The Conductive Performance Assessment Apparatus: The Design and Development of a Rigorous Conduction Test for Fire Attack Hoses

A Major Qualifying Project Report
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Abstract

Recent events have shown that fire attack hoses are burning through on the fire ground, leaving firefighters without water and putting their lives at risk. To address this concern, the National Fire Protection Association (NFPA) is contemplating how to revise its standard to include a more rigorous thermal performance test for fire hoses when no rigorous standardized tests currently exist. The Conductive Performance Assessment Apparatus was designed and created for this exact purpose, to expose hoses to conductive heat transfer at intensities similar to those found on the fire ground. If adopted into the national standards, this apparatus will eventually be used to test all new hoses entering the fire service.

Acknowledgements

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1.0 Introduction

The fire attack hose serves two main purposes: carrying the water that is crucial for fire suppression and providing firefighters with a lifeline to safety. The temperatures and conditions of the modern day ground have led to fire attack hose failures, some which resulted in fatalities. Standard hose construction methods and materials have remained constant for over 50 years, while the intensity of conditions on the fire ground have changed drastically. The result is two-fold, that materials used in the construction of fire attack hoses such as nylon 6.6 and polyester have decomposition temperatures hundreds of degrees lower than the temperatures they are exposed to and fire hoses currently manufactured meet a standard that does not require them to be to tested at conditions representative of a modern day fire ground.

1.1 Fire Ground Conditions

Modern day fire ground environments have evolved over the past several decades, resulting in more intense fire conditions. Residential structures are becoming larger, allowing for increased fuel loads. Also, open floor plans, which lack passive containment, are becoming more common. Newly-engineered glued beams and synthetic building materials, which ignite more easily and promote faster flame spread, have replaced traditional wood frames. Also, household items, such as furniture, electronics and appliances are more abundant and now constructed from more combustible synthetic materials. These new structure designs, building materials, and household commodities have led to more rapid fire growth and intense fire conditions. As a result, modern structures are reaching flashover conditions at a rate eight times faster than structures from fifty years ago. According to *Analysis of Changing Residential Fire Dynamics* published by UL, residential fire room temperatures often reach temperatures of 400°C (750°F), and can even get as hot as 1200°C (2190°F). While fire ground conditions have changed dramatically, fire attack hose construction has remained constant for over 50 years, even with the advent of more thermally resistant materials that have been incorporated in fire fighter PPE.

1.2 Construction of Fire Hoses

Structural firefighting is divided into two main categories- industrial and municipal. This study focuses on the fire attack hoses used for municipal firefighting, which involves residencies and commercial occupancies. These hoses are typically “lay-flat” and non-rigid, which makes them easily maneuverable while empty and facilitates efficient storage on fire engine hose beds. The majority of municipal fire attack hoses are purchased with nominal flow diameters of 1 ¾” or 2 ½” inches to optimize the volumetric flow rate of water onto the fire and the nozzle back pressure experienced by firefighters. Most models offer a range of diameters between 1 and 3 inches although the extremes are less commonly used by fire departments. The hoses are manufactured in lengths of 50 feet, can be coupled together to create a longer line if necessary, and are service tested to operate under pressures up to 400 psi [1]. In terms of weight, a 50ft length of 1-¾ inch diameter municipal fire attack hoses typically ranges from 12-23 lbs. A 2-½ inch line of the same length would be proportionally heavier. However, a lighter hose is preferred by firefighters as it is easier to maneuver in and out of burning buildings, especially those with multiple stories. The difference in weight between hose models is due to differences in material density and quantity.

There are the three principal lay-flat hose structures: single jacket, thru-the-weave extrusion, and double jacket. Single jacket hoses are most commonly used in industrial applications. Modern single jacket fire attack hoses are manufactured by bonding a single layer of woven fabric to an inner elastomer liner. These hoses have lower durability and are intended for less frequent use and less severe environments. Single jacket hoses are also convenient in situations where a lighter weight hose is preferred, such as high-rise firefighting. Thru-the-weave extrusion hoses are used both as fire attack hoses and water supply hoses, although they are less commonly used as fire attack hoses. Thru-the-weave extrusion hoses may be single or double jacketed, however, they differ from traditional single and double-jacketed hoses in how their inner jacket and liner are pressed into each other to form an interlocking weave. Double jacketed hoses are the norm when fighting municipal fires. The modern double jacketed fire attack hose consists of two layers of woven fabric, one of which is bonded to an inner liner. These hoses are used in situations where particularly harsh conditions and frequent use are expected [1]. This project will focus on modern, double jacketed fire attack hoses of various common sizes. The key components of these hoses are the inner liner, jacket material, and coating.

1.2.1 Liner Material

The inner liner maintains the hose's form and allows water to flow through without leaking or corroding the outer jacket material over time. Fire attack hoses are most commonly lined a with thermosetting synthetic rubber, such as ethylene propylene (EPDM rubber), or a thermoplastic material, such as polyurethane (TPU). Some fire attack hoses have liners made of nitrile, although this is less common. EPDM has the appearance of regular black rubber. EPDM is the synthetic rubber most commonly used in municipal fire hose liners. EPDM has a minimum service temperature of -60℃ and a maximum service temperature of 300℃.This material is used in fire attack hoses due to its high elasticity and strong resistance to heat, ozone, and weather [2]. TPU is the thermoplastic elastomer most commonly used in municipal fire hose liners. TPU is very versatile and has a high elongation and tensile strength, as well as the ability to resist oil, solvents, chemicals, and abrasion [3]. This material has a mildly transparent appearance.

1.2.2 Jacket Materials

The outer jacket is what protects the watertight liner and/or inner jacket from heat, abrasion, and puncturing [4]. Current fire hose jackets are manufactured almost exclusively with synthetic materials. Either nylon 6.6 or polyester fibers constitute the jackets of nearly all fire attack hoses on the current market. Polyester is crease-resistant, has the ability to retain its shape even when affected by moisture, dries quickly, and is resistant to light and weather [5,6]. Polyester fibers have a melting point temperature of approximately 250℃. In comparison, nylon 6.6 is known for its strong abrasion resistance and overall toughness. In general, this means that nylon 6.6 has a relatively long service life. The melting temperature of nylon 6.6 is slightly higher than that of polyester at 255℃ [6,7]. For both materials, their melting points allow them to survive most ambient conditions, however, contact with hot gas flows, flames or hot surfaces sufficient to heat the hoses at or above these temperatures causes material degradation or melting.

1.2.3 Coatings

A majority of fire attack hoses are sold with their jackets treated with a coating meant to enhance the hose performance on the fire ground, as well as increase the overall lifespan by preventing unnecessary wear and tear. The exact composition of the jacket coatings varies with each manufacturer and in many cases the exact composition of the coating material is considered a trade secret, limiting the information available about them. However their intended purposes can be categorized. The coatings tested were designated by manufacturers to provide either abrasion resistance or abrasion and heat resistance to the hose jackets they are applied to.

1.3 Lessons learned from the Fire Attack Hose Burn-through Database

Last year a team of WPI Students started a project to investigate fire attack hose burn-throughs in order to determine the significance of the problem within the fire community. The first ever Fire Attack Hose Burn-Through Database was created to catalogue fire hose burn-throughs in the United States [18]. It relies on the fire community to report burn-throughs that they experienced. Over 170 burn-throughs were reported in the first year alone, which clearly demonstrates that fire attack hose burn-throughs are not infrequent events.

Of the burn-throughs reported, 90% occurred due to conductive heat transfer. Conduction is the diffusion of heat by molecular activity from warmer to cooler bodies and requires direct physical contact between the two [8]. On the fire ground conductive heat transfer can occur either from debris falling onto the hose or from the hose being run across a hot surface. On July 11, 2011 in Tonawanda, NY a fire occurred in a residential home. A flashover had occurred prior to firefighter entry which cause the metal treatment on the back door to heat up to an extremely high temperature. When an attack team entered the building, the hose was dragged over the metal treatment and burst leaving two firefighters trapped in the house. Thankfully both firefighters were able to backtrack out of the building safely.

An example of debris falling onto the hose occurred on November 8, 2014 in Worcester, MA in a residential fire, Metal debris fell onto the hose which was caused the hose to lose pressure and burst. Debris in a fire often reaches extremely high temperatures. For example, pressed fiber insulation board, a common material used in buildings, can smolder and reach temperature between 770-790°C, and charred wood can reach temperatures up to 800°C [9,10].

2.0 Background

2.1 Existing National and International Standards

NFPA develops and publishes a set of codes and standards for public fire protection in the United States. NFPA 1961: Standard on Fire Hose, states the design, construction, inspection and testing requirements for all newly manufactured fire hoses. Fire attack hoses are manufactured to meet NFPA 1961 because of its widespread adoption in jurisdictions across the country. This standard includes kink tests, burst tests, and proof tests. NFPA 1961 does not explicitly define the testing method for heat resistance, but rather states that fire attack hoses must comply with heat resistance tests from UL 19, FM 2111 or an equivalent test. FM Approvals and Underwriters Laboratories (UL) are large scientific corporations that release standards for the quality assessment of various products [11]. The conductive heat resistance test set forth by UL 19 and FM 2111 involves heating a 2.5 x 1.5 x 8 inch steel block to 260 C (500° F) before stamping it on a water filled hose for 60 seconds. After 60 seconds, the steel block is removed, the hose is allowed to cool, and it is then pressurized to three times its service test pressure. If there is no leakage or damage that can be observed, the hose is considered to have passed the test [12].

When looking at international standards it was found that, like the US, most countries only require hoses to withstand a conduction test. It is notable, however, that international standards utilize temperatures and durations significantly higher than those used in NFPA 1961. The British standards provide an example that is consistent with standards used in other international countries. The BS 6391 Hot Surface Resistance Test requires fire hoses to be pressurized and exposed to a 300°C or 400°C filament rod for two minutes. The filament rod maintains a constant temperature and pressure on the hose, and the hose is placed vertically with the filament rod oriented horizontally. If the hose does not burst or leak, it passes the test [13]. The BS 6391 Heat Resistance Test requires a steel cube to be heated to 600°C, then stamped on a fire hose for 15 seconds. If the hose does not leak or burst during the duration of the tests, the hose is said to have passed [13].

The current conduction test for fire attack hoses included in NFPA 1961 has several limitations which include an unrealistically low heat stress not representative of the severity of the fire ground conditions and multiple problems that limit the repeatability of the test. Almost all the tests in NFPA 1961 require the hose to withstand conditions far above what they experience during regular use. For example, the pressure test requires hoses to withstand a pressure three times higher than a typical service pressure. The one exception is the conduction test. The conduction test only subjects hoses to a temperature of 500° F even though temperatures on the fireground are hundreds of degrees higher than that. NFPA 1971: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting requires much more rigorous thermal tests for footwear, even though footwear and hoses are exposed to identical conditions on the fire ground.

Additionally, the steel block begins to drop in temperature as soon as it is removed from the oven due to convective and radiative heat losses. By the time the block is stamped on the hose it is an unknown number of degrees cooler than when it was first removed from the oven. First, the NFPA 1961 conduction test allows for 5% variability in temperature. This allows for the temperature of the block to range from 475° F-525° F when it is removed from the oven. The block is also not placed consistently every test due to human error. All of these limitations result in a conduction test in NFPA 1961 that is not sufficiently repeatable.

2.2 Previous Work

A team of WPI students in 2015 took on the challenge of designing a more rigorous conduction test. A rigorous conduction test, hereby known as the "Hot Plate" test, was developed [14]. The Hot Plate test utilized a controlled hot surface to impart a conductive heat flux on a hose. The Hot Plate test apparatus went through a total of three design iterations. These iterations were aimed at advancing the rigor, repeatability, and realism of the test while attempting to debug data inconsistencies caused by water-damage and hose placement.

The 2015 team experienced several difficulties while designing their conduction test. A major problem occurred when the hose failed. The water that burst out of the hose would get into the electrical components of the hot plate, causing short-circuits. Further, the water that burst from the hose would dampen segments of the hose that were to be tested in later trials. This required a long intermission between trials to allow the hose to dry. If the hoses were not completely dry before the next trial, the damp hoses would exhibit different heat transfer characteristics than dry hoses. In another design in which the hot plate was stamped onto the hose, the aluminum extrusions and linear bearings used did not possess the high tolerances of more expensive, fluid lubricated linear rods and bearings. The mechanism used in this design was non-lubricated and required a larger amount of "play" to work properly. As a result, a discrepancy of four-to-six thousandth Newtons existed between the translating rods and the bearings causing a different amount of pressure to be exerted onto the hose each time. Data collected from using the hot plate test was largely inconclusive [14].

2.3 Goals

The goal of this project was to design a test to measure performance of a fire attack hose when subjected to a steady state conductive heat stress. This test should be accurate and repeatable, and not subject to previous errors. The test requires a degree of rigor where the hose is tested at temperatures closer to those that a hose will be exposed to on a modern day fire ground.

3.0 Methodology

The methodology provided the road map by which the project goals were met, the Conductive Performance Assessment Apparatus was designed and built, and the test apparatus and testing procedure was verified and validated.

A multi-part methodology was used in completion of this research. Design criteria were selected, that, if met, would ensure that the project goals would be achieved. These design criteria, in turn, guided the specifications of components for the apparatus. Table 1 displays the relationship between the project goals, the design criteria, and the design components. After the design components were specified, a prototype of the test apparatus was built and subsequently underwent testing to assess its performance.

Project Goals	Design Criteria	Design Components
Steady State Heat Stress	Constant Temperature	Strip Heater
Accurate and Repeatable	Constant Force	Hinge Mechanism
	Constant Temperature	Strip Heater
	Durable	Aluminum Framing, Stainless Steel and Aluminum Hardware
	Low Cost	Inexpensive Aluminum Framing
	Easily Quantifiable Pass/Fail Data	Pressure Transmitter
Eliminate Existing Conduction Test Problems	Constant Force	Hinge Mechanism
	Protection of Excess Hose	Tarp
	Heat Source without Integrated Electronic Components	Control Circuit - Solid State Relay and a PID controller
More Realistic Temperatures	Increased Temperature	Control Circuit/Strip Heater
	Variable Temperature	Control Circuit/Strip Heater

Table 1: Summary of Project Goals, Design Criteria, and Design Components

3.1 Design Criteria

There are nine design criteria, of which, one or more facilitate each of the project goals. The design criteria of maintaining a constant temperature is necessary to allow the apparatus to provide a steady heat stress throughout the test duration and to ensure accuracy and repeatability. The design criteria of maintaining constant force facilitates the goal of an accurate and repeatable test and the goal of eliminating existing conduction test problems. The design criteria for easily quantifiable pass/fail data allows the apparatus to deliver clear, repeatable results when testing fire attack hoses. Durability and low cost allow the apparatus to provide more accurate and repeatable results. The protection of excess hose along with utilizing a heat source without integrated electronic components eliminate existing conduction test problems. The design criteria of increased/variable temperature will ensure higher and more realistic temperatures.

3.2 Design Components

Each design component is a physical part selected from commercially available sources or custom designed and built for its ability to meet the design criteria. For example, a heating element was selected that would be able to cycle above a below a set temperature while remaining within a close range of that temperature. Also, a hinge mechanism was designed to apply a constant force. Various methods were used to help select appropriate design components. Engineers at Omega Engineering were consulted for their expertise in designing control circuits. Their recommendations were used to select the appropriate components for the control circuit and data acquisition systems. Lab managers here at WPI also recommended components to be used for the design. Research was conducted to ensure that the design components would meet the design criteria. The design components that were selected were used to build the prototype of the test apparatus.

3.3 Design and Build Prototype

After components meeting the design criteria were selected, the next step was to design and build a prototype of the test apparatus. After the prototype was designed and built, it underwent testing to assess its capabilities. The Conduction Performance Assessment Apparatus was assembled in the WPI Fire Protection Lab under the supervision of Raymond Ranellone Jr. Most parts were obtained through orders from engineering supply companies, but some parts were machine in the lab. First, the performance of individual components had to be verified. After verification of individual components, the entire system was tested as a whole. If the prototype failed during either the verification or validation stage then a design iteration would have to be undertaken. Testing was undertaken in the WPI Fire Protection Lab.

3.4 Verification of Components

An important part of the design process is the verification of the design components. Verification of a component involves testing that component to ensure that it performs as intended. If individual components do not work as they are supposed to then the apparatus as a whole will not meet design goals. The components needing verification were the heating element and the hinges. The verification of the heating element consisted of two parts. First, verification that the thermocouple attached to the heating element was accurately reading the temperature of the heating element. Second, verification that the controller was able to keep the temperature of the heating element within a small margin of error of the desired temperature. The verification of the hinge ensured that each time the hinge was placed on the hose it contacted the hose in the same location and applied the same amount of force to the hose. After the single component verification test the components were again verified when operating as a system.

3.5 Validation of Apparatus

Validation tests were conducted to determine whether that the apparatus could be used for successful conduction tests. A conduction test is considered successful if the apparatus works as intended and it can be determined whether a hose passes or fails. Conduction tests were performed on two different hoses, at two different temperatures. Hoses of different diameters were used to show that the apparatus is capable of testing different sized hoses. Additionally, hoses of different sizes have different thermal conduction properties because of the differing masses of water in the hoses.

4.0 Design of Test Apparatus

The test apparatus was designed to accurately and reliably expose fire attack hoses to conductive heat transfer. The test apparatus was designed to be structurally durable and to apply a conductive heating element uniformly to hoses being tested. Several concepts were considered before a cantilevered design that met all the design criteria was chosen. The final apparatus consists of four main parts: the frame, the cantilevered arm, the heating element, and the control/data acquisition system. The hose is held into place by clamps in front of the testing apparatus. Then the heating element, which is attached to the end of the cantilevered arm, is lowered onto the hose and subjects the hose to conductive heat transfer. The frame provides a durable and sturdy platform for the heating element and the cantilevered arm. The control and data acquisition system controls the temperature of the heating element, records the temperature of the heating element, and records the pressure in the hose. An appropriate power system supplies enough electrical power to support the operation of the apparatus. A CAD drawing of the apparatus is shown in Figure 1.

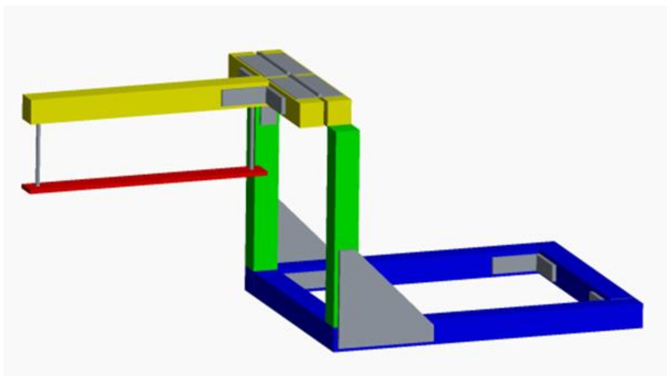

Figure 1: CAD Drawing of Test Apparatus

4.1 Heating Element

The selected heating element is a model CSH00024 Electric Strip Heater from Omega Engineering, shown in Figure 2 [15]. The strip heater is 1 ½ inches wide and 12 inches long with a 1-inch mounting tab on each end. The strip heater consists of inner coils covered in a stainless steel sheath. It operates by allowing a current to travel through the coils. The resistance provided by the coils transforms the electrical energy into thermal energy, which heats up the stainless steel sheath. The stainless steel sheath then transfers the thermal energy via conduction to the fire hose. The maximum sheath temperature is 1200 F. The strip heater is powered by 120VAc current and has a maximum power output of 400 W.

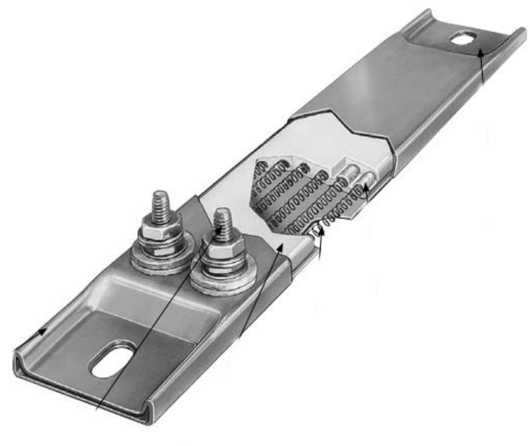

Figure 2: Cutaway Diagram of Strip Heater

4.2 Cantilevered Arm/ Hinge

The cantilevered arm is 15 inches long and constructed of t-slotted aluminum extrusion. It is attached to the support arm of the frame by two stainless steel hinges, seen in Figure 3. It is attached to the heating element with two stainless steel studs. On the top of the cantilevered arm are several iron-based bolts. These are used to attach the magnetic level, since the aluminum that makes up the rest of the apparatus is non-magnetic.

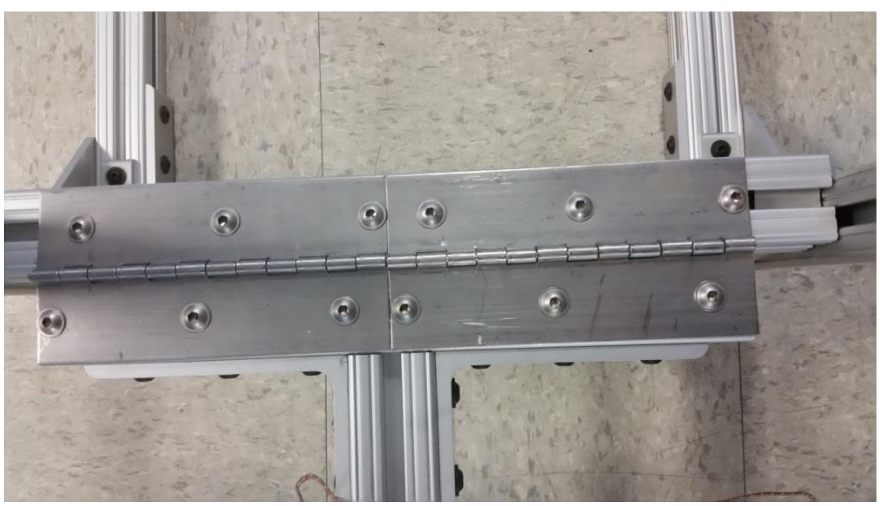

Figure 3: Top-down View of Hinges

4.3 Frame

The frame is constructed of t-slotted aluminum extrusion and utilizes both aluminum and steel hardware. The frame consists of a wide base, seen in Figure 4, which measures 18 inches by 18 inches with two 12 inch "support posts" rising from adjacent corners of the base. Connecting the two support posts is a 15 inch piece of aluminum extrusion, which is referred to as the "support arm". Attached underneath the support arm are two L-brackets connecting the support arm to the support posts, seen in Figure 5. By loosening the screws in the support posts, the support arm can be raised or lowered, which allows the apparatus to be adjusted for hoses of various diameters. Additionally, the apparatus is secured to a plywood base with L-brackets and screws to ensure maximum stability, seen in Figure 6.

Figure 4: Base of Apparatus

Figure 5: L-brackets on Support Post

Figure 6: Wooden Base for Apparatus

4.3.1 Hose Positioning

The hose is positioned in front of the testing apparatus, perpendicular to the heating element, seen in Figure 7. The hose is at a distance such that the center of the heating element makes contact with the top of the hose when the cantilevered arm is lowered. Two clamps are used to hold the hose in place, seen in Figure 7. The clamps are attached to the plywood base to ensure a consistent positioning of the hose. One clamp is used to prevent water from leaving the end of the hose in order to maintain a constant pressure in the hose. The other clamp is used only to hold the hose in place.

Figure 7: Hose Positioning

4.4 Control/Data Acquisition

In order to set and maintain the temperature of the heating element a control circuit consisting of a solid state relay and a PID controller was implemented. The solid state relay is a model SSRDC100V from Omega Engineering [16]. The PID controller is a model CN74000 from Omega Engineering [17]. The PID controller monitors the temperature of the heating element via Type-K thermocouple attached to the surface of the heating element. The solid state relay acts as a switch to regulate current to the heating element. The solid state relay, the PID controller, and the heating element are powered by a 120VAc wall outlet. A picture of the PID controller is shown in Figure 8. A wiring diagram for the control and data acquisition system is shown in Figure 9.

Figure 8: PID Controller

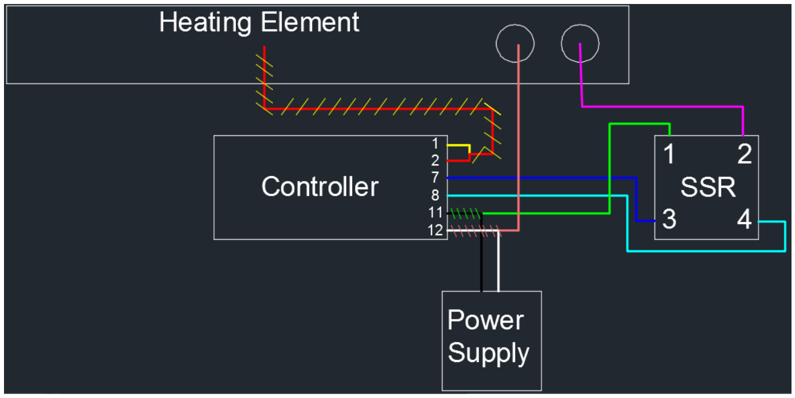

Figure 9: Wiring Diagram

During each test, the temperature of the heating element and the pressure of the fire hose are collected. The temperature is recorded using a Type-K thermocouple connected to the PID controller. The pressure data is collected using a Wika Type A-10 General Purpose Pressure Transmitter connected to a National Instrument NI-9201 +/-10V Analog Input Module. A National Instrument LABVIEW SignalExpress software is used to record the temperature and pressure data.

4.5 Cost

The apparatus was designed as economically as possible. Cost was a factor in determining which components to use in the apparatus. The total cost of the apparatus, data acquisition, and controller was $669.28. While more money is capable of buying better components, the components selected for the apparatus met our design criteria. A table summarizing the total costs is shown below in Table 2.

Component	Price
Framing	$169.09
Hardware	$140.19
Heating Element	$64
Electronics	$296
Total	$669.28

Table 2: Total Cost of Apparatus

4.6 Problems Encountered

During the design phase and the testing phase several design challenges were encountered. They were each addressed before finalizing the design.

4.6.1 Design Issues

Thermocouple did not read an accurate temperature on the heating element

The preliminary design for attaching the thermocouple to the heating element consisted of securing the thermocouple to the heating element with high-temperature cement. Then, the thermocouple was wrapped with insulation to eliminate heat loss to the air and allow the thermocouple to make an accurate reading. Two problems arose with this design. First, when applying cement it was impossible to completely eliminate air pockets in between the thermocouple and the cement. This meant that the thermocouple could not read the temperature of the heating element accurately. Second, the cement was not strong enough to hold the thermocouple in place. When applying the cement the first few times the thermocouple shifted during drying. Subsequent attempts used clamps to hold the thermocouple in place during further applications. Unfortunately, even after the cement dried it was not strong enough to hold the thermocouple in place if it experienced even a minor bump.

The solution to this problem was to place the thermocouple underneath one of the terminals on the strip heater. Although this part of the heating element did not get as hot as the center, the temperature at the terminal was able to be correlated with the temperature at the center of the heating element, which is the hottest part. Although in theory the correlation would work, the controller was not able to keep the center of the heating element at a constant temperature, only the point at the terminal. The point at the terminal was at a constant temperature, but the center of the heating element could vary up to 50 F. Since testing would occur at the center of the heating element, a new solution was needed.

A second, successful, solution was implemented. A small post was attached below the cantilevered arm on the apparatus. Then, the thermocouple was placed in between this post and the heating element (see Figure 6.1). When the heating element was raised into place and secured, the thermocouple stayed firmly in place between the heating element and the post. This design proved successful for the rest of the verification testing.

4.6.2 Testing Issues

Hose melting and forming a seal with the heating element

Two modes of hose failure were observed during validation testing. The first method of failure was an explosive burst. When this happened, the depressurization of the hose would propel the cantilevered arm off of the hose and into the resting position while most of the water from the hose left the hose in a single, large burst. The second mode of failure was a sustained leak. This mode of failure saw the water leave the hose much more slowly, through smaller openings than the burst failure. It also did not propel the heating element off of those hose. It was determined that the behavior of the material in the hose contributed to leak failures. When the hose melted, it often formed a "seal" with the heating element which prevented water from leaving the hose. Thus, water could squirt out in small amounts around the heating element, but could not leave through the large hole covered by the heating element.

The issue that arises from leak failures is that it is not possible to determine when the hose fails, only if it fails. This is because the heating element is manually removed at the end of the test. At this point it is possible to determine whether failure occurs or not. Before the end of the test, however, there is no discernible difference between a hose that hasn't failed and a hose that has failed, but has sealed to the heating element.

Thermocouple insulation became wet and allowed the thermocouple to slip out of position

When hose failure occurred, sometimes the water leaving the hose would soak the insulation holding the thermocouple in place. Once the insulation was wet it was unable to hold the thermocouple in place or insulate the thermocouple properly which in turn led to inaccurate temperature measurements. This issue was mitigated by the time during which it occurred. Due to its nature, it only happened after the failure of a hose. Once a hose fails, temperature measurements are not necessary. This problem was addressed by performing a quick verification test on the thermocouple after each test that resulted in failure. If the temperature reading was obviously inaccurate or if a hand-held multi-meter read a different temperature then the heating element would be unmounted, the insulation would be replaced with new, dry, insulation, the thermocouple would be repositioned, and the heating element reattached.

5.0 Verification of Design

An important part of the design process is the verification of the components. If individual components do not work as they are supposed to then the apparatus as a whole will not meet design goals. The components of the apparatus design that were verified were the heating element and the hinges.

The verification of the heating element consisted of two parts. First, it was verified that the thermocouple attached to the heating element was accurately reading the temperature of the heating element. Second, it was verified that the controller was able to keep the temperature of the heating element within a small margin of error of the set temperature. The verification of the hinge ensured that each time the hinge was placed on the hose it contacted the hose in the same location and applied the same amount of force to the hose.

5.1 Heating Element

The first verification test ensured that the attached thermocouple was reading the temperature of the heating element accurately. To conduct this verification test, the temperature of the heating element was measured with a completely insulated standalone thermocouple and a multi-meter. An insulated thermocouple would give the most accurate results. If the temperature displayed by the PID controller matched the temperature read by the multi-meter, it could then be determined that the thermocouple attached the heating element was giving accurate readings. The heating element began at room temperature and was allowed to heat up to 700 F. The temperature measured by the installed thermocouple and the multi-meter was observed and compared throughout the test. Visual verification confirmed that the temperature of the installed thermocouple and the standalone thermocouple were the same. Once it was verified that the installed thermocouple was reading the temperature of the heating element correctly the second verification test could be conducted.

It was necessary to ensure that the heating element could maintain a constant temperature before performing any testing involving hoses. The heating element was programmed to remain at a temperature of 700° F for 6 minutes. The temperature was measured every second over that period. The results of this verification test are shown below in Figure 10.

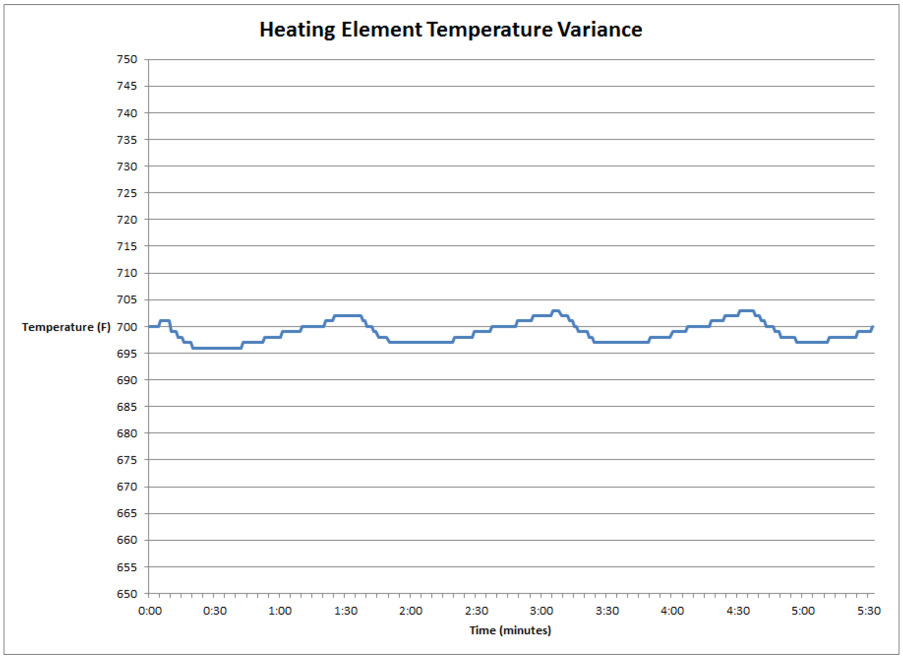

Figure 10: Heating Element Verification Test Temperature Data

The test was concluded after 5 minutes and 32 seconds because the PID controller had completed four complete cycles, i.e., the temperature had gone above and below 700° F four times. The temperature stayed between 696° F and 703° F for the entire test. This resulted in an error of ±0.57%. The median temperature was 699° F and the mean temperature was 698.9° F.

5.2 Hinges

The first step in the positioning test was to pressurize the hose to 120 psi; the pressure validation testing would be performed at standard operating pressure. The heating element was left at room temperature and was lined up with a line stamped on the hose. The cantilevered arm was raised and lowered five times. Each time the level was lowered, the level indicated that the cantilevered arm was level and the heating element lined up with the line on the hose. This satisfied the positioning verification test.

To measure the amount of force the hinge applied, the cantilevered arm was lowered onto a force plate multiple times and the force applied was recorded. The force test was performed 10 times. The results from the force test are shown below in Figure 11.

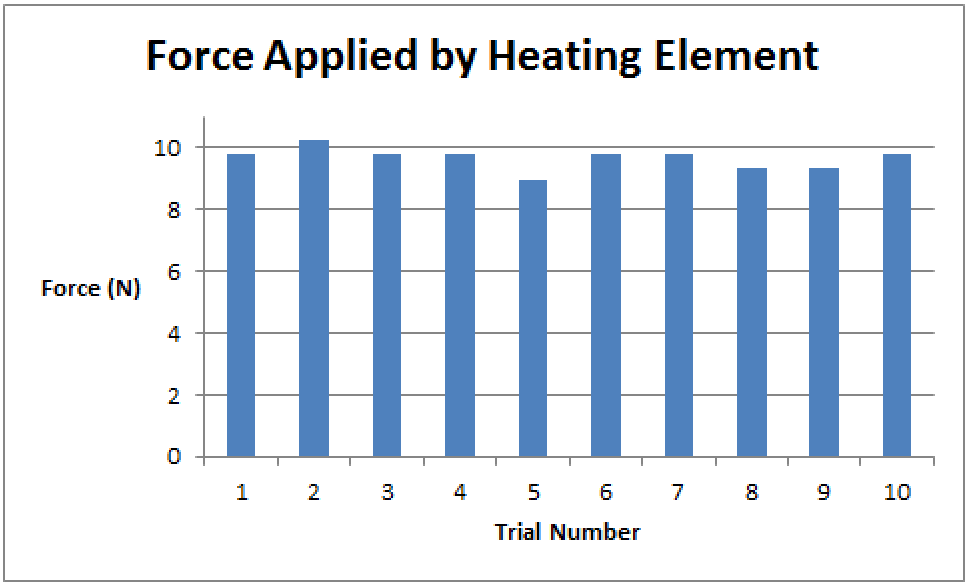

Figure 11: Force Application Verification Test Data

The force test resulted in an average value of 9.67 N, a median value of 9.8 N, and a standard deviation of ±0.367.

6.0 Validation of Test Apparatus

A series of 12 tests were conducted to demonstrate that the apparatus can operate and provide meaningful data for hoses of different diameters tested at a range of temperatures. A 1 ¾" hose and a 2 ½" were used during the tests. The tests were conducted at 500° F and 600° F. The 1 ¾" and 2 ½" hose were tested three times at 500° F and three times at 600° F to validate the test repeatability.

6.1 Findings/ Results

The apparatus worked exceptionally well during all of the tests at 500° F and 600° F. When the heating element came into contact with the hose it lowered in temperature slightly due to conductive heat loss to the hose. The controller was able to bring the temperature of the heating element back to the target temperature in a short amount of time. The controller was able to maintain the temperature of the heating element at a set point within an of error of less than 3% which is narrower than the 5% acceptable error in the current NFPA conduction test. For data from the tests performed please reference Appendix III

6.2 Hose Data Collected

The conduction test in NFPA 1961 considers a hose to have failed if it cannot be pressurized to its service pressure after the 60 second test. Since this apparatus is meant to replace the current NFPA conduction test, the same concept of failure was used during validation testing. Any hose that remained pressurized at 120 psi after the 60 second exposure to the heating element was considered to have passed the test. Any hose that failed to do so was considered to have failed the test. The pressure of the hose was observed at the end of each test. Pass/fail data from all six validation tests conducted on the 1 ¾" hose are shown below, in Table 3. The data in the table shows that the apparatus is able to perform repeatable tests on fire attack hoses that result in clear pass or fail outcomes.

1 3/4" Hose	
Test	Pass/Fail
500 F - Trial 1	Pass
500 F - Trial 2	Pass
500 F - Trial 3	Pass
600 F - Trial 1	Fail
600 F - Trial 2	Fail
600 F - Trial 3	Fail

Table 3: Pass/Fail Results for 1 3/4" Hose

6.3 Existing Problems Solved

One of the design goals was to address and eliminate all the problems encountered with previous designs. The main problems that were addressed were the hoses dampening, the electronics short-circuiting, and the hose lying flat during testing.

Hoses dampening

The MQP team last year encountered inconsistency in their tests when water from a test where a hose failed dampened the length of hose they were going to test next. The wet hose had different thermal properties than a dry hose and introduced variability into their tests. This problem was solved by covering the section of the hose not being tested with tarps to prevent water from soaking the hose.

Electronics getting wet and short-circuiting

Similar to the issue of the hoses dampening, last year's MQP team faced issues with their electronics short-circuiting after getting wet during tests where hoses failed. In order to prevent this from happening, several levels of prevention were used. Once the controller was set to the correct temperature, the controller and solid-state relay were placed inside of a plastic bag. The plastic bag was then placed inside of a waterproof box. Only the insulated wires coming out of the controller and solid-state relay came out of the box. Finally, a tarp was placed over the wires and box to prevent water from pooling around them.

Hose lying flat

Last year's MQP team faced issues in the repeatability of the placement of their heating element on the hose because their hose was not positioned identically during each test. This issue was solved with the positioning of the hose clamps. Although they are slightly elevated off of the ground, they are level with each other and close enough together that the hose is able to lay level between them. The water pressure in the hose further helps the hose stay rigid and level throughout the entire test. They are also wide enough that the hose can be moved closer to or farther away from the testing apparatus in order to make sure the heating element is positioned accurately.

7.0 Discussion and Conclusion

The Conductive Performance Assessment Apparatus designed and tested in this research provides the testing capabilities necessary to ensure firefighters are equipped with hoses that will meet the rigor of the modern day fire ground. The apparatus performed better than expected in both verification and validation testing. It was demonstrated that the apparatus is able to conduct conduction tests that provide more repeatable data than the test procedure currently used in NFPA 1961. If this apparatus is implemented into the conduction test in NFPA 1961, it can be assured that every NFPA stamped hose will be exposed to the same thermal stress during conduction testing. It was also demonstrated that the apparatus is capable of performing conduction tests at temperatures higher than 500° F. If the standard for fire attack hoses requires them to be tested at temperatures closer to those they will face on the fire ground then the chance of a burn-through occurring decreases. If the standard is updated to include this higher temperature, the apparatus will still be capable of performing repeatable tests. Fewer burn-throughs means that firefighters will be safer when fighting fires and their ability to protect civilians and property will be enhanced.

8.0 Future Work and Recommendations

The test apparatus met all of its design goals and is capable of functioning as a more reliable and repeatable conduction test for fire attack hoses. The following recommendations are offered for the further refinement of the apparatus:

Employ a more powerful strip heater

The apparatus was able to perform tests at 500° F and 600° F with no issue. When the heating element was brought up to higher temperatures, however, it took longer to reach those temperatures and had some trouble maintaining those temperatures during testing. A more powerful strip heater would be able to overcome heat losses to the air and conduction losses to the rest of the apparatus. A more powerful strip heater would be able to perform tests even more similar to conduction temperatures hoses face on the fire ground. Additionally, no study was done on the effectiveness of the heating element after repeated use. If the heating element does lose effectiveness after repeated use, then it should replaced regularly in order to maintain maximum performance.

Insulate the parts of the strip heater not being used for testing

Even without a more powerful strip heater, more insulation on the heating element would result in higher temperatures and more steady temperatures during testing. By adding insulation to all parts of the heating element that are not required for testing, convection and radiation losses would be minimized. This would allow almost all of the power used by the heating element to be used for conduction heat transfer.

Design a better system for attaching the thermocouple

Although the positioning of the thermocouple worked during testing, the issue with wet insulation reduced the apparatus's ease of use. Changing the insulation and repositioning the thermocouple after failed tests is time consuming and can lead to error. A design that would prevent the insulation from getting wet would allow tests to be run without the concern of having to reposition the thermocouple.

Expand the validation of the apparatus through different types of hose

For a more rigorous verification of the testing apparatus performing tests a range of different types of hoses is suggested. Hoses have different liner and outer jacket materials, these materials all have different material properties which means they react differently when heat is being applied through a conductive force. Through past research it was found that EPDM lined hoses ruptured energetically, suffering an instantaneous and complete loss of pressure. On the other hand, TPU lined hoses slowly lost pressure through one or more pinhole- sized holes. If the apparatus can successfully test all different types of hoses, it will have achieved the goal of being a repeatable test.

9.0 References

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10.0 Appendices

Appendix I – Testing Procedure

Appendix I

Testing Document

MQP 3 - Fire Attack Hose Conduction Test

Contents

Testing Checklist

This checklist lists all the steps necessary to perform the fire attack hose conduction test. It is designed to be referenced during the test. For more detailed instructions see the “Testing Procedures” section. The “Testing Procedures” section should be reviewed completely before performing any tests.

1. Check to make sure all the electrical connections are secure
2. Position and pressurize the hose
3. Adjust the heating element to the proper height
4. Lift the cantilevered arm to the resting position
5. Turn on the heating element and wait for it to reach the set temperature
6. Place the cantilevered arm in the testing position so that the heating element makes proper contact with the hose
7. Leave the heating element on the hose for the prescribed length of time
8. After the prescribed time has passed (or when failure occurs), lift the heating element from the hose and place the cantilevered arm back in the resting position
9. Turn off the heating element and wait for it to cool before setting up the next test
10. If failure occurred, check the thermocouple and insulation to make sure it is dry and reading correctly

Testing Procedures

This section provides detailed instructions and references on how to properly perform the fire attack hose conduction test. This section should be reviewed completely before performing any tests. Once familiar with the “Testing Procedures” section, the “Testing Checklist” should be used during all tests to ensure all of the necessary steps are performed.

1. Check to make sure all the electrical connections are secure
    a. Wiring for the heating element, controller, and solid state relay (see Appendix I.B.1)
    b. Wiring for the pressure transducer and data acquisition software (see Appendix I.B.2)
2. Position and pressurize the hose
    a. For complete instructions on pressurizing hose see Appendix I.C
3. Adjust the heating element to the proper height
    a. Place the cantilevered arm in the testing position (See Appendix I.A.1)
    b. Loosen the two screws holding the support arm to the support posts. Adjust the height of the support arm until the heating element contacts the top of the hose and is level. (See Appendix I.B.3)
    c. Tighten the screws holding the support arm to the support posts, making sure that the support arm is level.
4. Lift the cantilevered arm to the resting position (See Appendix I.A.2)
5. Turn on the heating element and wait for it to reach the set temperature
    a. Turn on the heating element by plugging the power cord into a wall 120 Vac outlet
    b. In order to set the temperature to the desired temperature follow these instructions:
        i. Press the INDEX button until you reach the temperature menu
        ii. Use the UP and DOWN buttons until you reach the desired temperature
        iii. Press the ENTER button
        iv. Press the INDEX button until you return to the operation menu

            See Appendix I.A.3-I.A.5

            Note: Instructions for more advanced settings can be found with the documentation left with the testing apparatus or online at http://www.omega.com/Manuals/manualpdf/M4439.pdf
    c. The heating element is at the set temperature when the measured temperature on the operation menu matches the set temperature

        Note: Due to the way the controller operates the measured temperature is expected to fluctuate within ± 5^{o} F

6. Place the test arm in the testing position so that the heating element makes proper contact with the hose
    a. Proper contact is defined as contact between the heating element and the hose where the heating element is level and makes contact directly on top of the hose

       Note: Contact made during testing should be in the exact same position as the contact made in Step #3.

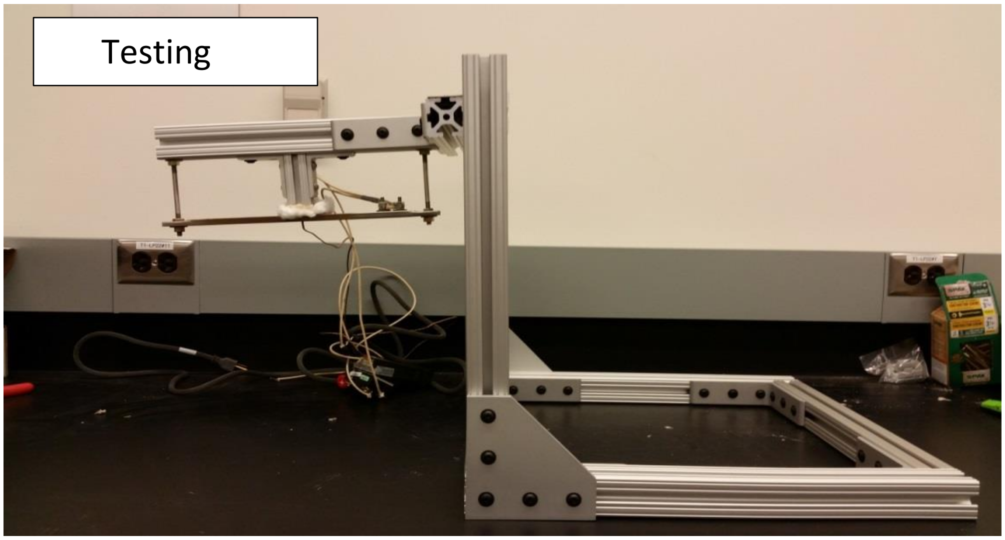
7. Leave the heating element on the hose for the prescribed length of time
8. After the prescribed time of time has passed (or at failure), lift heating element from hose and place the test arm back in the resting position
    a. Failure is determined by the moment the hose noticeably begins to lose pressure.
9. Turn off the heating element and wait for it to cool before setting up next test
    a. The heating element is turned off by unplugging the system from the wall
    b. Alternatively, the controller may be set to Automatic Control Mode and the Output set to 0%. This allows you to use to thermocouple to monitor the temperature of the heating element while it is cooling.

       Note: See the complete instructions for the controller for instructions on how to operate the controller in Automatic Control Mode

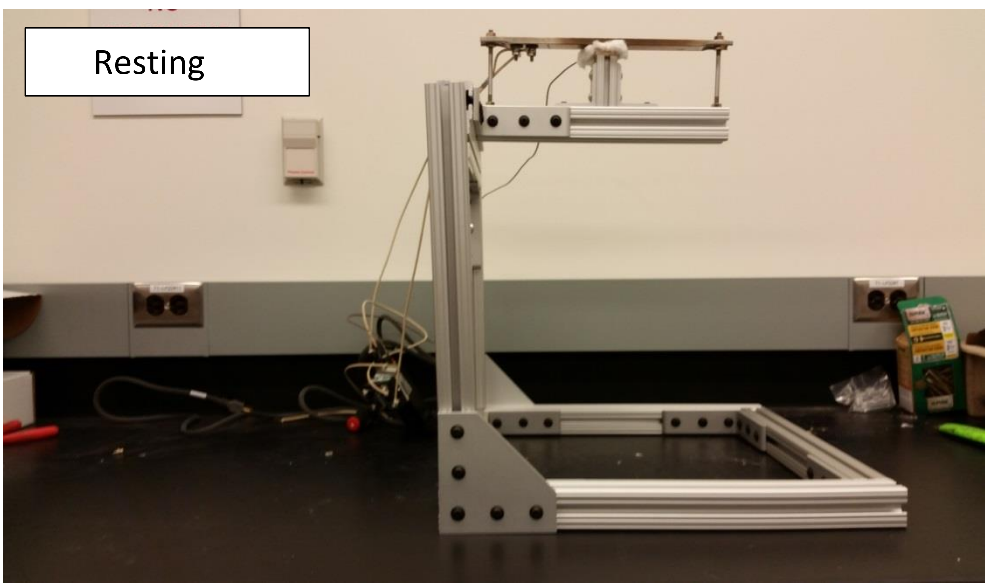
10. If failure occurred, check the thermocouple and insulation to make sure it is dry and reading correctly
    a. If the insulation around the thermocouple is wet, it must be replaced in order for the thermocouple to function correctly.
    b. To change the insulation, remove the nuts holding the heating element to the cantilevered arm and remove the heating element. Remove the wet insulation, dry the area, and place new, dry, insulation in place. Hold the thermocouple in place as the heating element is placed in position and the nuts are tightened. The thermocouple should be flat against the center of the heating element and should not be able to move.

Appendix I.A – Reference Pictures

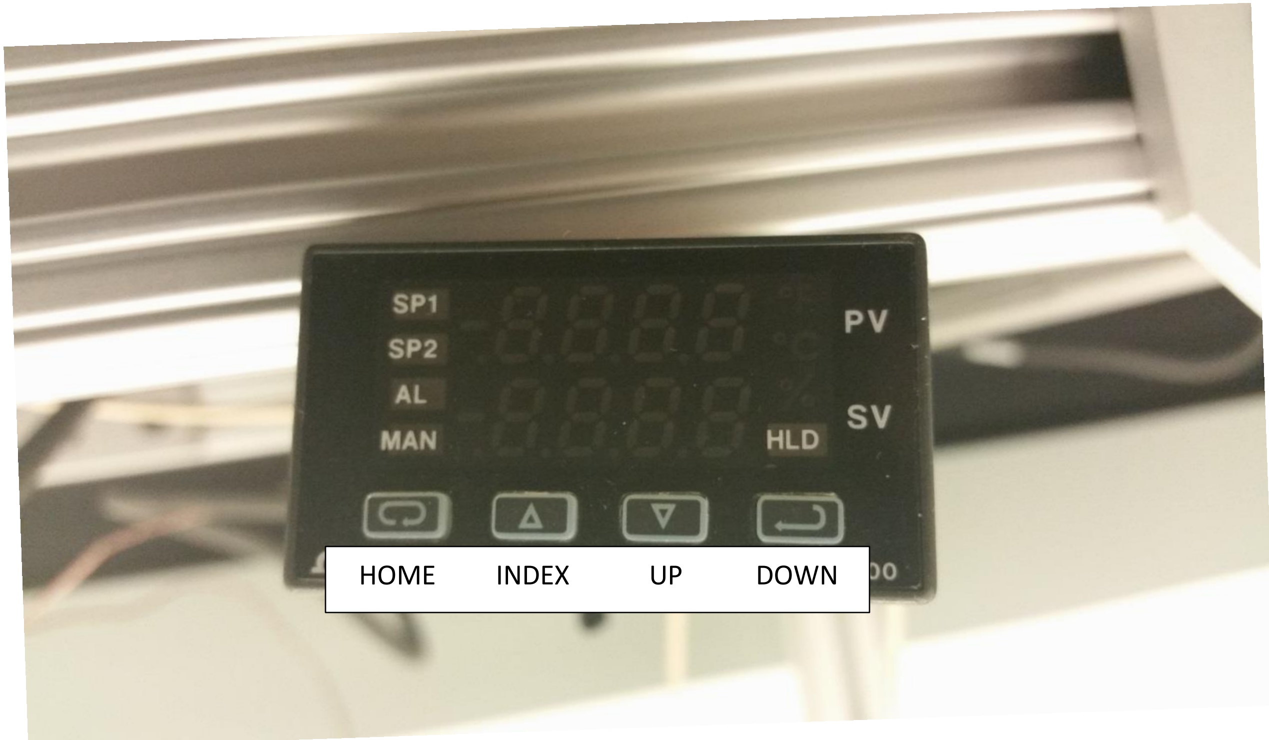
Appendix I.A.1



Appendix I.A.2

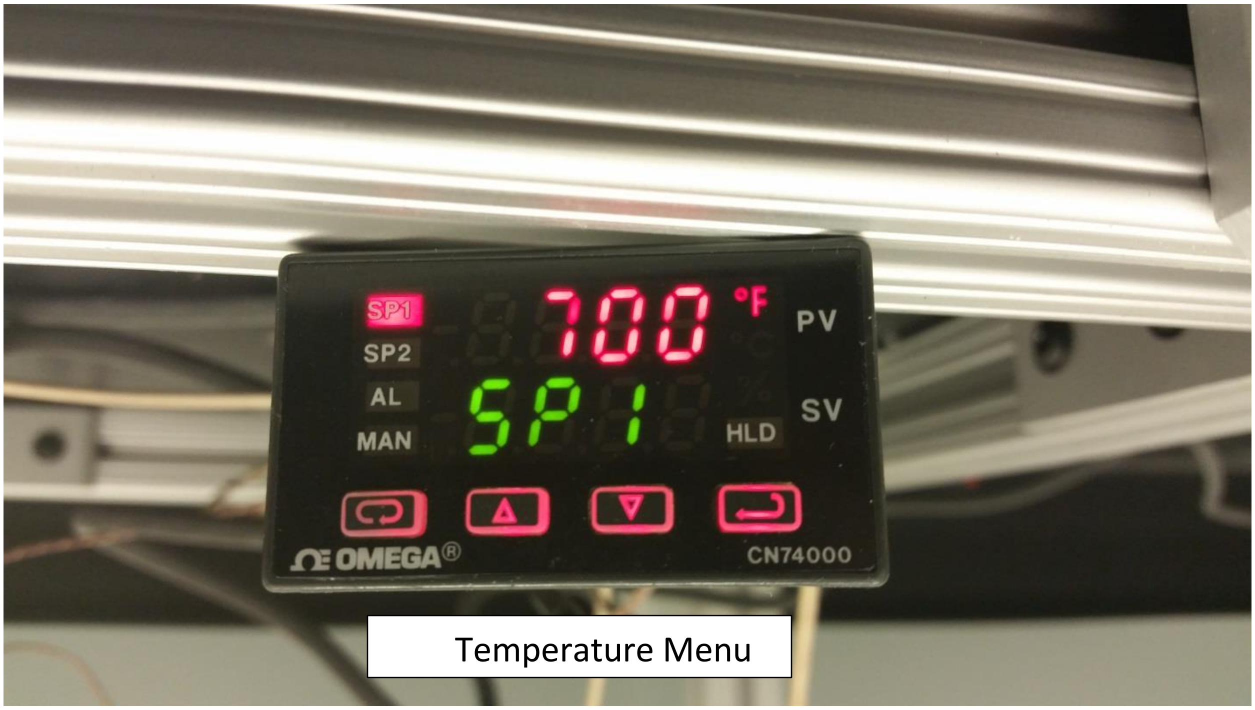


Appendix I.A.3



Appendix I.A.4

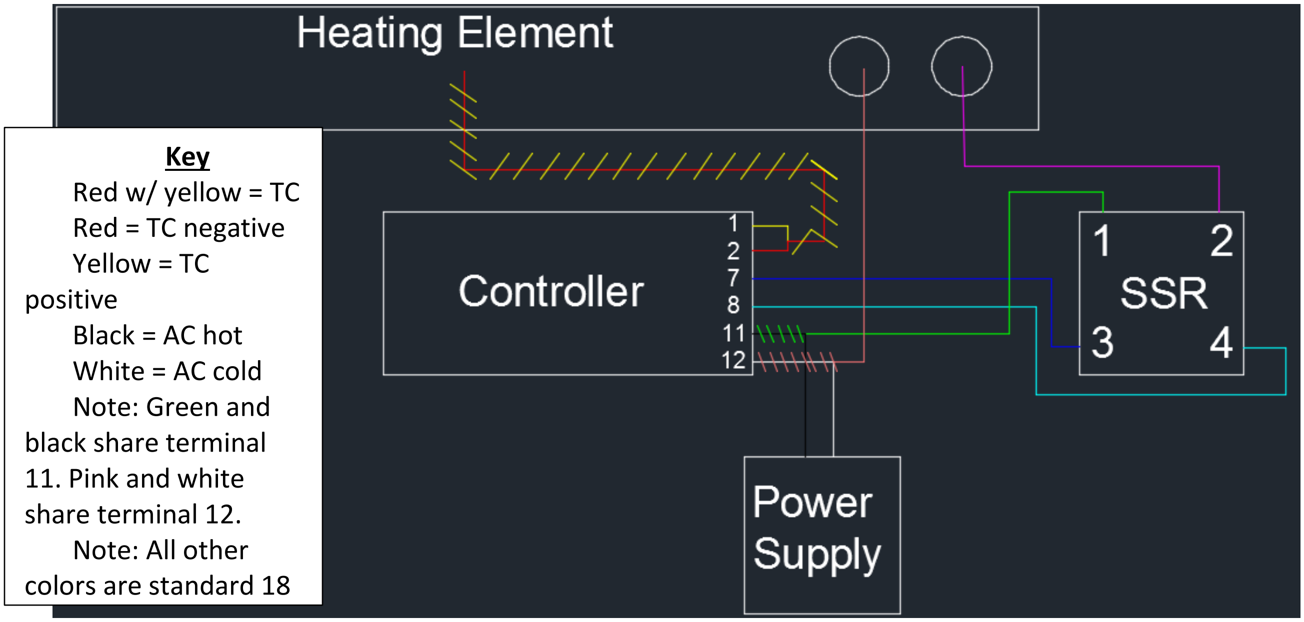
Appendix I.A.5



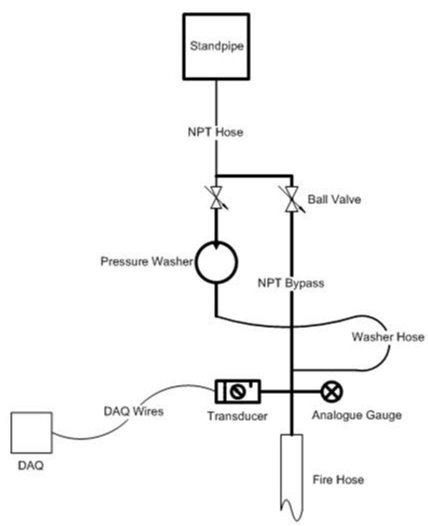
Temperature Menu

Appendix I.B – Wiring Instructions

Appendix I.B.1



Appendix I.B.2



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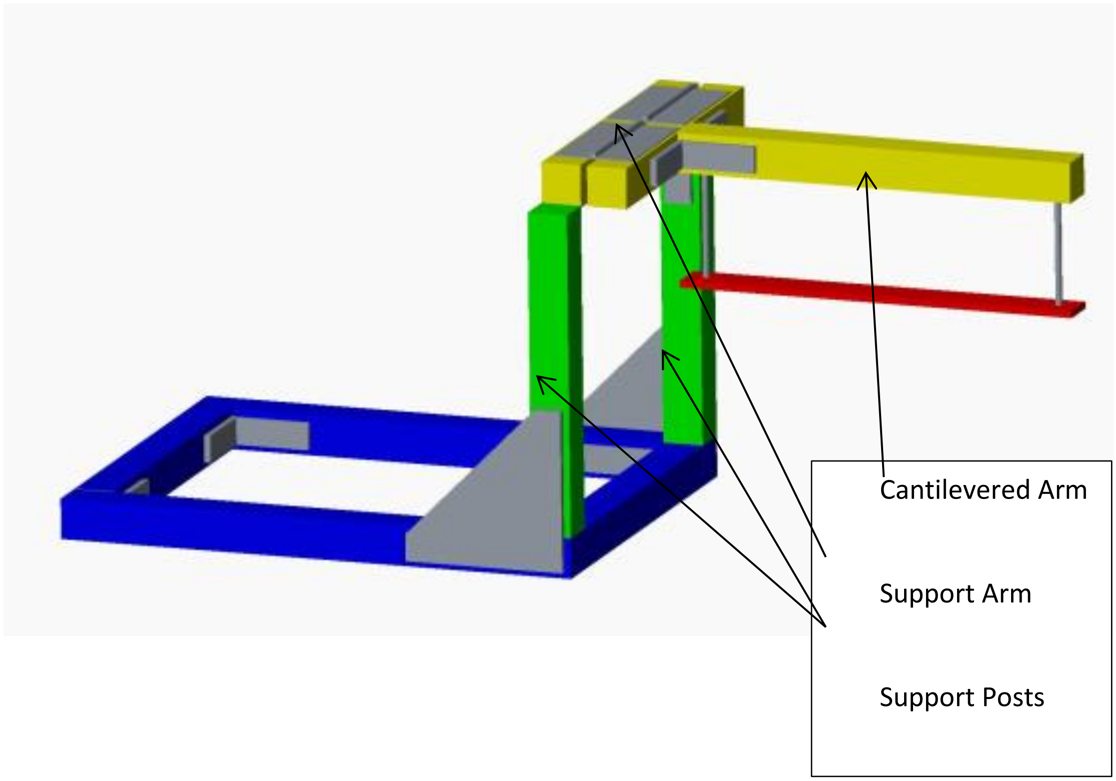

Appendix I.C – Hose Pressurization Checklist

1. Clamp the end of the hose
2. Make sure the ball valve (blue valve) is open
3. Open the standpipe valve and allow water to fill the hose until it reaches an equilibrium pressure (around 50-60 psi)
4. Close the ball valve
5. Close the standpipe valve
6. Make sure the pressure washer valve is open
7. Run the pressure washer until the hose reaches 120 psi

    Note: The ball valve or relief valve can be opened to bleed pressure if the pressure exceeds

    120 psi

8. Close the pressure washer valve
9. Run the test
10. Slowly unclamp the hose and allow the excess water to run into the drain

Appendix II – Validation Test Pressure Data

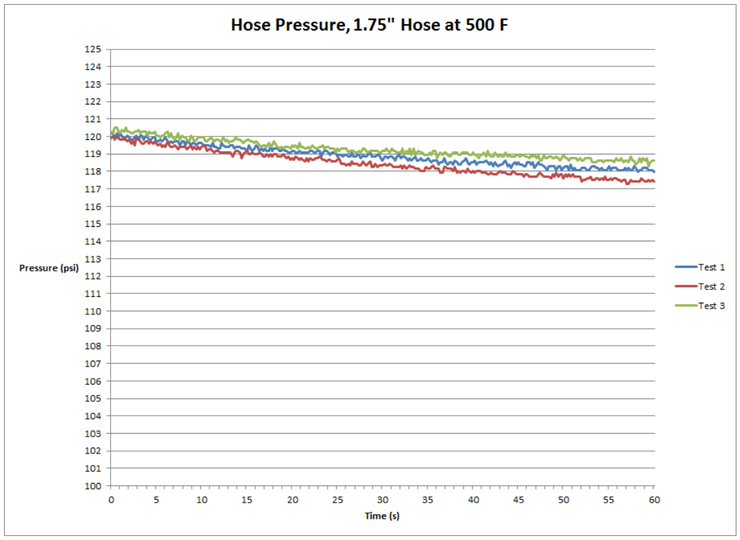

Figure 12: 1 3/4" Hose at 500° F Pressure Data

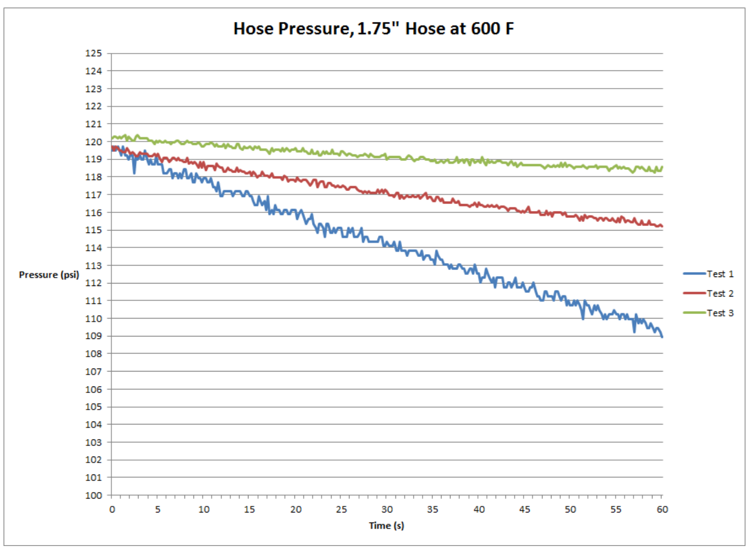

Figure 13: 1 3/4" Hose at 600° F Pressure Data

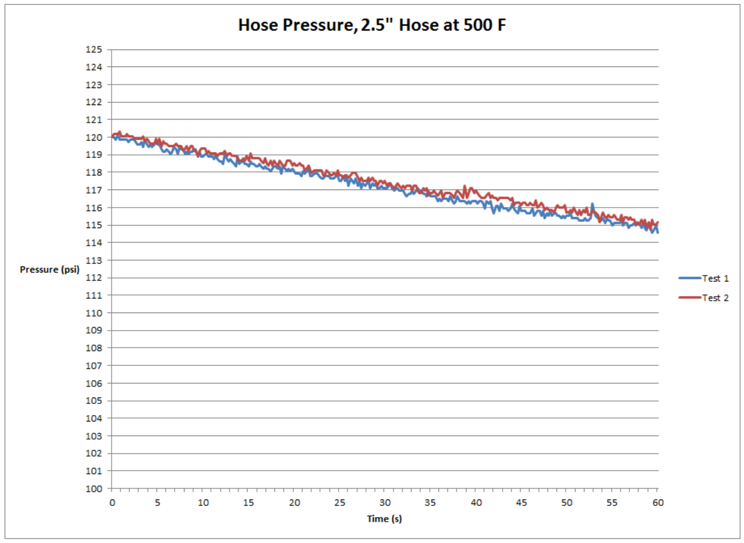

Figure 14: 2 1/2" Hose at 500° F Pressure Data

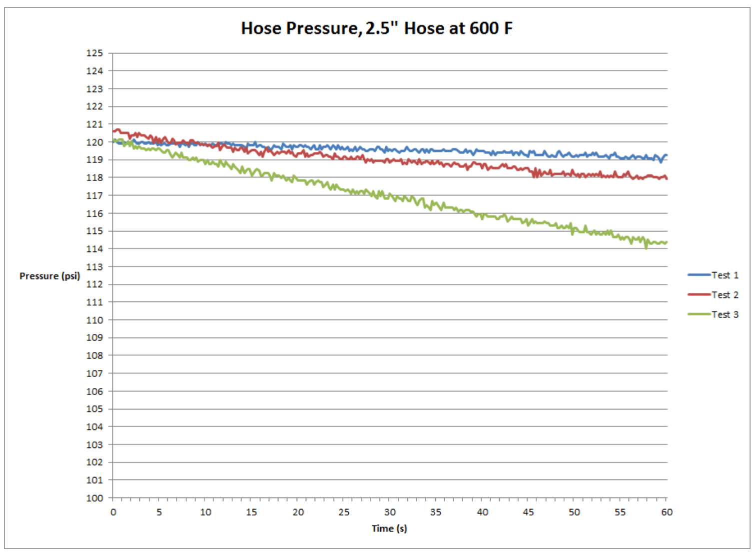

Figure 15: 2 1/2" Hose at 600° F Pressure Data

Appendix III – Validation Test Temperature Data

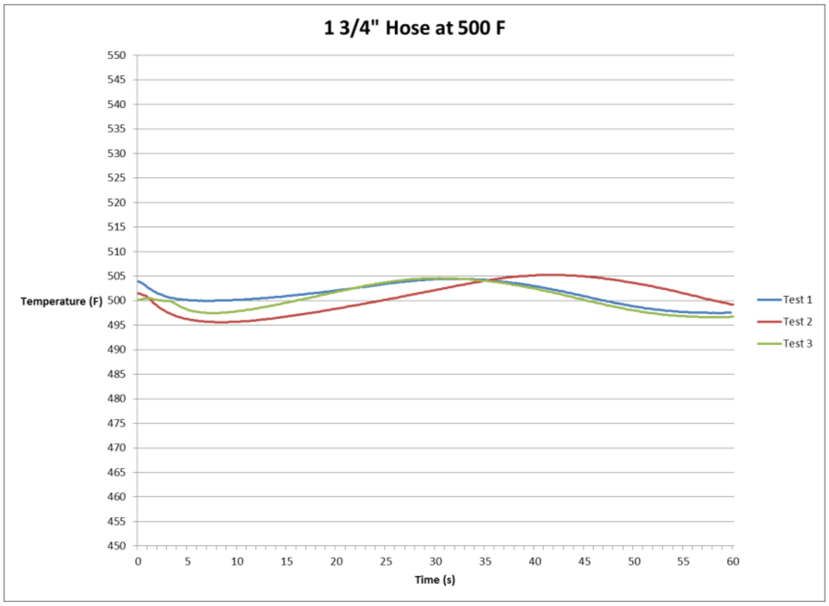

Figure 16: 1 3/4" Hose at 500° F Temperature Data

Figure 17: 1 3/4" Hose at 500° F Temperature Data

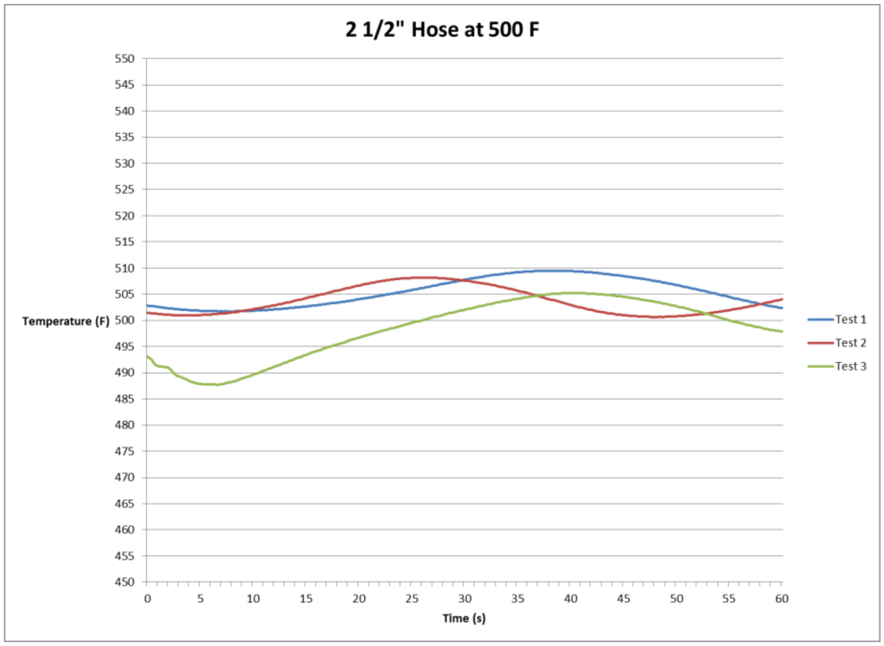

Figure 18: 2 1/2" Hose at 500° F Temperature Data

Figure 19: 2 1/2" Hose at 600° F Temperature Data