allows for instantaneous data to be collected and transferred into Excel for further data analysis. However, the process of creating the SignalExpress program needs to be repeated before each test, which should be avoided due to time constraints. LabVIEW is a virtual instrumentation program with increased functionality and a more useable interface, compared to SignalExpress. Once a LabVIEW program is created, it can be repeatedly used for each test, thus saving time.

8.3 Add a Second Heating Coil to the Prototype Apparatus

The duct heater within the prototype apparatus requires a significant amount of current to operate. A single coil of the heater was used during testing because the power sources within the lab could not sustain the use of more than one coil. Utilizing an auxiliary power source within the testing facility will allow for the use of an additional coil. The use of this coil would allow the air within the testing chamber to reach higher temperatures, thus expanding the capabilities of the apparatus.

9.0 Works Cited

[1] *Standard on fire hose*. (2007). Quincy, MA: National Fire Protection Association.

[2] Gates, P., Macsata, A., & Scangas. (2015). The Conductive Performance Assessment Apparatus: The Design and Development of a Rigorous Conduction Test for Fire Attack Hoses. *The Conduction Performance Assessment Apparatus*. Retrieved December 8, 2017.

[3] Kerber, S. (2011). Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes. *Fire Technology, 48*(4), 865-891. doi:10.1007/s10694-011-0249-2

[4] Modern Residential Fires. (n.d.). Retrieved December 08, 2017, from https://newscience.ul.com/articles/modern-residential-fires

[5] *Standard on protective ensembles for structural fire fighting and proximity fire fighting*. (2006). Quincy, MA: National Fire Protection Association.

[6] Mensch, A., & Bryner, N. (2011). Emergency first responder respirator thermal characteristics :. doi:10.6028/nist.sp.1123

[7] Krasny, J., Rockett, J. A., & Huang, D. (1988). Protecting fire fighters exposed in room fires: Comparison of results of bench scale test for thermal protection and conditions during room flashover. *Fire Technology,24*(1), 5-19. doi:10.1007/bf01039637

[8] Donovan, J., Murphy, J., Gates, P., & Scangas, C. (2016). An Analysis of Modern Day Fire Attack Hose. *An Analysis of Modern Day Fire Attack Hose*.

[9] Fire Hose. (n.d.). Retrieved December 08, 2017, from http://www.madehow.com/Volume-4/Fire-Hose.html

[10] Polyester Fiber and Resin Material Safety Data Sheet. (2006, June). Retrieved from https://www.epiloglaser.com/assets/downloads/polyester-msds.pdf

[11] User, S. (n.d.). Plastic Design . Retrieved December 08, 2017, from http://www.plasticdesignmfg.com/

[12] Guzy, M., (2014, August 01). A Guide to Hose Selection. Retrieved December 08, 2017, from http://www.firerescuemagazine.com/articles/print/volume-9/issue-8/vehicle-operation-and-apparatus/a-guide-to-hose-selection.html

[13] Fire-fighting hoses - Non- percolating layflat delivery hoses and hose assemblies for pumps and vehicles . (2012). *German Fire Hose Standard, DIN 14811*.

[14] Herb, L. A., & St. John, A. (2017, April 01). Thermal Failure of Hoselines: An Analysis of the Data. Retrieved December 13, 2017, from http://www.fireengineering.com/articles/print/volume-170/issue-4/features/thermal-failure-of-hoselines-an-analysis-of-the-data.html

[15] Tukaew, P., Murphy, J., Knoff, C., Capuano, A., & Donovan, J. (2016). Thermal Performance Assessment Chamber: The Design and Development of a Novel Fire Attack Hose Testing Apparatus . *Thermal Performance Assessment Chamber*. Retrieved December 8, 2017.

[16] Lawson, J. R. (2009). Fire Facts. *Heat Flux, Temperature, & Thermal Response* . Retrieved from http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=903600

[17] Steckler, K. D., Quintiere, J. G., & Rinkinen, W. J. (n.d.). Flow Induced By Fire in A Compartment . *NBSIR 82-2520*.

[18] Massetani, G. P., Barden, J. A., Siragusa, T. A., & Velo, J. L. (2008, January). *Pump Operations* [PDF]. San Francisco: Division of Training.

[19] Infrared Heaters, Quartz Heaters. (n.d.). Retrieved December 08, 2017, from https://www.omega.com/pptst/QF_HEATERS.html

[20] Roberson, J. A., Elger, D. F., Williams, B. C., & Crowe, C. T. (2013). *Engineering fluid mechanics*. Hoboken, NJ: John Wiley & Sons, Inc.

[21] McMaster-Carr. (n.d.). Retrieved December 08, 2017, from https://www.mcmaster.com/#inline-fans/=1a4zow2

[22] Marley Engineered Products . (n.d.). Retrieved December 08, 2017, from https://www.marleymep.com/

[23] Coils. (n.d.). Retrieved December 08, 2017, from http://www.goodmanmfg.com/products/air-handlers-and-coils/coils

[24] N., R., J., B., & D. (2017, March 20). PID Controller for Temperature, Process and Strain Control. Retrieved December 08, 2017, from https://www.omega.com/pptst/CNPT_SERIES.html

[25] J. S., U., Z, M., N., & M. (2016, March 03). 1/16 DIN Temperature Controllers. Retrieved December 08, 2017, from https://www.omega.com/pptst/CN740_SERIES.html

10.0 Appendices

10.1 Appendix A: Fire Service Conversations

Town	PSI	Additional Notes
Worcester	140	
Northbridge	150	Failure when hose burts. Use double jacet
Uxbridge	110	Smooth bore nozzle at 200 ft with double jacket (1 3/4")
Mendon	140	
Auburn	140	60 psi per 100 ft and then add nozzle pressuer
South Boston	140	Call back between 9-4 PM
Framingham	120	
Southborough	130	60 PSI per 100 ft of line plus additional PSI for nozzle
Westborough	150	Dispatcher, doesn't know pressure adding but knows the average is 150
Northborough	140	Change the pressure to the fire (fluid hydaulic) solid bore and comination nozzle
Naples, FL	150	Call back from dispatcher
Houston (Texas)	150	
San Francisco, CA	150	See Email
Seattle, WA	150	Depends on high rise, single family, low rise and which hose. 200 ft 1 3/4"
Lakewood Colorado	140	Varies per nozzle
Milwaukee Wisconsin	150	
Clark County, Nevada	120	Nozzles are between 50 and 100 with avage 50 for the hose
Idaho Falls, Idaho	150	Depends greatly on which nozzle they use (smooth bore or fog)

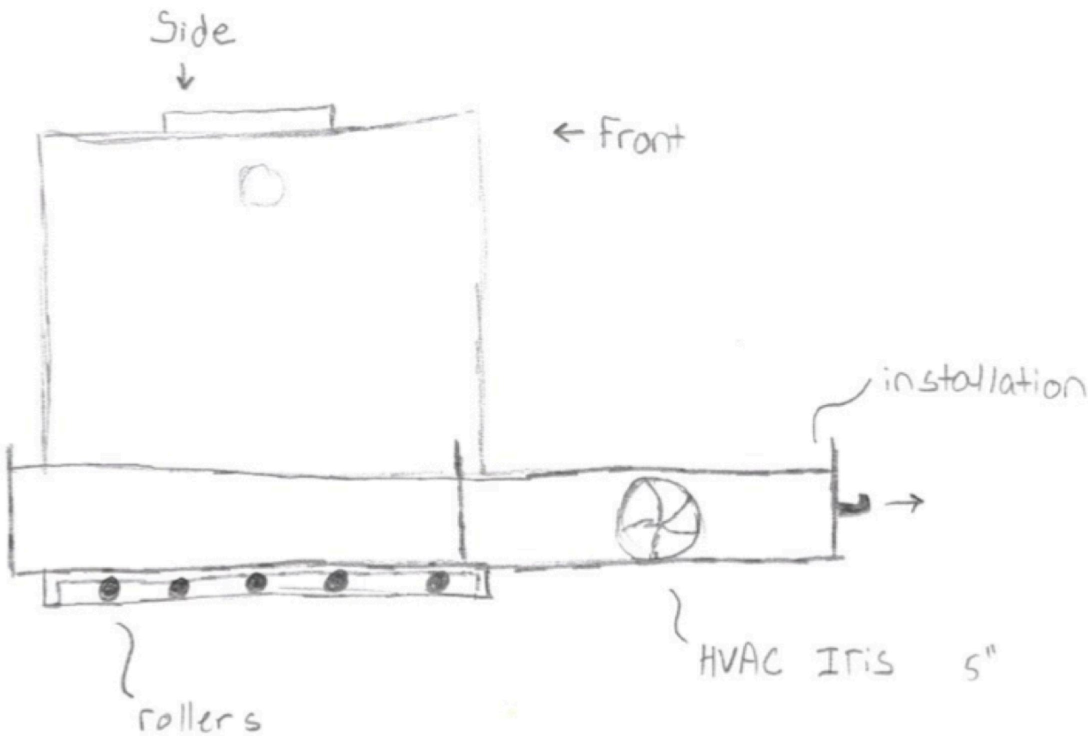
Average	140
Maxium	150
Minimum	110
Standard Deviation	12
Number of data points	17

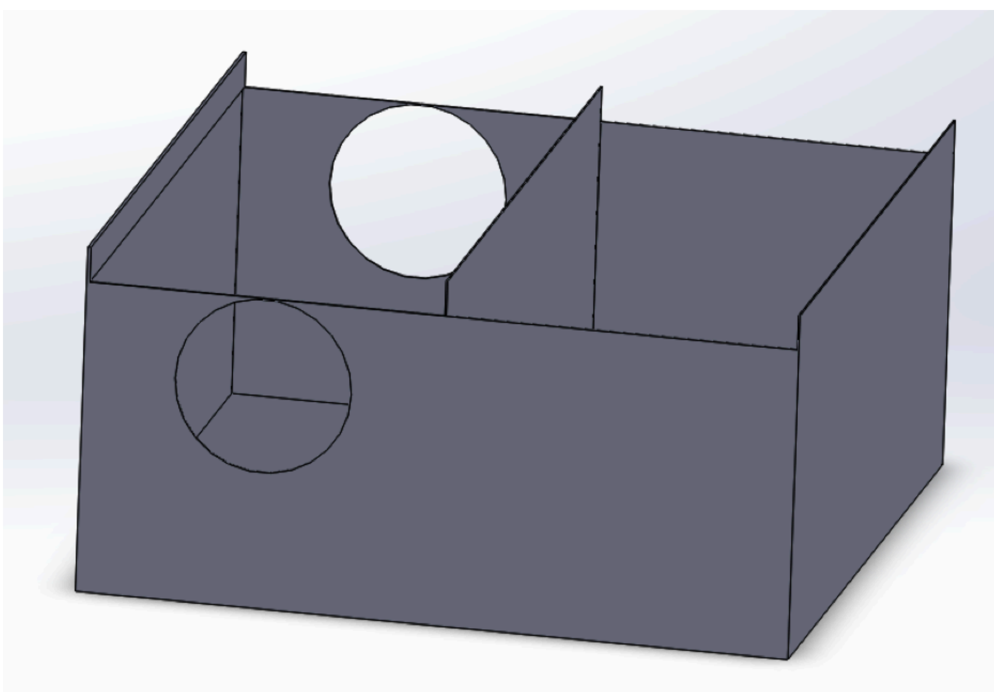
10.2 Appendix B: Inline Fan Calculations Within Excel

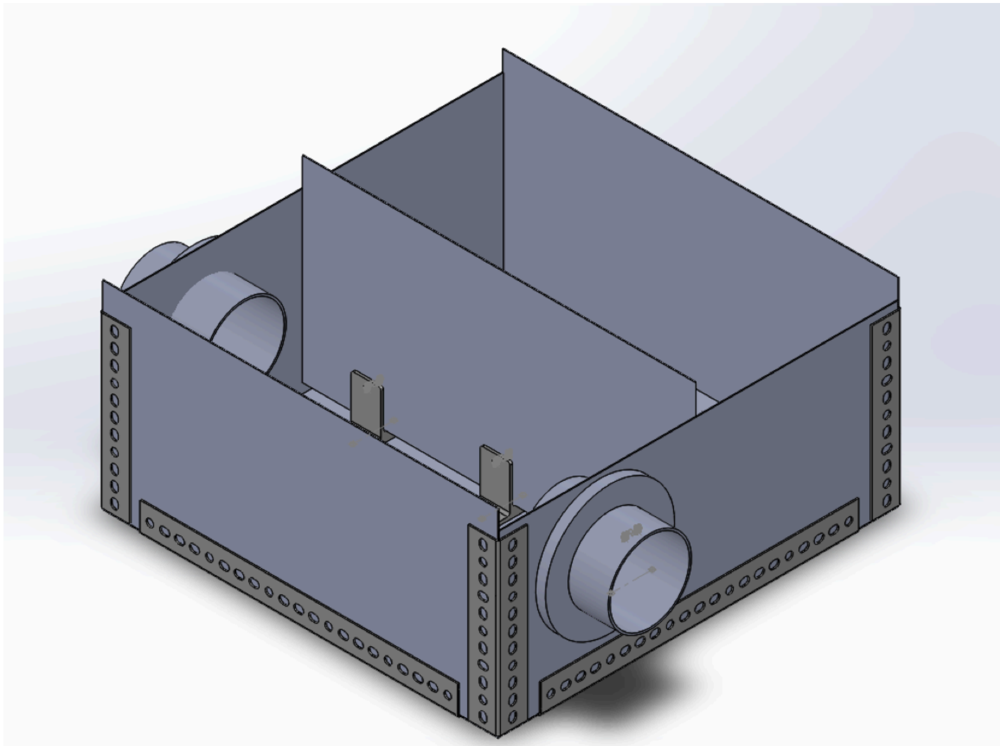
Input Parameters		
Gravity	9.81	(m/s^2)
Head Loss	20	m
Diameter	0.038	m
Length	2	m
Kinematic Viscosity	5.51E-05	(m^2/s)

Trial	f	V	Re	Calculated f	$\dot{V}$ (CMM)	$\dot{V}$ (CFM)
1	0.09	9.10	6E+03	0.1	0.01032232	21.85495423
2	0.085	9.37	6E+03	0.095	0.01062157	22.48856237
3	0.08	9.65	7E+03	0.09	0.01094847	23.1806795
4	0.075	9.97	7E+03	0.08	0.01130753	23.94090285
5	**0.07**	**10.32**	**7E+03**	**0.07**	**0.01170441**	**24.78118877**

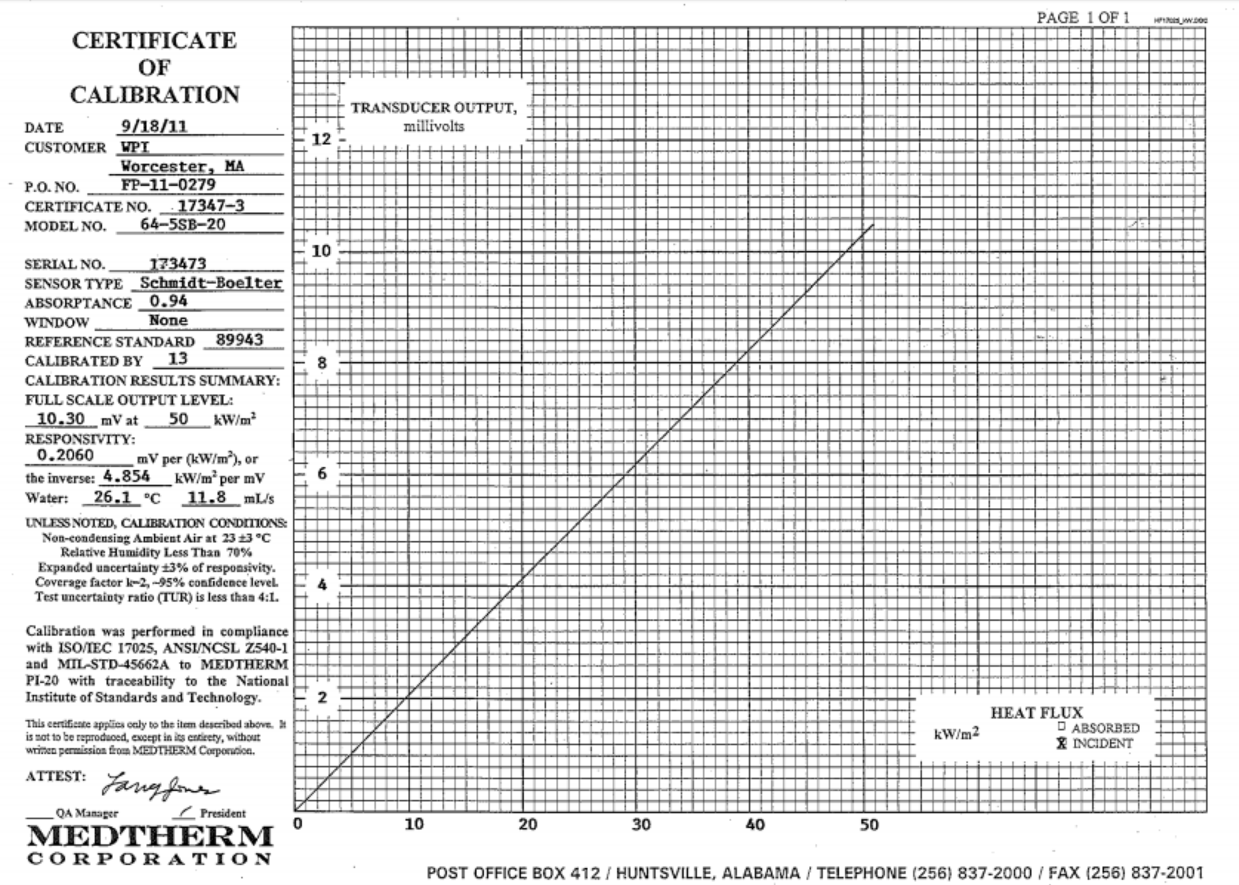
10.3 Appendix C: Pictures of Initial Drawer Designs







10.4 Appendix D: Certificate of Calibration for the Heat Flux Gauge



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CERTIFICATE OF CALIBRATION

DATE 9/18/11
CUSTOMER WPI
Worcester, MA
P.O. NO. FP-11-0279
CERTIFICATE NO. 17347-3
MODEL NO. 64-5SB-20

SERIAL NO. 173473
SENSOR TYPE Schmidt-Boelter
ABSORPTANCE 0.94
WINDOW None
REFERENCE STANDARD 89943
CALIBRATED BY 13
CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
10.30 mV at 50 kW/m²
RESPONSIVITY:
0.2060 mV per (kW/m²), or
the inverse: 4.854 kW/m² per mV
Water: 26.1 °C 11.8 mL/s

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

This certificate applies only to the item described above. It is not to be reproduced, except in its entirety, without written permission from MEDTHERM Corporation.

ATTEST:

QA Manager ✓ President

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10.5 Appendix E: Hose Failure Photos