Re-Design, Construction, and Validation of an Apparatus Used for Performance Testing of Fire Attack Hoses Subject to Conductive Heat Transfer

Major Qualifying Project Report

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Abstract

This project re-designed, constructed, and validated an apparatus that can provide repeatable and reliable results for the time to failure of a fire attack hose that is charged with water and then subjected to a conductive heat load. Each component of the apparatus was re-designed and tested to meet the performance criteria specified. The apparatus was validated through performance testing and provided clear evidence that it can be used to accurately compare the properties of fire attack hoses.

Acknowledgements

The team would like to thank our advisor Professor Kathy Notarianni, and WPI FPE Lab Director Raymond Ranellone for their guidance throughout the project. We would also like to acknowledge the Fire Protection Engineering Department, Mechanical Engineering Department, and the Civil Engineering Department for their support of the project. Additionally, the team would like to especially thank Trevor Borth, and Diane Poirier for their help and support.

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1.0 Introduction

The two critical functions of a fire attack hose are: 1) carrying water used for the suppression of fire; and 2) providing firefighters with a lifeline to safety. The fire attack hose provides a lifeline to safety in that a firefighter may follow the hose line back out of the building. Even more importantly, water from the hose provides a way to cool the immediate surroundings of the fire fighter, facilitating escape. The importance of the fire hose means that it must be able to withstand the tough conditions of the fireground without failing from the intense heat. Unfortunately, current commercially available fire attack hoses are constructed of the same materials that were introduced approximately 50 years ago. These hoses have very limited heat resistance and conditions on the modern fireground often exceed their capabilities leading to failure of the hose due to burn-through. Hoses are manufactured and designed in accordance with national specifications that require standardized performance testing of the hose. However, the standardized test methodology for conductive heat transfer prescribed in the applicable standards is not repeatable, and does not test the performance of a hose when subjected to conductive heat at levels similar to those that the hose may experience on the fireground. In addition, results from current standardized testing are reported as pass/fail only. No time to failure data is recorded, thus, the effect of each component of a hose construction on the time to failure of the hose cannot be determined. In the following sections 1.1 through 1.3, the team addresses the main concerns regarding modern fire attack hoses, previous research achieved by WPI project groups, and a means of developing a prototype apparatus to expose the hose to appropriate thermal conditions.

1.1 Problem

Over the past few years, researchers at Worcester Polytechnic Institute (WPI) have been examining the extent of fire attack hose burn-through incidents. This research has documented and demonstrated the rate of occurrence of fire hose burn-throughs that is even greater than was originally anticipated. Fire attack hose burn throughs can be catastrophic to firefighters who rely on sufficient hose pressure in order to put out the fire. With this hose pressure compromised, the risk for the firefighter is greatly increased. On March 26, 2014 Firefighter Michael Kennedy and Lieutenant Edward Walsh of the Boston Fire Department were killed while operating in a burning structure. Their fire attack hose line burned through, leaving them without water, and likely contributed to their death [1]. This burn through left researchers questioning the adequacy of current fire hose testing and reporting standards. On the testing side, there are shortfalls of current testing relating both to the test rigor as well as to the test repeatability. Current standardized test methods for conductive heat transfer occur at temperatures below those found on a modern day fireground. Also, because the conductive heat source used during testing is losing heat at an unknown rate due to ambient temperature in the room, the current test is not repeatable. In order to subject a fire hose in a repeatable way and to test the hose subjected to thermal conditions representative of the modern fireground, a new apparatus must be designed and constructed. Results of the new test must be reported in more detail than pass/fail because when tasked with determining the appropriate fire hose, Fire Departments must consider the time to failure, rather than simply a pass or fail criteria. This information will assist them in selecting the hose to purchase.

There are many fire attack hoses that are marked National Fire Protection Association (NFPA) compliant and are commercially available for use by the fire service. Although each of these hoses has passed the standardized test for conductive heat transfer prescribed in the NFPA Standard 1961 *Standard on Fire Hose*, these fire attack hoses are all different in the key components that are used to construct them, and therefore have the possibility of failing at different times and under different conditions. The fire attack hose can be characterized by four parameters: the jacket type, liner type, unit weight, and coating material. All of these factors likely affect the time to failure for the hose, but some of them may affect the performance of the hose more than others. While an effort to design a thermally resistant fire attack hose (often referred to as a Next Generation fire attack hose) is ongoing, there are two developments to be made: (1) A standardized test method capable of testing existing and prototype fire attack hoses at elevated temperatures with repeatable results, and (2) a method of comparing fire attack hoses given differing construction parameters.

1.2 Previous WPI project group achievements

The Next Generation Fire Attack Hose Project, advised by WPI Fire Protection Engineering Professor Kathy Notarianni, was created with the objective to develop a fire hose that can withstand the harsh thermal conditions on the fireground. Multiple different project teams have each worked on different aspects of this project, achieving advances such as:

- Creation of a national database documenting hose burn through incidents
- Review of national and international standards and test methods
- Preliminary Testing of a Matrix of Hose constructions
- Identification and testing of higher performing materials
- Development of a standardized testing apparatus for convection and radiation using a hose pressurized with air
- Improvement of a standardized testing apparatus for convection and radiation using a hose pressurized with water
- Development of a standardized testing apparatus for conduction using a hose pressurized with air

The Next Generation Fire Attack Hose research project created a national database that documented burn-through events [5]. A survey was developed and sent out to fire departments around the country with the goal of determining the frequency of burn-throughs and what causes them. This revealed that burn-throughs occur much more frequently than previously thought [5]. The next Interactive Qualifying Project (IQP) team analyzed NFPA 1961 and NFPA 1971

Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting to compare testing standards for hose and personal protective equipment (PPE). The result of their analysis showed that hoses are not tested as vigorously as a firefighters' PPE [6]. The team also enhanced the national database that was implemented by a previous group.

The first Major Qualifying Project (MQP) team developed the first methodologies and datasets for assessing the performance on an array of ten fire attack hoses and candidate fire attack hose materials when exposed to conductive, radiative and flame impingement heat stresses along the fireground [7]. With the replication of a foreign fire attack hose performance standard against a test matrix, this team demonstrated that hose jacket material may have an impact on flame resistance, and that the American standard lacked the same rigor. The next MQP team aimed to investigate the thermal performance of materials currently used in high heat environments, and investigate candidates for the outer jacket of a next generation fire attack hose. This project revealed that several materials have better resistance to a radiative heat flux than nylon 6,6 and polyester. With measurements of burn-throughs, this team gauged whether these outer jackets would outperform current materials in terms of radiative heat performance.

An apparatus was designed by another MQP group to address the convection and radiation that fire hoses experience on the modern fireground. This team built a test chamber that used several components such as a fan, ductwork, and heating elements to simulate the modes of heat transfer that hoses should be tested for in addition to conduction [10]. The most recent MQP team to research the Next Generation Fire Attack Hose was able to re-design and enhance the convective and radiative testing apparatus to make it more representative of the conditions of the fireground [11]. The biggest difference between this MQP group and the previous convection and radiation project is that the hose is pressurized with water and not air.

Another MQP team focused on the creation of a standardized testing apparatus for conduction. The apparatus was designed to measure the performance of a fire attack hose when subjected to a steady state conductive heat stress. The apparatus is able to test hoses at current NFPA requirements for conduction but was created for more rigorous testing [9]. This testing is at temperatures closer to those that a hose will be exposed to on a modern day fireground [9]. Similar to the first MQP group that worked on the convection and radiation project, this apparatus was only used for hoses pressurized with air. The previous project aimed to design an apparatus capable of testing the failure times of fire attack hoses due to conductive heat transfer at temperatures representative of the fireground, allowing for the production of valuable information for fire departments to use in the selection of hoses.

1.3 Project Scope

This project serves to show that the redesigned apparatus is capable of providing consistent results in relation to temperature and time to failure. Once the verification is completed, the reactions of charged hose lines constructed with different liner and coating materials will be analyzed following testing in laboratory-controlled fireground conditions. The time to failure for each fire hose is the main factor tested. Failure occurs when water is seen discharging from the hose burnthrough location.

Numerous stakeholders including firefighters, manufacturers of products & materials, testing facilities, codes & standards development organizations, local and federal governments, and the public will benefit from our group's apparatus. The completion of our project will result in an apparatus that provides a reliable and repeatable measure of fire attack hoses' ability to resist failure caused by conductive heat transfer. The apparatus will improve upon the testing required by NFPA by providing the capability of repeatable testing at a wide range of temperatures. As a next generation fire hose is designed, this apparatus will be able to produce the testing conditions necessary to determine its performance on a fireground.

2.0 Background

2.1 Current Standardized Testing

The vast majority of fire attack hoses used by today's firefighters are designed and developed in accordance with NFPA 1961 *Standard on Fire Hose*. This standard establishes the minimum requirements for a new fire hose but does not describe the testing method for heat resistance. Instead, the standard references American National Standards Institute/Underwriters Laboratory (ANSI/UL) 19 and Factory Mutual Approvals (FM) 2111 performance tests, which focus on conductive heat transfer from a steel block [2]. FM and UL are the companies that lay out the procedures for the tests referenced by NFPA. For this specific test, the block is heated to 260℃(500℉) and stamped onto a water-filled hose for 60 seconds. However, after the block is heated, it begins losing heat to the ambient air surrounding it. By the time it is stamped onto the hose, there is no measurement on the temperature actually being applied to the hose; this creates an uncertainty that is unacceptable. The British Standards Institution (BSI) also came out with a series of Heat Resistance and Hot Surface Resistance tests. These tests are more rigorous than the tests approved by the NFPA, but utilize the same theory of a heated steel block or filament rod on a hose surface [3]. In order to incorporate other modes of heat transfer, a German DIN 14811 Flame Resistance Test utilizes a flame impingement on the charged fire hose. Surprisingly, this is the only test in the world that measures the performance of the hose up against an open flame [4].

It has been argued that a fire attack hose is exposed to the same operational environment and fireground conditions as firefighter's personal protective footwear [12]. Personal protective equipment has been subject to significant improvements and much more rigorous testing with respect to compliance standards over the past few years. Thermal advancements and technologies must be adapted to fire attack hoses to allow the hose to meet the same standard as personal protective equipment, or the safety of firefighters will be dangerously compromised.

To ensure fire hoses meet more rigorous thermal performance requirements than specified in NFPA 1961, all fire attack hoses must undergo the following tests according to

NFPA 1971 *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*: Conductive Heat Resistance Test 2, Flame Resistance Test 4, Radiant Heat Resistance Test 1, and the Thread Melting Test [12]. All tests must be conducted with charged and uncharged lines, in a horizontal position, and shall be deemed safe for use as a fire attack hose based upon failure times. Fire attack hoses must meet these demands after the effective date: February 26, 2018. In accordance with the results obtained from this project only the Conductive Heat Resistance Test and the Thread Melting Test can be verified.

The Conductive Heat Resistance Test is used to evaluate the properties of the garment shoulder and knee areas which are more likely to experience a reduction in thermal insulation due to compression. This requirement sets a minimum of 20 minutes of exposure to a hot plate heated to a temperature of 260 °C ± 5 °C (500 ℉ ± 10 ℉), using a Type J or Type K thermocouple to read temperatures. One specimen should be tested. This test shall represent conditions equivalent to the conduction experienced by a hose along the modern fireground.

The Thread Melting Test is used to evaluate the thread used in the construction of the hose to determine whether it has the minimum heat resistance as the fabric used in the construction of the hose. The temperature at which the thread melts or experiences signs of decomposition is recorded, and if the thread melts below 260 °C (500 °F), the hose has failed. Thread melting is a significant factor to consider when attack hoses are subject to high heat conditions, and must undergo such tests to understand how thread material contributes to hose failure. All hoses are then subject to undergo hydrostatic pressure tests in order to properly determine burst or failure times during these thermal assault tests. Hoses are required to meet these testing demands to ensure that it is safe for use as a fire attack hose.

2.2 Fireground Conditions

All three modes of heat transfer (conduction, convection, and radiation) affect the rate of growth of the fire and the level of hazard to firefighters and their gear/equipment. The WPI database of fire attack burn-throughs demonstrated that the dominant mode of heat transfer in over 90% of hose burn-throughs is conduction. Therefore, our project focuses on the development of an apparatus to measure the performance of a fire attack hose when subjected to conductive heat transfer.

Conduction is a diffusion process where thermal energy is transferred through physical contact. This transfer occurs at the molecular level—from one body to another—when heat energy is absorbed by a surface and causes the molecules of that surface to move more quickly. In the process, they bump into adjacent molecules and transfer the energy to them, a process which continues as long as heat is still being added. The process of heat conduction always occurs from a hot body to a cooler body [21]. The rate of heat transfer is dependent upon the difference in temperature of the two bodies and their thermal properties. In today's fireground conditions, the conductive heat source that could be seen is falling debris on the fire hose. The material of the debris could be a hot roof after flashover dropping down onto the hose, or the hose being stretched over a hot metal floor plate or handrail. Both of these scenarios could inflict damage on the hose via conduction due to the fact that they are likely to have extremely high temperatures in a fire.

The rate of development of fires and the associated conditions on the fireground have intensified over the past several decades due to changes in: interior design of spaces, the type and amount of furniture in the building, and materials used in building construction. Residential buildings have become larger, increasing the fuel load of the structure. Also, the idea of open floor plans have contributed to an increased air flow and also lack of containment [13]. Newly engineered glued beams and other synthetic building materials are being used and are easily combustible, promoting a faster flame spread. Because of the previously mentioned factors, modern structures are reaching flashover conditions at a rate eight times faster than they were fifty years ago [13]. It is thus imperative that fire attack hoses be thermally resistant, and that performance of a fire attack hose be verified by standardized testing at realistic temperatures. Currently, however, there is no apparatus available that can test the performance of a hose when subjected to the elevated temperatures that are seen on the modern fireground. The modern fireground prior to flashover can reach up to 260 ℃(500 ℉) according to NFPA 1971 [24].

2.3 Fire Attack Hose Construction

The majority of fire attack hoses purchased today are what is referred to as a “double jacket” hose. The term “double jacket” refers to a hose construction type where an inner liner is bonded to an outer jacket. This outer jacket may also have an abrasion coating to provide increased protection for the hose while it is dragged around on rough surfaces. The inner liner is most commonly manufactured using Ethylene Propylene Diene Monomer (EPDM) [15], or Thermoplastic Urethane (TPU) [17]. The inner liner of a hose is used for the primary function of allowing water to flow from the water supply to the hose nozzle positioned by the firefighters. These lining materials cannot withstand extreme conditions and high temperatures, which is why they have an outer jacket to protect them. Outer jackets are typically made of Polyester or Nylon-66, and when these materials begin to melt is when the inner liner becomes exposed. Neither Polyester nor Nylon-66 have good heat resistance. Polyester has a melting point of about 260 ℃ [19], while Nylon 66 has a melting point that ranges between 220 and 250 ℃ [14]. Lastly, in addition to hoses that are treated with an abrasion coating, others are sold as having been treated with an abrasion *and* heat resistive coating. The composition of the coatings varies by manufacturer and is not typically disclosed. However, these coatings are designed to increase the performance of the hose. A “next-generation” thermally resistant fire attack hose is needed. However, while in Research & Development phase, there are a lot of options when it comes to designing such a hose because of the various liner, jacket, and coating options. The reason for our re-design is to develop an apparatus capable of testing both new/prototype as well as existing hoses with different constructions. The results of these tests will help to determine the most favorable properties when it comes to designing and selecting a fire attack hose for use.

2.4 Original Conduction Apparatus

The original conductive test apparatus was designed to gauge the reliability of a municipal fire attack hoses when exposed to the level of conductive heat transfer seen on a modern fireground. The test apparatus was developed for structural durability, to apply a heating element to hoses, and to produce a repeatable testing procedure for hoses pressurized with air [9]. The apparatus is constructed of 80/20 bars for structural durability, which supports the frame. The original apparatus includes a cantilevered arm that was used to lower the heating element to make contact with the hose. A Proportional-Integral-Derivative (PID) controller is regulated by temperature measurements made with a Type K thermocouple. The thermocouple is wrapped in insulation on top of the heating element in order to accurately measure the temperature of the element. It also includes a solid-state relay and a data acquisition (DAQ) system. Before pressurizing the hose, it is clamped down to prevent air leakage throughout the test. The heating element is then lowered down by the cantilevered arm onto the hose which subjects it to conductive heat transfer [9]. The AutoCAD drawing shown in Figure 1 below is the original conduction apparatus:

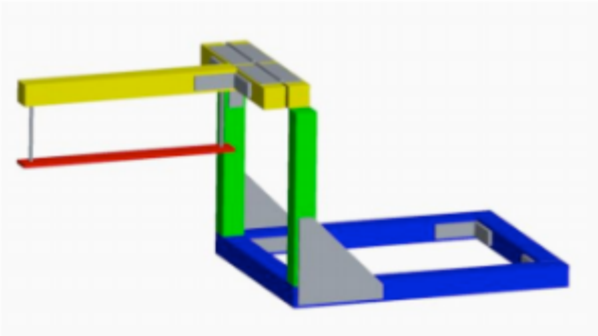


Figure 1: Original Conduction Apparatus AutoCAD drawing

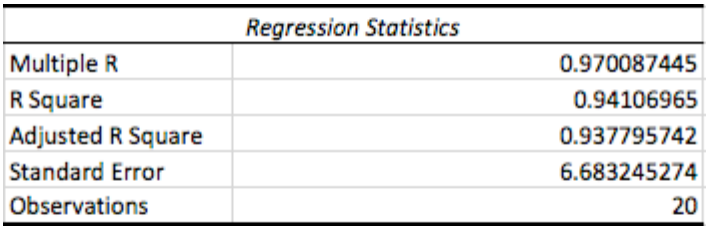
2.5 Data Extrapolation

Linear Regression is a commonly used analysis technique for interpreting multi-variable data. The goal of a linear regression is to determine the relationship between independent variables and a dependent variable by developing an equation of a line that is the “best-fit” given the known data points plotted on a graph. The line formed by the equation can be used to determine how accurately each independent variable correlates to the outcome or dependent variable [18].

One of the most important characteristics of the linear regression is known as the coefficient of determination, which is symbolized by R^2. This variable represents what percentage of the variability in the dependent variable is explained by the regression model. A value close to 0 implies that almost none of the variability in outcomes can be explained by the model [18]. On the other hand, a value of 1 and -1 implies that all of the variability is explained by the model where 1 is a positive correlation and -1 is a negative correlation. So, the closer the R^2-value is to 1 or -1, the higher the correlation between the variables.

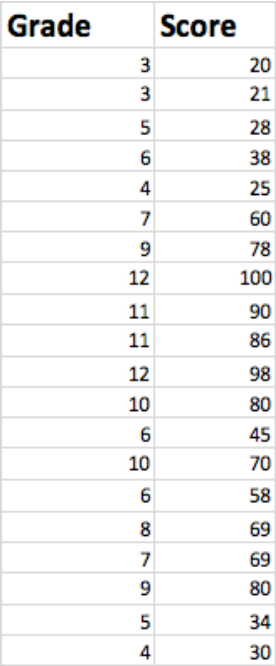
Another important variable in the linear regression is the p-value, which tests the significance of the regression equation. A p-value close to 0 is indicative of statistically significant results, which implies that the independent and dependent variables are related [18]. The following sample analysis can be used as an example to illustrate the idea of a linear regression and the interpretation that can be done:

Suppose a group of 20 students, randomly selected from grades 3-12, were given the same exact exam that included basic math, algebra, geometry, and calculus problems. Suppose we wanted to know whether or not the grade level of the test-taker was related to the final score (out of 100) that was achieved. The following data was compiled and graphed as shown below:



Regression Statistics	
Multiple R	0.970087445
R Square	0.94106965
Adjusted R Square	0.937795742
Standard Error	6.683245274
Observations	20

Figure 3: Example Regression Statistics



Grade	Score
3	20
3	21
5	28
6	38
4	25
7	60
9	78
12	100
11	90
11	86
12	98
10	80
6	45
10	70
6	58
8	69
7	69
9	80
5	34
4	30

Figure 2: Example Group Scores

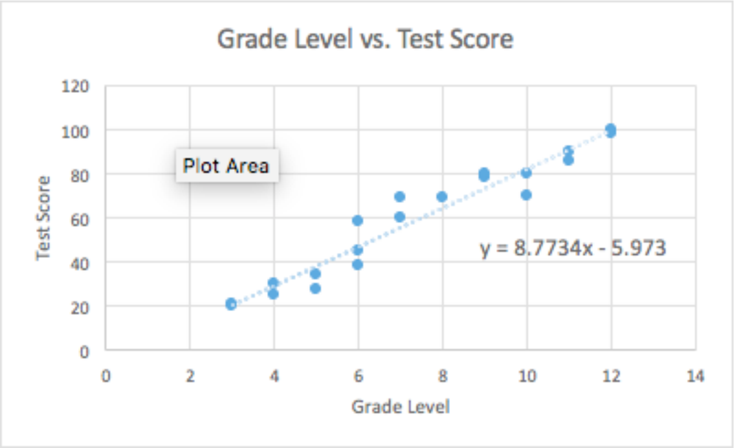


Figure 4: Example Linear Regression

Using Microsoft Excel, a line of best fit can be created using the slope value of 8.77 and the y-intercept of -5.97. The R^2 value was around .94 and the p-value achieved was 1.634×10^{-12}, which are high and *extremely* low, respectively, signifying that the independent (grade level) and dependent (test score) variables are related in a statistically significant manner. Linear Regression Analysis can be run using the Data Analysis Toolpak of Microsoft Excel 2016 [20].

3.0 Methodology

3.1 Mission Statement

The goal of this project was to re-design, construct, and validate the use of an apparatus that can provide repeatable and reliable results for the time to failure of a fire attack hose that is charged with water to 150 +/- 7 psi and then subjected to a conductive heat load.

3.2 Research Methods

This project is to be completed in three basic phases: 1) development of performance criteria for and the re-design/construction of the conduction testing apparatus; 2) verification of each component of the apparatus to ensure that it can meet its designated performance criteria; and 3) system wide validation through performance testing of various fire attack hoses.

1. Phase 1) Design
    a. Testing with Original Apparatus
    b. Development of Performance Criteria
    c. Design of the Apparatus
    d. Construction of a Prototype Apparatus

Phase 1 was dedicated to the evaluation, design, and construction of the apparatus. Performance criteria were developed to ensure that the conditions experienced by the fire attack hose closely resemble those on a fireground. The re-design was completed by evaluating each component of the original apparatus and procedures outlined by the previous project team. Next, each component was improved upon to increase consistency during testing. Upon completion, each component of the newly designed apparatus was tested for results that are consistent and repeatable, allowing for accurate testing of fire attack hoses.

2. Phase 2) Component Verification
    a. Development of Methodologies in Verification of Each Individual Component
    b. Development of a Standardized Hose Testing Procedure for use of the Apparatus

Phase 2 was performed to ensure that each of the components throughout the system can meet the performance criteria. Verification methodologies were established to demonstrate a consistent way of testing individual components against our established performance criteria. A hose testing procedure was constructed to provide a uniform and repeatable process that could be followed step-by-step to mitigate inconsistencies.

3. Phase 3) System Validation
    a. Confirmation of Accuracy and Consistency of Test Results
    b. Development and Execution of Hose Performance Testing

Phase 3 was completed in order to validate that the apparatus as a whole could be used to produce repeatable results useful for comparison of different hoses. Initial testing of a Kochek fire attack hose was conducted to determine repeatability and consistency of test results. Through several tests, the apparatus maintained its construction, verifying the structural integrity of our design. After each test, a linear regression analysis was conducted to analyze the ability of the apparatus to produce consistent results. We then used the apparatus to test three hoses with different constructions to show that the apparatus can be used to accurately compare different hoses.

4.0 Design and Construction of the Prototype Apparatus

This chapter will correspond to the first phase of the Methodology. Following the evaluation of the original apparatus, performance criteria was established and agreed upon. The new performance criteria guided our re-design and construction of the conduction apparatus to ensure that it was capable of being used to compare different fire attack hoses and their resistance to failure caused by conductive heat transfer.

4.1 Testing with the Original Apparatus

Phase 1 began with an evaluation of the original apparatus. Before making improvements, testing with the original apparatus was conducted in order to determine if the apparatus could produce repeatable and reliable results for a linear regression model. Following testing, the results showed that original apparatus had problems in its design, and those problems had to be analyzed. The existing apparatus was built to test hose performance when charged with air and exposed to a high heat conduction. Our group started by running hose performance tests using this apparatus, but replaced the air charged hose by a hose charged with water. Figure 5 below shows the previous apparatus.

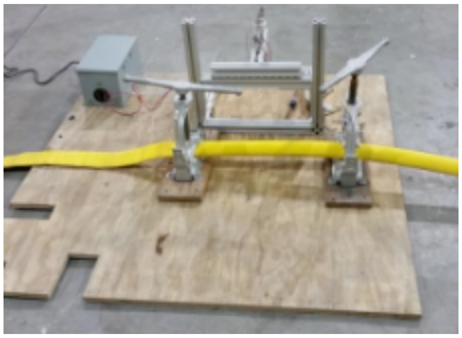
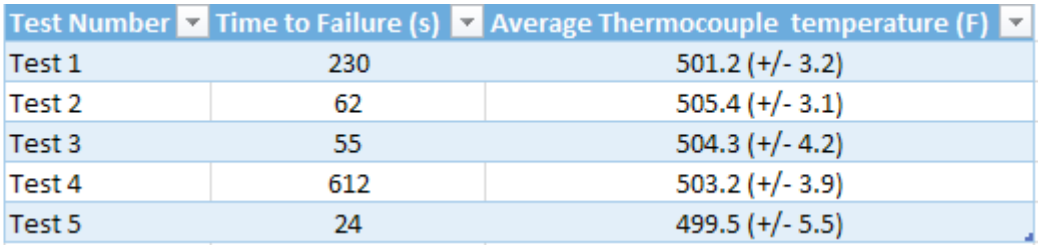


Figure 5: Original Conduction Apparatus

Tests were conducted using the previous team's procedure, however, our team changed the way performance data was collected. The previous team tested hoses at 500℉ and 600℉ and recorded if the hose passed or failed. Our team measured the elapsed time between the heating element making contact with the hose, and the hose meeting the set failure criteria. This was measured by a team member with a stopwatch. Measuring time to failure allowed hoses to be compared by performance at a specified temperature. The procedure involved clamping a hose at one end as shown in Figure 5 and pressurizing the hose with water to 150 +/- 7 psi. After the PID reached the set temperature, the cantilever arm was placed on the hose such that the hose made contact with the heating element, beginning the test. Multiple tests were run to see if the apparatus could produce similar results.

4.1.1 Results of Tests with Original Apparatus

Five tests were carried out using the same hose. The hose construction was a polyester outer jacket with an EPDM liner material and no coating. Table 1 below shows the time to failure of the hose during each of the five trials and the average temperature read by the thermocouple on the original apparatus described in section 2.4.



Test Number	Time to Failure (s)	Average Thermocouple temperature (F)
Test 1	230	501.2 (+/- 3.2)
Test 2	62	505.4 (+/- 3.1)
Test 3	55	504.3 (+/- 4.2)
Test 4	612	503.2 (+/- 3.9)
Test 5	24	499.5 (+/- 5.5)

Table 1: Time to Failure and Average Thermocouple Temperature Original Apparatus Test Results

From the table, it is shown that the time to failure varied between about 24 and 612 seconds, corresponding to a 2450% variance and a 220 second standard deviation. This variation in time to failure was unacceptably high, and showed that the apparatus lacked the ability to obtain consistent results. It is also important to understand that, as described in section 2.4 of this report, the heating element is controlled by a singular thermocouple. The apparatus also could not handle the water pressure, as the cantilever arm would be flung into the air causing a safety issue.

4.1.2 Problems to Analyze

The data obtained from each of the five tests showed that the apparatus was unable to produce consistent results. Since the previous team measured only whether a hose would pass or fail at a given temperature, they did not encounter the same inconsistencies. The team speculated the following were the most likely causes for the inconsistent data:

1. Inconsistent force being applied to the hose by the heating element
2. Different contact angles between heating element and hose due to hose diameters
3. Lack of temperature uniformity being applied to the hose

After listing the problems, the team made the decision to re-design the original apparatus such that a consistent time to failure is achievable for a given hose type tested at a set temperature. The team also looked into safety additions to protect the operator from potential harm and the apparatus from damage caused by the pressure release during a hose failure. The following sections in this chapter detail the process by which the team addresses these potential inconsistencies.

4.2 Develop New Performance Criteria for Prototype Apparatus

The team established performance criteria to inform the selection of components for the prototype apparatus. The performance criteria developed were:

1. The force applied to the hose by the heating element should have a maximum variation of 0.2 lbf at any expected testing height
2. The contact angle must not vary between tests
3. A maximum temperature variation of +/- 2% across the area of the heating element to be in contact with the hose
4. Hose must achieve and maintain a pressure of 150 +/- 7 psi for the duration of the test until failure
5. The hose is deemed to have failed when water is seen discharging from the hose burnthrough location

4.2.1 Force Performance Criteria

The prototype apparatus was designed with a linear sliding rail that will place the heating element in contact with the top of the fire hose that is charged with water. Due to the slight variation in diameters of different hoses, the height at which the linear rail will contact the hose may vary slightly. The group then determined that the force produced by the element onto the hose should not vary by more than 0.20 lbf at any potential testing height.

4.2.2 Contact Angle Performance Criteria

In order to ensure the contact angle between the heating element and hose remained constant between tests, our team replaced the cantilevered arm with a sliding linear rail. This ensured that the element remains horizontal and slides down vertically to contact the top of the hose.

4.2.3 Heating Element Performance Criteria

The prototype apparatus was designed to produce consistent temperatures representative of falling debris or hot surfaces that a fire attack hose may come in contact with. Consistent temperatures are needed in order to compare hoses to each other.

The performance criteria specified by the team is the temperature across a three-inch span with a variation of +/- 2% from the average temperature before and during the test until failure.

We are concerned only over a three-inch span because the heating element will not create a contact area of greater than three inches with a hose. The three-inch span is fixed on the heating element as each hose will come in contact with an area within the same three inches.

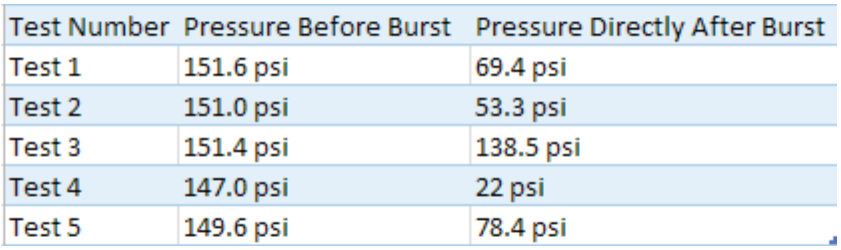
According to the NFPA 1961 standard, fire attack hoses are subjected to 500 ℉ for one minute and all hoses burnt through at 600 ℉ when pressurized with air and tested by the original conduction apparatus [9]. So, we decided to use the average of these two temperatures (550 °F) as a baseline temperature at which we would test. A temperature variation of +/- 2% allows a temperature differential along the three-inch span to be no more than 22 °F, representative of overall uniformity.

4.2.4 Hose Pressure Performance Criteria

The apparatus was designed to test water-charged fire attack hoses at standard operating pressures that are used by the fire service. The convection and radiation apparatus MQP team spoke with 15 different fire departments and concluded that the testing pressure would be set to 150 psi +/- 7 psi [11]. The exit pressure on the fireground is dependent on the nozzle utilized and can range from 50-100 psi out of the nozzle. The hose must be pressurized even higher to accommodate for friction losses; the calculated pressure came to 140 psi [11]. 150 +/- 7 psi was used to be conservative and to include the tolerance of the pressure gauge [11].

4.2.5 Hose Failure Performance Criteria

The hose is deemed to have failed when water is visibly seen discharging from the hose burnthrough location. The criteria for hose failure was determined by visualization of the test results from the original apparatus, which are discussed in section 4.1.1. Fire attack hoses burst in two ways: catastrophically causing water jets to shoot out in the direction of the burst, or more slowly like a leak in a pipe. However, in both cases, a pressure drop and the sight of water were observed. Table 2 below shows the pressures before and directly after bursting.



Test Number	Pressure Before Burst	Pressure Directly After Burst
Test 1	151.6 psi	69.4 psi
Test 2	151.0 psi	53.3 psi
Test 3	151.4 psi	138.5 psi
Test 4	147.0 psi	22 psi
Test 5	149.6 psi	78.4 psi

Table 2: Hose Pressures Before and After Failure

From the naked eye it is clearer to see water leaking or bursting from the hose, than it is to determine exactly how much pressure was lost at that instant. Based on these observations and results, the sight of water from the hose burnthrough area is acceptable as a performance criteria for determining hose failure.

4.3 Design of Prototype Apparatus

With the performance criteria in place, the team determined the modifications necessary to address inconsistencies. Several components were then selected, purchased, and incorporated into the redesign of the original apparatus. In order to meet the performance criteria, the following improvements were made:

1. Addition of linear rails to eliminate force and contact angle inconsistency
2. Addition of a copper block to the heating element to provide a more uniform temperature distribution to apply to the hose
3. Construction of a pressure rig to provide hoses with a constant pressure 150 psi
4. Construction of safety mechanisms on the apparatus including plexiglass to mitigate liquid spraying and a stopper that prevents the heating element from becoming detached from the apparatus

No changes were made to the PID controller or Steady State Relay. Together, these modifications resulted in the construction of the prototype for an apparatus that can be used repeatedly and provide accurate data.

4.3.1 Addition of Linear Rails

The most integral part of the re-designed conduction apparatus was the addition of the linear rails. The linear rails were added in order to ensure that the force produced element was applied to the hose in a consistent and even fashion, regardless of height. This construction replaced the hinged cantilever arm that the original conduction apparatus had. They were constructed using 80/20 bars that were one inch in width. An important part of this design was the linear motion slides that were used. These slides were sized for one-inch width 80/20 bars and also included track rollers for smooth sliding during operation. The arm that holds the heating element and copper block is bracketed to the linear motion slides so the slides and the arm move together as one unit. In order to reduce friction as we adjust the height heating element, a lubricant was added to the linear rails. A visual aid of the linear slides can be seen below in Figure 6:

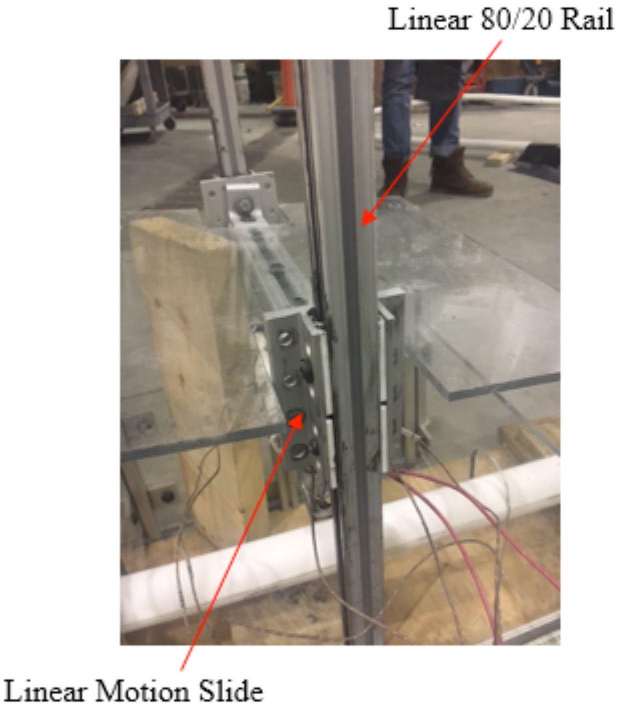


Figure 6: Linear Motion Slides

4.3.2 Addition of Copper Block

The heating element used for the re-design was a stainless steel 120V AC Electric Strip Heater from Omega Engineering (serial number CSH00024). The element was then modified by the addition of insulation, Arctic Silver ceramique thermal cooling compound, and a copper block. The following describes how the addition of these components created a more uniform temperature surface.

The team welded six thermocouples across a three-inch span in the middle section of the heating element to determine the temperature difference that could be in contact with the hose. Figure 7 shown below provides a visual of the six thermocouples on the heating element.

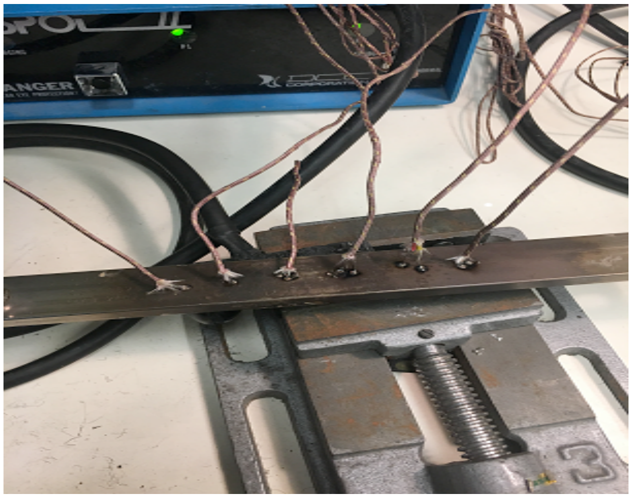


Figure 7: Heating Element Testing

The heating element was turned on with a PID set temperature of 500 °F. The data displayed a 50-degree temperature difference across the six thermocouples. Due to this disparity, uniform heating and thus, consistent test results would be difficult to obtain. In order to address this problem, we called Omega Engineering to see if this was a defect in the heating element. According to the engineer we spoke with, they have never collected data on the temperature disparity across the element. The recommendation was to wrap the element in insulation in an attempt to achieve a more uniform distribution of heat. So, we wrapped the heating element in insulation, leaving bare the two-inch area that had the highest likelihood to come in contact with the hose during testing, as seen in Figure 8 shown below:

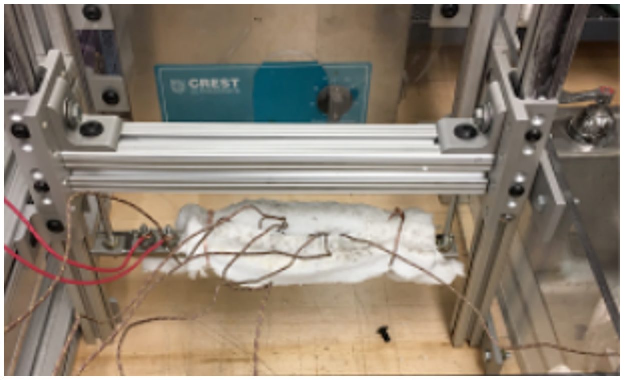


Figure 8: Heating Element Testing with Insulation

The variation in temperature measured along the same area of the element was still an unacceptably high 40 degrees. This temperature variance did not fit within the performance criteria. The performance criteria was set to be +/- 2% of the set temperature which would allow a temperature difference of +/- 11 degrees. A potential solution was to attach a thermally conductive block to the bottom of the heating element. This was an attempt to uniformly absorb and distribute heat along the block so that it, instead of the element itself, may come in contact with the hose with a consistent temperature. The material that fit our needs of high thermal conductivity was copper, which has a thermal conductivity of 401 W/mK. In order to increase the likelihood that the heat would be uniformly distributed across the copper, we used Arctic Silver ceramique thermal cooling compound between the element and the copper. This compound allowed for more surface contact between the heating element and the copper. The next step was to collect temperature data along the copper block to see if the temperature range would be within our performance criteria. Temperature data had previously been collected by welding thermocouples to the element. However, the copper was nearly impossible to weld to. Our solution to this problem was to drill holes in the sides of the copper block that thermocouples could be inserted into, as seen in Figure 9 below. The length from hole 1 to hole 4 was four inches. Figure 10 shown below shows the copper block and the thermocouple locations on the sides.

Figure 9: Copper Block Thermocouple Testing

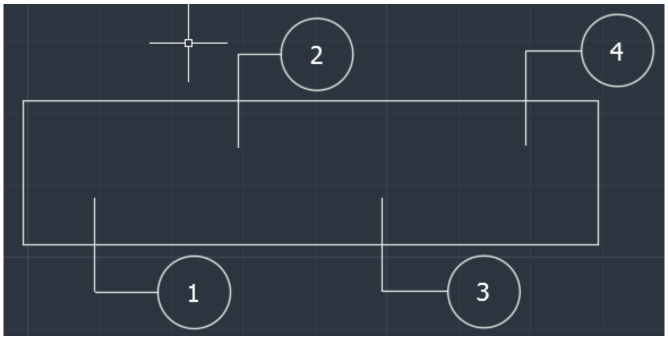


Figure 10: Thermocouple Locations on Copper Block

With the insertion of the thermocouples, tests were carried out to measure the temperature difference along the copper block. The PID was set to 500°F and the temperatures were recorded. The tests showed the temperature between thermocouple 1 and 4 had a difference of 10 °F. This was within the performance criteria stated earlier. However, being that this would eventually need to withstand the failure of a charged hose, the thermocouples needed to be more secure, so that they would not fall out. First, we attempted to use the ceramique cooling compound on the thermocouples before sliding them into the holes on the side of the copper block. However, the thermocouples were still not secure. The solution was to use small pieces of copper wire to slide into the holes *with* the thermocouples. This provided the secure connection we needed to withstand hose failures, and also efficiently transferred heat from the copper block to the thermocouples.

4.3.3 Construction of Hose Pressure Rig

The hose pressure rig was assembled with the goal of pressurizing the attack hose to 150 psi. Because the maximum residual water pressure provided in the combustion lab is 50 psi, a pressure washer which acts as a pump to increase pressure output was attached to the rig to increase the pressure to the desired 150 psi. The pressure rig includes a valve near the water supply that is used to purge the remaining air out of the line to allow for the hose to be completely charged with water. The rig also included a drain near the hose inlet that was used to discharge the remaining water after the hose burst during testing. The rig was constructed with a pressure gauge next to the transducer that was used to manually verify that the transducer and the data acquisition system is reading the pressure through the hose correctly. The connections throughout the pressure rig were sealed tight using both plumber tape and pipe dope in order to prevent leaking. Figures 11 and 12 accurately display the full hose pressure rig and its components.

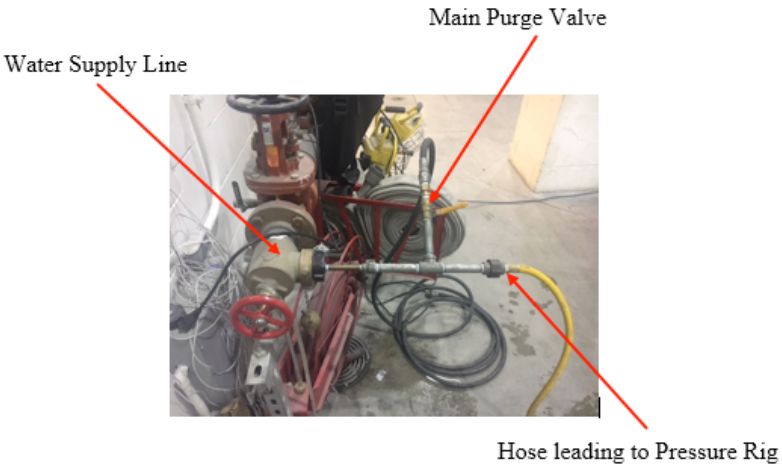


Figure 11: Water Supply Rig

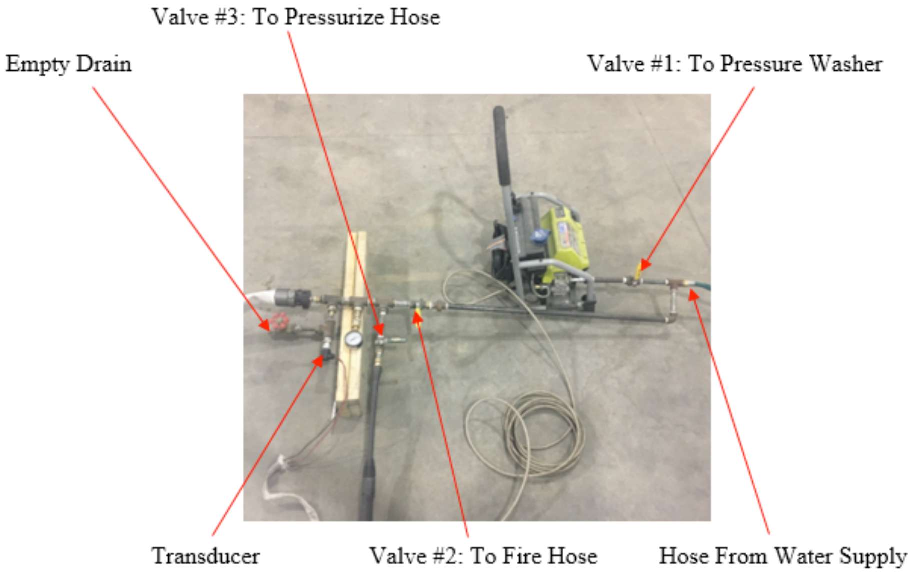


Figure 12: Pressure Rig

4.3.4 Construction of Safety Additions

The safety additions that were added to the conduction apparatus consisted of a plexiglass enclosure and a safety lock. The plexiglass enclosure was added because of the nature of the failures witnessed during the team’s original tests. The hose is to be charged to 150 +/- 7 psi and tested until failure, which meant that failures were quite catastrophic. The plexiglass enclosure significantly minimized risk of injury for any person in the lab during testing by preventing water from shooting up into the air. The safety lock is in place to prevent the slides on the linear rails from flying off of the tracks. It is on the top of the apparatus, and swings over the lid of the enclosure, ensuring that it would be stopped before the arm with the heating element and copper block comes off of the apparatus.

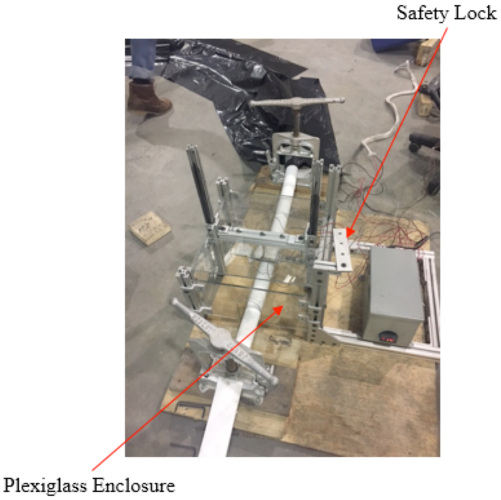


Figure 13: Safety Additions

4.3.5 Acceptable System Components From the Previous Design

The PID controller was used to control the temperature of the heating element. The PID used was the Omega Engineering model CN74000 controller. This model is used for Type K thermocouples with the temperature range of -200 to 2500 °F (-129 to 1371 °C), using a supply voltage of 100 to 240 Vac nominal, consuming 5 VA maximum. The accuracy of the readings are within +/- 0.25% of span and +/- 1 least significant digit.

The Solid State Relay that we used was the Omega Engineering SSRDC100V. The relay functions by opening and closing the circuit that provides current to the heating element which causes the coils to heat up. The opening and closing of the circuit is represented by oscillations seen on the PID. The opening and closing is based on the data collected by the PID through thermocouples attached to the heating element.

The power system used during the construction of the conduction apparatus included the wiring of the PID and a transducer. The PID wiring diagram is shown in Figure 11 below.

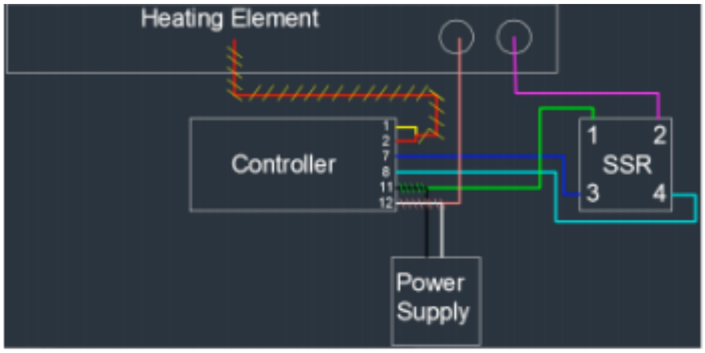


Figure 14: Wiring Diagram for Apparatus

The power supply listed is a 120V AC wall outlet, and the PID controller takes the thermocouple directly from the heating element and relays that to the labview data acquisition program. Labview also takes in the temperature from the thermocouples on the copper block and the voltage from the transducer.

The Transducer that we used was manufactured by Wika gauges (serial number 1A002LW992C). This device was used to collect pressure data from the hose that was then monitored in labview. The pressure from the hose is measured by a voltage signal produced from the pressure of the hose and the voltage from a power supply. This voltage is then converted into pressure by a multiplying a factor given by the manufacturer. This specific transducer spanned 0 - 10 V correlating to 0 - 200 psi (i.e 5V = 100 psi). Being that the hose would be charged to 150 psi during testing, the transducer would suffice and be more accurate than the analog pressure gauge.

To properly gauge the temperatures acquired across the heating element, and voltage received from the pressure transducer, a data acquisition system is necessary. A CompactDAQ Chassis with LabVIEW software is used to customize the acquisition, analysis and presentation of measurement data. For the purposes of obtaining data concerning the temperature readings across a series of thermocouples and pressure from the transducer simultaneously, a multiple chassis data acquisition platform is required. Therefore the team chose to utilize the NI cDAQ-9174 model. Separate distinctive modules are installed into the chassis to obtain data regarding the open-thermocouple detection along the heating element, and the input voltage signals received from the transducer. The models chosen for these modules are NI-9213 and NI-9202 respectively. LabVIEW software was used to efficiently organize the acquired data into a tabular layout within a Microsoft Excel document. The data organized from the LabVIEW program depicts the temperature of the heating element, temperatures of thermocouples 1 through 4, and the voltage signal received from the transducer.

5.0 Verification of Prototype Apparatus

This section provides testing methods for each of the components described in the previous section. The results were then analyzed to verify that each component meets the performance criteria specified by the team.

5.1 Verifying the Force Disparity is Negligible

5.1.1 Force Testing Method

One variable that had the potential to significantly affect the time to failure for a given hose was the force with which the heating element was placed onto it. Upon initially installing the linear sliding rail onto the apparatus, the weight of the rail seemed to vary depending on its position relative to the ground. So, we decided to test the force at different heights to determine that there was not a difference.

The scale that we used to perform the testing was the AND GP-30K in Kaven Hall which is the Civil Engineering Department Building. Due to the large size of the scale, the apparatus was elevated off the table using wooden blocks in order to run a test on even ground. This was done by using 2x4 scrap pieces of wood found in lab. The picture can be seen below with a 2x4 on two opposite sides, elevating the apparatus slightly above the level of the scale:

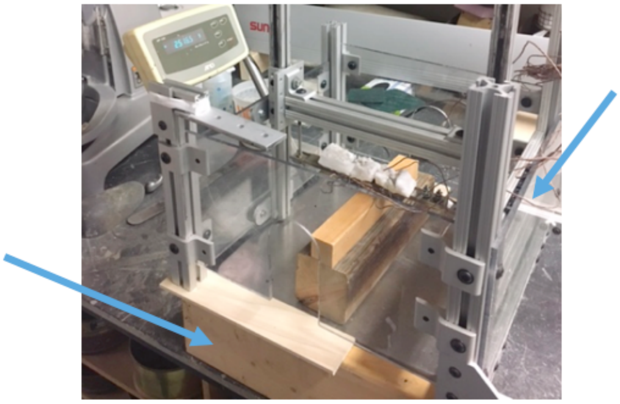


Figure 15: Force Testing

Once the apparatus was elevated, it became necessary to build up to the linear rail. This is because the linear rail does not slide all the way to the ground. It has bolts built into the 80/20 bars on which it slides that prevent it from sliding below a certain level. So, the next step was to determine the height range that the top of a 1.75” hose would sit during testing. This was determined by measuring the height of the clamps that the hose sits on during testing and considering the diameter of the hoses to be tested. We then used scrap wood, the top of which would represent the lowest height that the top of the hose would potentially sit during an actual test. The approximate range above this initial height can be seen below:

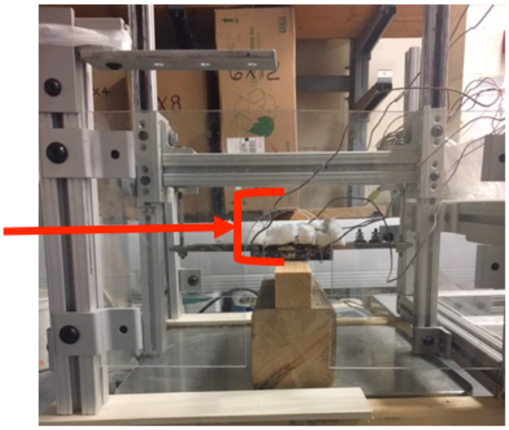


Figure 16: Approximate Range of Initial Heights

This range was an approximate span of just over one inch. Testing the force of the rail at other heights would be redundant because during testing with the whole apparatus, the top of a 1 ¾ in hose would never be outside of this range.

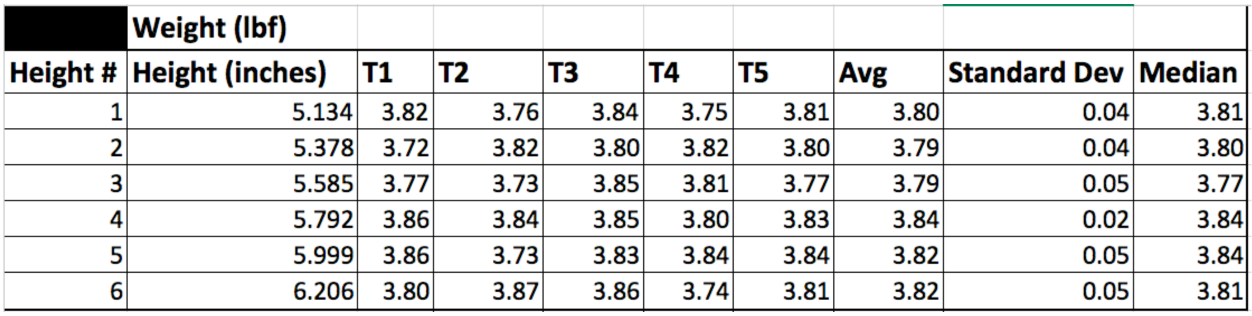
To test different heights, we used thin pieces of plywood to add to the already-existing blocks of wood to simulate a hose with a slightly larger diameter due to a different construction and deformation due to water pressure. The sheets of wood can be seen in the Figure 17 below:

Figure 17: Increments Increased By

After the addition of another sheet, we zeroed the scale and ran five trials, recording the force (in lbf) produced by the linear rail. This process was repeated until the height range from 5.134 to 6.206 inches had been accounted for.

5.1.2 Results of Force Testing

The results for the five trials at each of the six test heights are summarized in the table below:



	Weight (lbf)								
Height #	**Height (inches)**	**T1**	**T2**	**T3**	**T4**	**T5**	**Avg**	**Standard Dev**	**Median**
1	5.134	3.82	3.76	3.84	3.75	3.81	3.80	0.04	3.81
2	5.378	3.72	3.82	3.80	3.82	3.80	3.79	0.04	3.80
3	5.585	3.77	3.73	3.85	3.81	3.77	3.79	0.05	3.77
4	5.792	3.86	3.84	3.85	3.80	3.83	3.84	0.02	3.84
5	5.999	3.86	3.73	3.83	3.84	3.84	3.82	0.05	3.84
6	6.206	3.80	3.87	3.86	3.74	3.81	3.82	0.05	3.81

Table 3: Force Testing Raw Data

The height was measured from the bottom of the apparatus to the top of the wood, which represents the position that the top of the hose would be in during an actual test. The "Avg" represents the mean value of each of the five trials at that specific height. The "Standard Dev" represents the standard deviation at that specific height, while the median represents the median trial value at that specific height.

Figure 18 shows the variation by trial for each height while Figure 19 shows the median and average as height of the linear rail increases. They can be seen below:

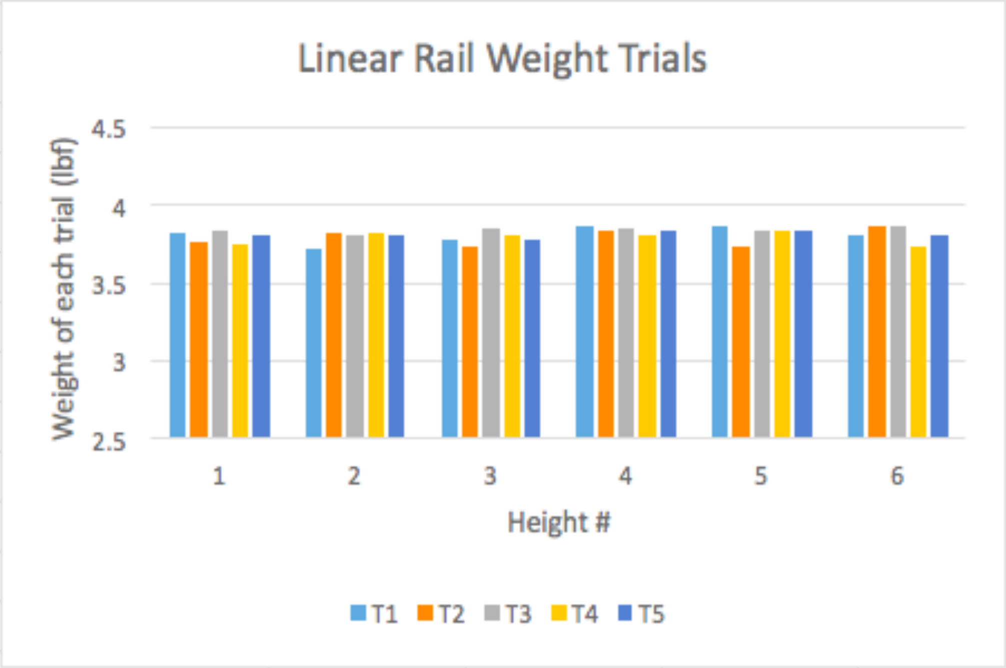


Figure 18: Linear Rail Weight Trials

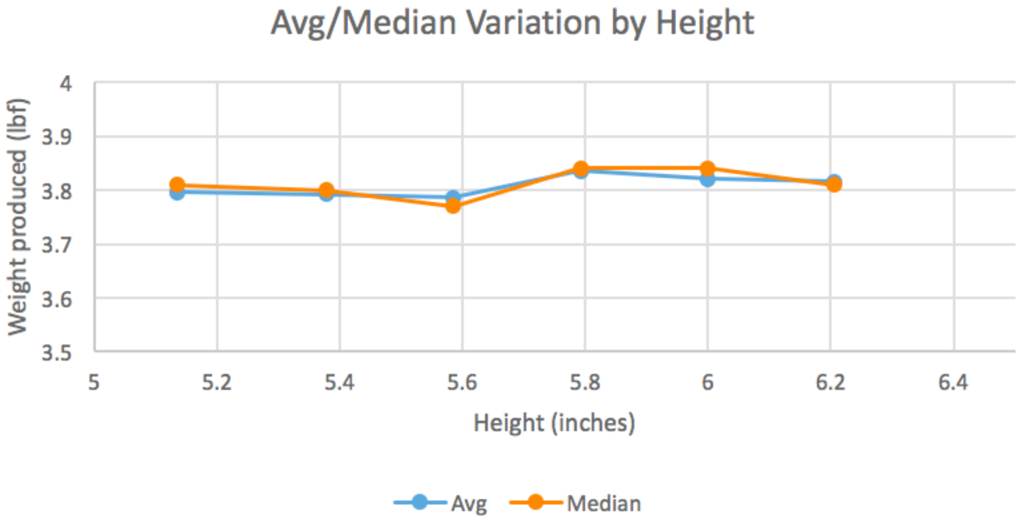


Figure 19: Variation by Height

The mean force discrepancy was only 0.05 lbf. The variation in force for any of the trials was 0.15 lbf over a 1.1 inch height range. This is a 3.94% discrepancy, which is insignificant.

The standard deviation was not more than 0.05 lbf for the trials at each height. After analyzing the data, the team deemed the discrepancy in force at different heights was negligible.

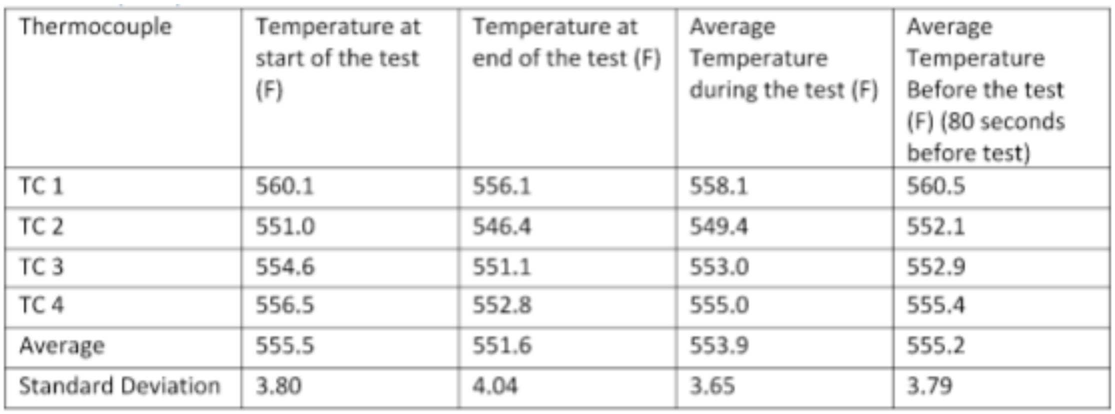
5.2 Verifying Heating Element Uniformity

5.2.1 Heating Element Testing Method

The addition of the ½ inch copper block to the heating element meant that the temperature of the PID and heating element would be greater than that of the copper block. This is due to the thickness of the block and the heat loss to the surrounding ambient air. Therefore, the PID was set to a higher temperature so that the area that comes in contact with the hose, is at the desired test temperature. The copper block has four thermocouples evenly distributed throughout the span of the block to accurately measure its temperature. The heating element has a thermocouple welded to it that is connected to the PID and is controlled by the set point. The four thermocouples from the copper block and the one from the heating element/PID are connected to a module in a chassis for the DAQ system to accurately record the temperatures. When the power is plugged in, the PID will increase the temperature of the heating element and copper block system until it is at the set point for testing. For the team, this meant anywhere between 540 ℉ and 570 ℉ depending on the type of hose and the level of heat resistance being tested. In order for the heating element to be verified and acceptable for testing, the performance criteria needed to be met. The performance criteria specified by the team is the temperature across a three-inch span with a variation of +/- 2% from the average temperature before and during the test until failure. Testing would not be run until all four of the thermocouples in the copper block are within +/- 2% of each other. The average temperature before and during the test will be monitored using the thermocouples in the copper block and the DAQ system.

5.2.2 Results of Heating Element Testing

The results from the heating element testing verify that it is capable of maintaining the temperature across the hose contact area within the desired performance criteria of +/- 2% from the average thermocouple readings before and during the test until failure. Shown below is the thermocouple table for Test #2 for the Kochek DJ 17515-2 which has a polyester outer jacket, an EPDM liner material, and no coating. For this test, the desired temperature was 550 °F. As shown in the table, the average thermocouple temperature to start the test was 555.5 °F, which is well within the 2% variance as specified in the performance criteria. The table shown below adequately represents the general thermocouple temperatures experienced during all of the tests conducted, for each desired temperature.



Thermocouple	Temperature at start of the test (F)	Temperature at end of the test (F)	Average Temperature during the test (F)	Average Temperature Before the test (F) (80 seconds before test)
TC 1	560.1	556.1	558.1	560.5
TC 2	551.0	546.4	549.4	552.1
TC 3	554.6	551.1	553.0	552.9
TC 4	556.5	552.8	555.0	555.4
Average	555.5	551.6	553.9	555.2
Standard Deviation	3.80	4.04	3.65	3.79

Table 4: Hose DJ 17515-2 Test 2 Thermocouple Table

5.3 Verifying Constant Pressure

5.3.1 Hose Pressurization Testing Method

To properly pressurize the hose to 150 psi, as detailed in the performance criteria section of this report, the hose pressure rig was utilized. The desired pressure, 150 psi, is representative of a 7.5 Volt pressure differential received by the DAQ system from the pressure transducer. Once a hose is attached to the pressure rig, the hose is then introduced to residual pressure of 50 psi from the attached water main. The hose is allowed to run for about a minute to purge the hose of air, ensuring a steady stream. Simultaneously the backflow hose from the water main purge is opened for the same purpose, then closed. Once the water appears to be steady, the hose clamps are then tightened to close the hose system, and valve 2 is closed. Valve 3 is then opened, allowing for the pressure washer to be used to increase the pressure to the desired level by triggering activation through the handle. Once the pressure washer is no longer in use, valve 3 is closed. The pressure must be increased substantially due to a pressure drop-off that occurs as the pressure stabilizes throughout the hose. This pressure drop eventually levels off after about one minute has passed. If the pressure settles above the desired level, the empty drain is then opened to relieve any unwanted pressure. These steps are to be followed multiple times to allow for the hose to properly stabilize around the desired pressure monitored through the LabView voltage chart.

5.3.2 Results of Hose Pressurization Testing

The results from the hose pressurization testing verifies this component of the apparatus, and is kept within the performance criteria of a +/- 7 psi range from the pressure experienced before and during the test until failure. The figure shown below shows the pressure remaining within the specified +/- 7 psi range during the first test of Kochek hose DJ 17515-2 which has a polyester outer jacket, an EPDM liner material, and no coating. The figure shown below adequately represents the general pressure level experienced during all of the tests conducted.

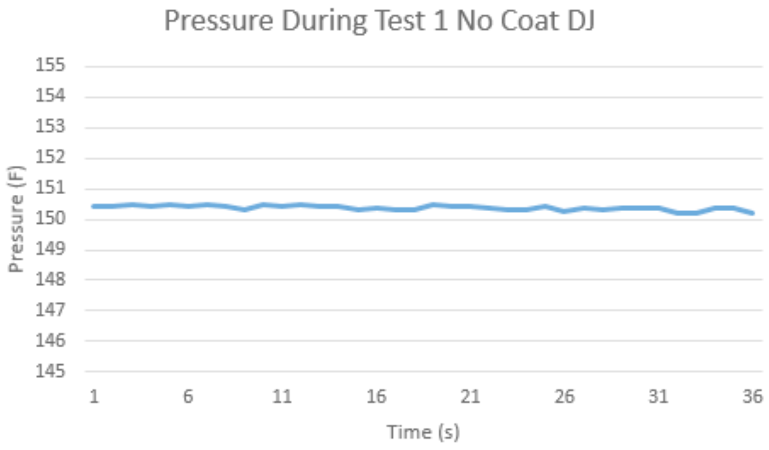


Figure 20: Hose Pressurization Results

5.4 Conclusion for Verification of Prototype Apparatus

The results of the force testing show that the discrepancy in force displayed by the results of this testing was negligible, proving that the height of the hose during testing is insignificant. The heating element testing and the hose pressurization testing both fall within the performance criteria specified in section 4.2. The plexiglass enclosure and the addition of the safety lock were verified as a part of performance testing. Because each component of the prototype apparatus is verified, the apparatus as built is deemed satisfactory in both re-design and construction, therefore physical testing of hoses can be done in order to validate the test apparatus.

6.0 Validation of Test Apparatus

The following chapter proves the validation of the test apparatus. Now that we proved the force is within our criteria, the heat is uniform, and the pressure is constant, the performance testing was done. The performance testing followed the standard operating procedure developed by the team outlined in Appendix A. Before the validation of the system and the performance testing can be achieved, the variables in the study must be chosen. With the variables determined, the system must be validated to ensure it can provide consistent results for a single hose and be capable of repeatable testing. Following the validation of the system, the performance testing can begin where the apparatus will provide consistent results for hoses with different properties.

6.1 Variables

This section will outline the control, independent, and dependent variables for the tests. These variables were selected to isolate the liner type and coating type in order to determine whether or not this apparatus could be used to compare hoses with different properties.

6.1.1 Control Variable: Temperature of Copper Block at Start of Testing

The temperature of the copper block at the start of the test was controlled. Control was achieved by using the DAQ system and the PID. Once the temperature was set on the PID, we monitored the temperatures recorded by the DAQ system. To maintain consistency between tests, we monitored the temperatures of all four thermocouples to ensure that the temperatures were within 2% (+/- 11 degrees) of each other and that the average temperature was within the temperature range being tested. In order to achieve the specified temperature range along the copper block, the PID was manually adjusted to increase or decrease the temperature. Once the temperature ranges fit our performance criteria and remained at a steady-state, the test was run.

6.1.2 Independent and Dependent Variables

The three hoses tested allowed for two independent comparisons. A table of the hoses tested can be seen in Table 5 below.

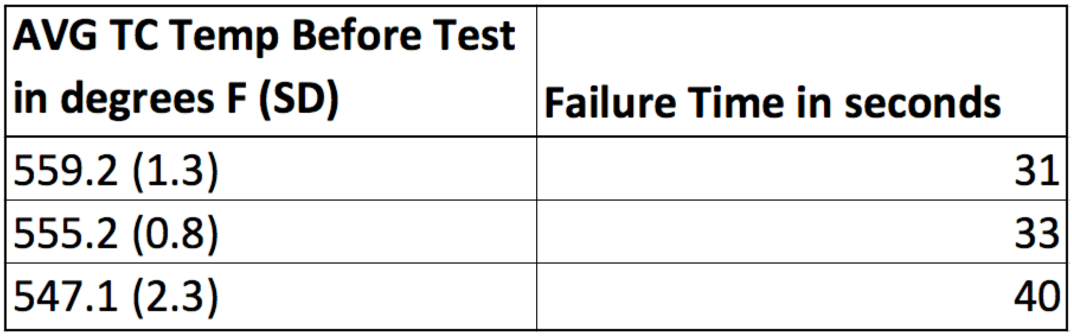
Hose Name	Hose 1	Hose 2	Hose 3
Jacket Material	Polyester	Polyester	Polyester
Liner Material	EPDM	EPDM	TPU
Coating	No Coating	Heat and Abrasion Coating	No Coating
Manufacturer	Kochek	Kochek	Kochek

Table 5: Hoses Used for Testing

We were able to determine the effect of varying liner types by testing Hose 1 and Hose 3, and the effect of heat and abrasion coating by testing Hose 1 and Hose 2. The two liner types that are being compared are EPDM and TPU, while the coating types include no coating and a heat and abrasion coating. The dependent variable we measured is the time to failure. By comparing the failure time for each hose, we came to a conclusion regarding the resistance to failure caused by conductive heat transfer. Table 5 is also referred to in section 6.3 Performance Testing.

6.2 Validation of the System

The system was tested to see if it provides consistent results while remaining intact after the completion of multiple tests. Hose 1 from Table 5 was tested at three different starting temperatures and the time to failure was recorded for each test. Figure 21 displays the average thermocouple temperature for each test with the standard deviation, as well as the time to failure.



AVG TC Temp Before Test in degrees F (SD)	Failure Time in seconds
559.2 (1.3)	31
555.2 (0.8)	33
547.1 (2.3)	40

Figure 21: Test Results for Validating the Apparatus

The visual representation of these test results can be seen in Figure 22, which displays the results of a linear regression analysis that produced an R^2 value of 0.986, which shows a strong correlation between the starting temperature and the failure time of this hose.

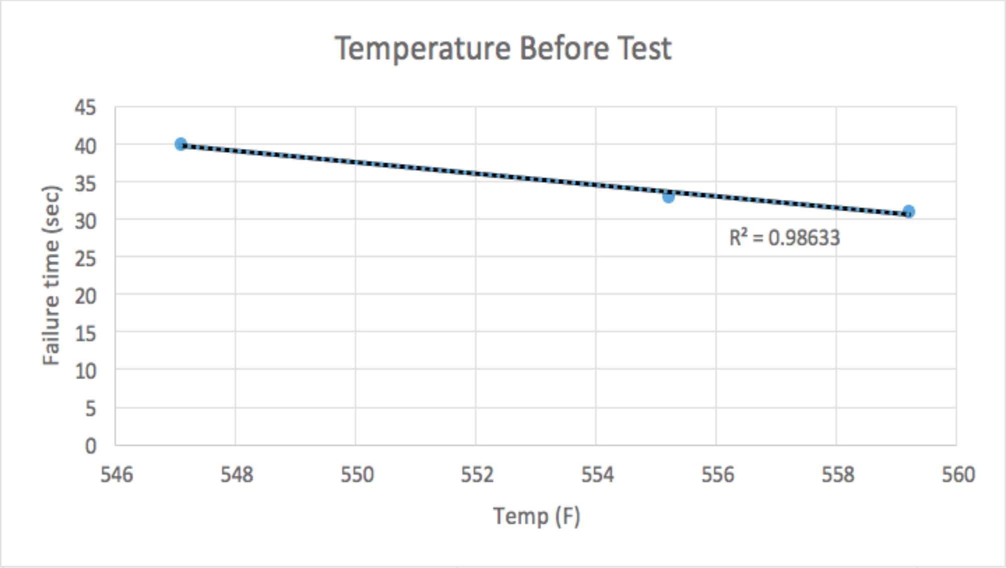


Figure 22: Comparison of All Three Test Failure Times

The results of the tests showed that the apparatus could produce consistent data that was repeatable for a single hose. The results also showed that the apparatus can maintain its construction after several high-pressure hose failures. This led us to conclude that the apparatus was validated and could be used to compare the performance of different hoses.

6.3 Performance Testing

Three hoses were selected that differ in the type of liner and the use of a coating vs. no coating. The hoses used are listed in Table 5 in section 6.1.2. Each hose was tested three times. The average initial temperature of the copper block was between 560-570, 550-560, and 540-550 ℉ for tests 1, 2, and 3 respectively. Below are the main findings from the testing:

- The Heat and Abrasion coated hose can withstand temperatures up to 550 ℉ without failing, and can withstand 560 ℉ for at least 47 more seconds, than the non-coated hose.
- When the EPDM liner hose fails, it loses at least 5 psi over the course of 1 second. When the TPU liner fails, the pressure drop is less catastrophic, in that it does not lose 5 psi over the course of 1 second
- The hose with TPU liner fails 12, 7, and 24 seconds faster than the hose with EPDM liner at 560, 550, and 540 ℉ respectively
- Strong correlation was found between temperature at the start of the test and failure time for the Heat and Abrasion coated hose
- Moderate correlation was found between temperature at the start of the test and failure time for the TPU lined hose and for the EPDM lined hose

The following sections show the results that led us to these findings.

6.3.1 Comparison of Hoses

After completing the tests, the results were graphed to compare each hose's measured time to failure and the set temperatures. Figure 23 below shows the measured time to failure of the tests for each hose.

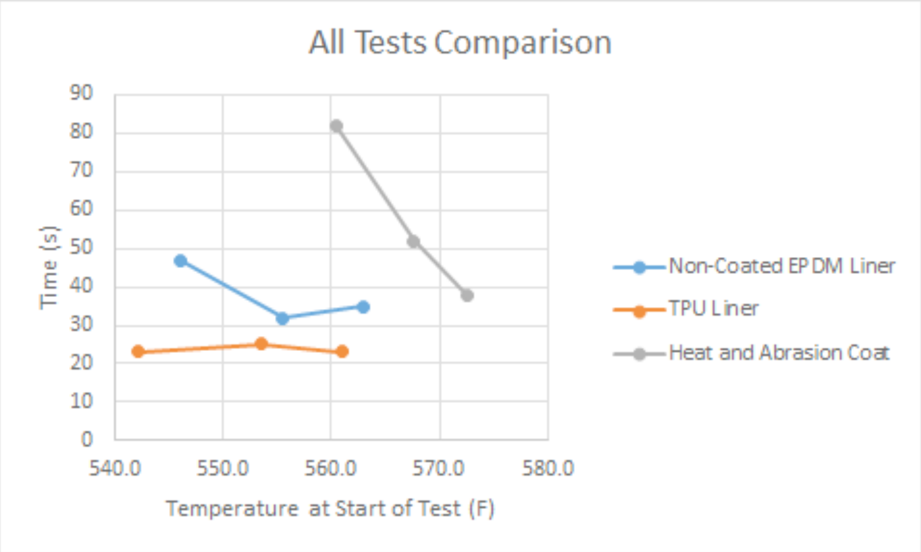


Figure 23: Comparison of All Three Hose's Failure Times

From the figure above, it can be seen that the apparatus is capable of comparing the time to failure of fire attack hoses with different properties. From here, the team compared the different properties of the hoses. The comparisons made were the use of a heating and abrasion coating vs. no coating, and the difference in liner type.

6.3.2 Comparison of Coatings

As expected, the measured time to failure for an individual hose is a function of the copper block starting temperature. In order to quantify the effect of using a heat and abrasion coated hose along the modern fireground, we did a direct comparison of the heat and abrasion coat and the non-coated hose with EPDM liner. This comparison can be seen in the figure below:

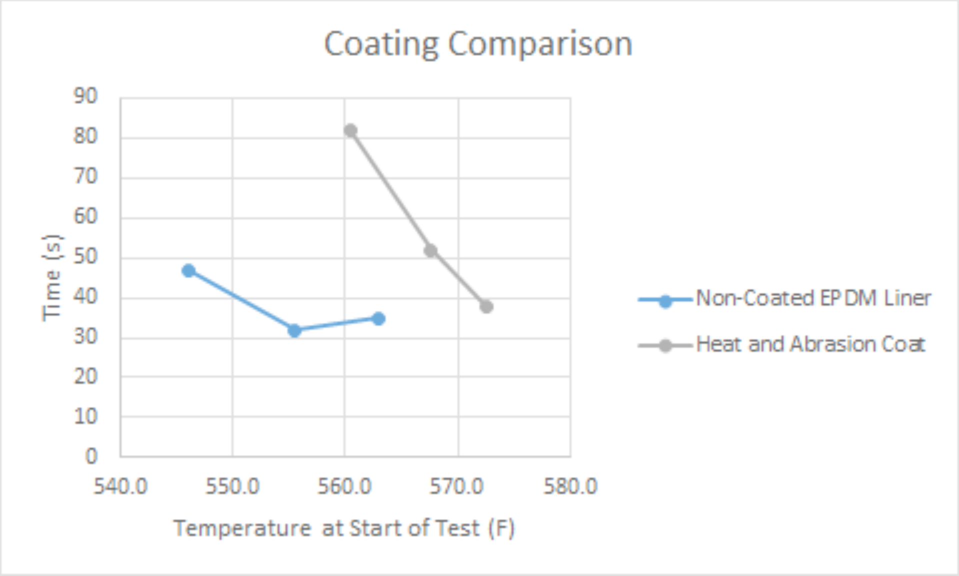


Figure 24: Comparison of Different Hose Coatings

The Heat and Abrasion Coated hose has a first measured time to failure at 560 °F, according to Figure 24. This is because it was originally tested at 540 ℉ and 550 °F, both of which were not hot enough to produce a hose failure after 10 minutes of testing. In order to acquire comparable data, we kept increasing the temperature until we saw failure. Because of these tests, it was determined that the Heat and Abrasion Coated hose was able to withstand temperatures up to 550 ℉ without failing. According to these results, the coated hose would also likely withstand 560 ℉ for approximately 47 more seconds than the non-coated hose. Raw data from the coating comparison can be seen in Appendix B.

6.3.3 Comparison of Liner Types

The re-designed conduction apparatus was also used to determine the magnitude of the difference in time to failure of hoses that have different liner types. Lab observations showed that the EPDM liner fails differently than the TPU liner. The EPDM liner ruptured and had a large drop in pressure while the TPU liner had a leak and a small drop in pressure. The figure below shows the pressure drop of each hose at the point of failure. As seen by the graph, when an EPDM liner hose fails, it loses at least 5 psi over the course of 1 second. When the TPU liner fails, the pressure drop is less catastrophic, in that it does not lose 5 psi over the course of 1 second.

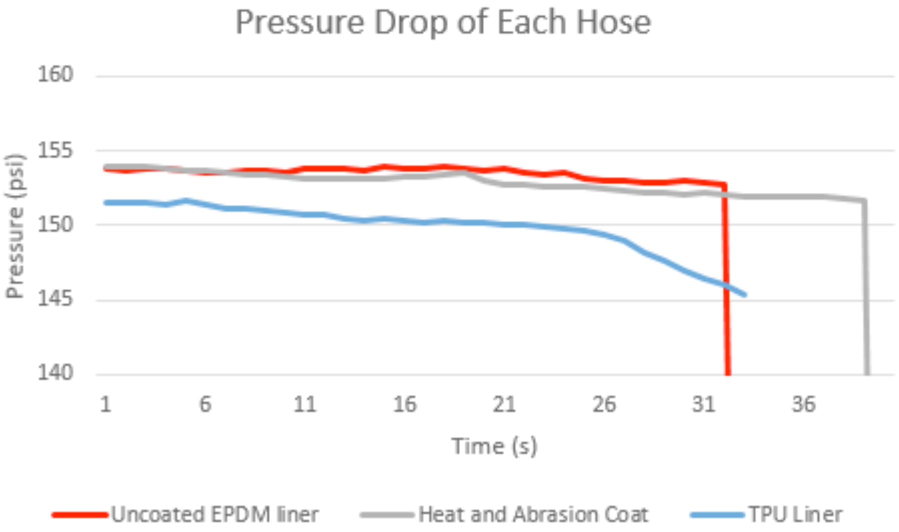


Figure 25: Pressure Drop of Each Hose

The time to failures were also compared. The time to failures of the TPU lined hose and the EPDM lined hose can be seen in Figure 26 below.

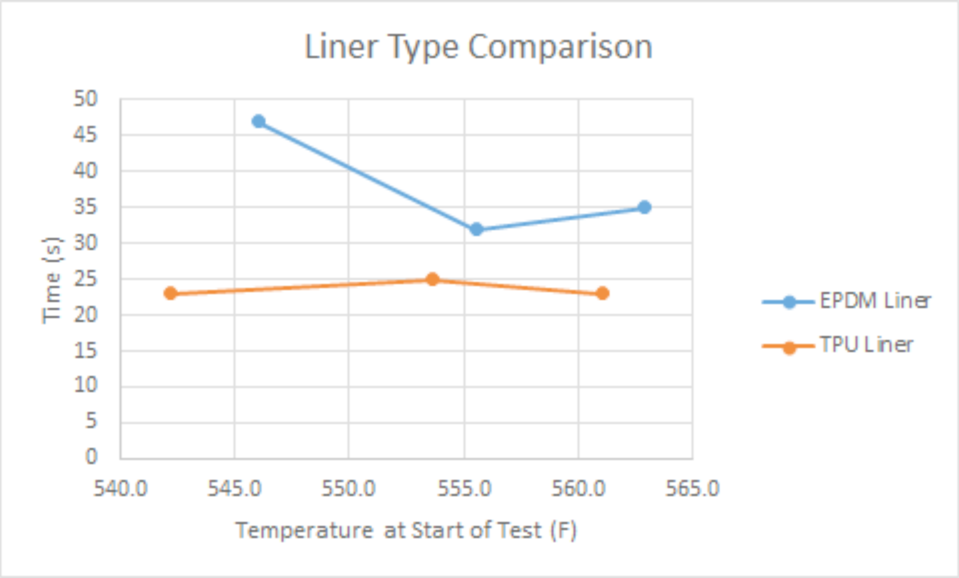


Figure 26: Liner Type Comparison

As seen from Figure 26, the hose with TPU liner fails 12, 7, and 24 seconds faster than the hose with EPDM liner at 560, 550, and 540 ℉ respectively. Raw data from the liner comparison can be seen in Appendix B.

6.3.4 Measurement Uncertainty

An observation from Figure 26 shows that both hoses do not completely follow the expected inverse relationship between temperature and time to failure. To address this issue, the team looked at the average temperature during the test over time for the three tests with the TPU liner. The behavior of the temperature during the test is representative of each test with the other hoses. This was done in order to determine if the temperature of the copper block during the tests was reading the same temperature, explaining why the failure times did not decrease every time that the temperature increased. This figure can be seen below:

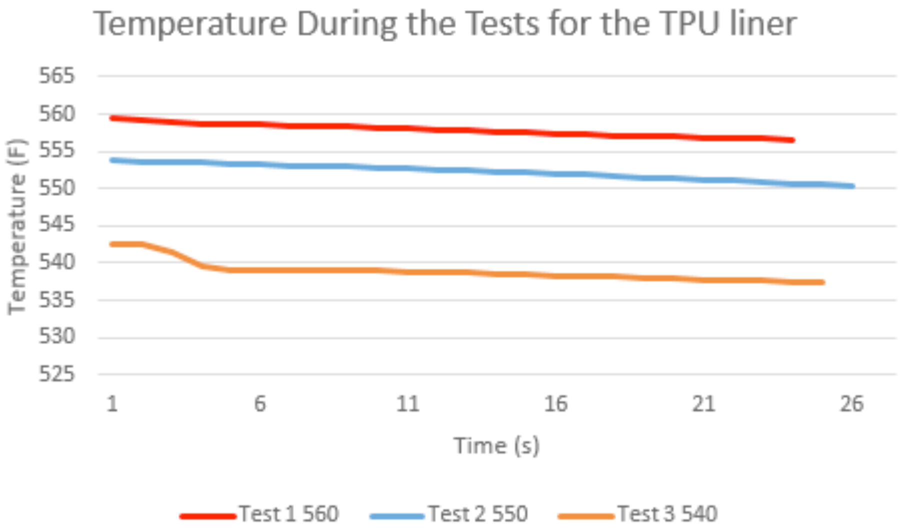


Figure 27: Average Temperature During the Tests for the TPU Liner Hose

Based on Figure 27, we see that the temperatures during the tests decrease during the test. This was determined to be attributed to the heat transfer to the hose but this does not explain why some of the tests do not follow the inverse relationship completely.

A factor that does play a larger role in the uncertainty is in the hand time from the stopwatch. As the block is being placed on the hose, the person holding the stopwatch has a delay seeing the block touch the hose and there is a reaction time to stopping the stopwatch as the hose fails. With failure times that are this close, a majority of the uncertainty lies with the stopwatch recording time. From this, the team declared the uncertainty within a test can range between two and three seconds.

6.3.5 Extrapolation of Results

Following the comparison of the liner and coating types, the team performed a linear regression analysis in order to determine the correlation between temperature at the start of the test and time to failure time for hoses with both liner types and hoses with both Heat and Abrasion coatings and no coatings. An R^2 value between 0.7 and 1.0 shows a strong correlation, where an R^2 value between 0.5 and 0.7 shows a moderate correlation. The figure below shows the actual failure times from the Heat and Abrasion coated hose, the predicted time to failures, and the R^2 value produced from the linear regression model.

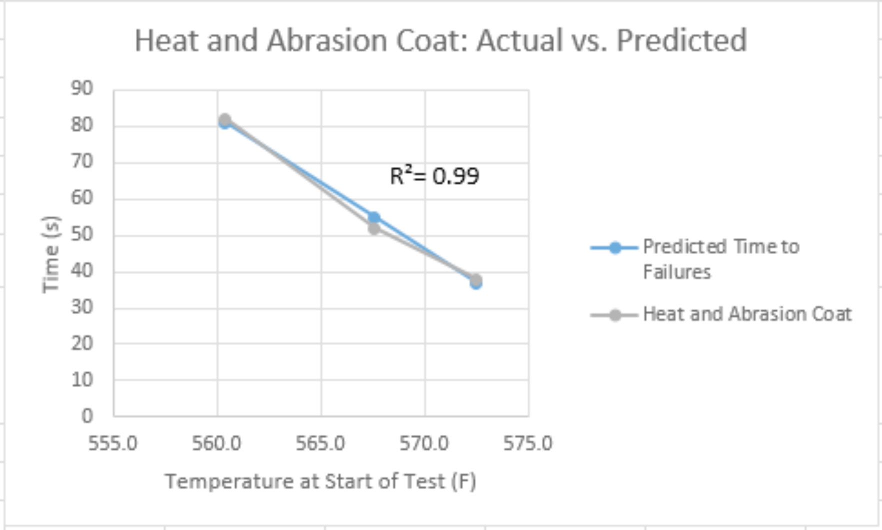


Figure 28: Heat and Abrasion Coating: Actual vs. Predicted

Based on the linear regression, there is a strong correlation between temperature at the start of the test and failure time for Heat and Abrasion coated hose with an R^2 value of 0.99. The figure below shows the actual failure times from the non-coated TPU liner hose, the predicted time to failures, and the R^2 value produced from the linear regression model.

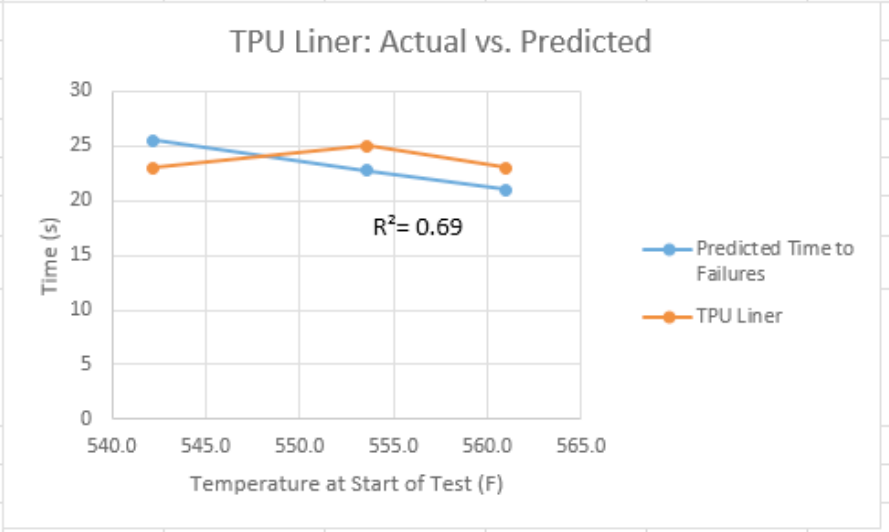


Figure 29: TPU Liner: Actual vs. Predicted

The figure below shows the actual failure times from the non-coated EPDM liner hose, the predicted time to failures, and the R^2 value produced from the linear regression model.

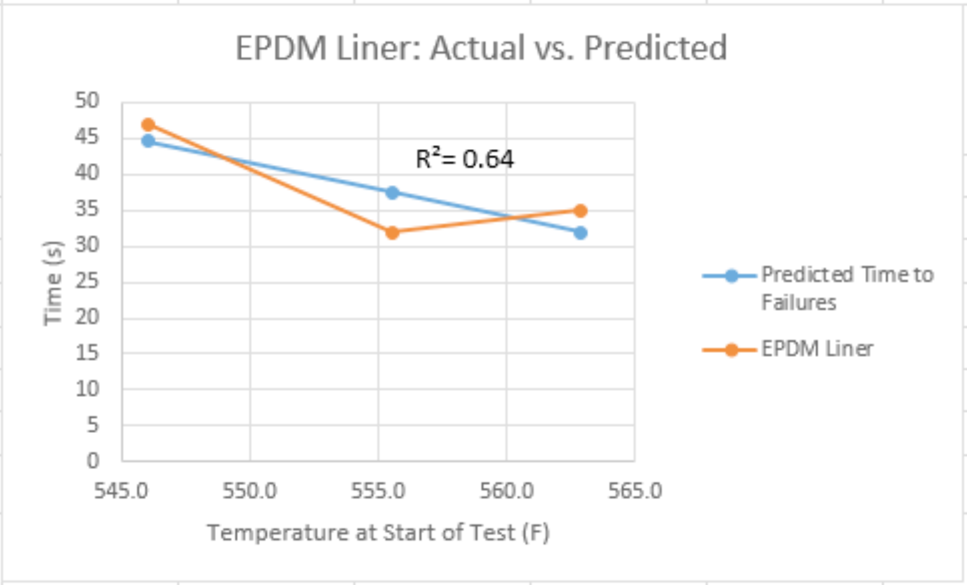


Figure 30: EPDM Liner: Actual vs. Predicted

Based on the linear regressions, there is a moderate correlation between temperature at the start of the test and failure time for the TPU liner hose with an R^2 value of 0.69 and for the EPDM liner hose with an R^2 value of 0.64. Raw data from the actual vs. predicted graphs can be seen in Appendix B.

7.0 Conclusion

The team was able to accomplish re-designing the original conduction apparatus to produce reliable and repeatable tests. The apparatus can be used to collect the data needed to compare fire attack hoses with different properties while they are fully charged with water. Consistent results were proven with a statistical correlation between temperature of the copper block and time to failure for hoses with and without coating, and hoses with distinct liner types. Controlled laboratory conditions were used to simulate the conduction that is seen in modern fire situations. Our team verified the re-design of the conduction apparatus by verifying the temperature of the heating element, hose pressure, force applied to the hose, and physical testing of charged fire attack hoses. The physical testing resulted in the time to failure for each fire attack hose. Failure occurred when water was seen discharging from the hose burnthrough location. To analyze the results of our testing, a linear regression model was used to determine the correlation between the test conditions and the time to failure of each hose. The control variable used in this analysis was the temperature of the heating element at the start of testing. The independent variables used were the liner material and the hose coating. The dependent variable used in this analysis was the time to failure. Our project was completed when we had consistent and comparable results that provided clear evidence that this apparatus can be used to accurately compare the properties of fire attack hoses.

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Appendices

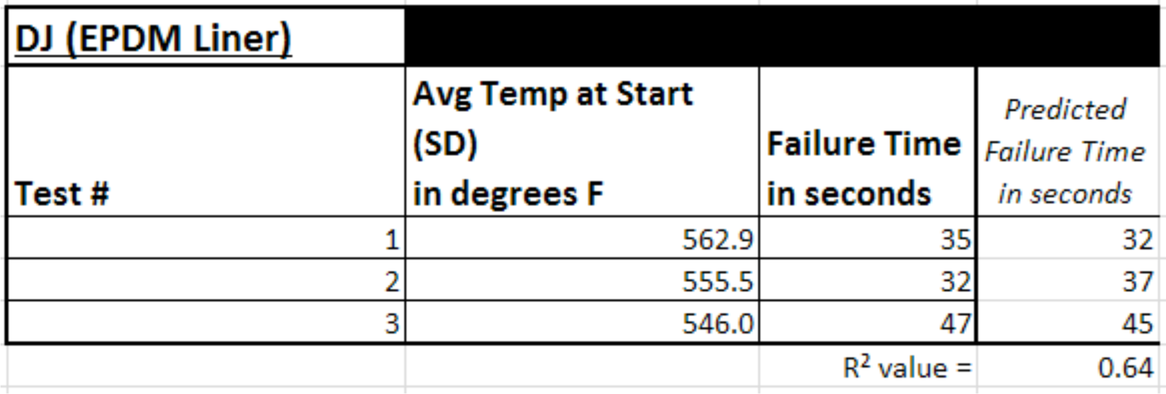
Appendix A

1. Set up Hose Pressure Rig to Water Supply Line using green garden hose
    a. Make sure all valves are closed
    b. Connect the transducer to the hose pressure rig and plug transducer into electrical outlet
2. Secure Fire Attack Hose for testing onto the end of the pressure rig
    a. Open floor grate to drain
    b. Lay hose flat and use serpentine pattern until the hose is fed through the apparatus and into the drain
    c. Cover the part of the hose near the apparatus in trash bags and elevate on 2x4s, to ensure the hose does not get wet following failure
3. Open the water supply line to fill the hose pressure rig with water. Check for leaks. If there are leaks, turn off the water supply and tighten the components of the pressure rig and repeat until there are no leaks
4. When there are no leaks, slowly open valves 1 and 2 allowing water to fill up the fire hose and discharge directly into the drain in the lab
5. Let the hose discharge into the drain for 2 minutes to ensure there are no air pockets in the hose
6. Clamp the hose down using the clamp on the platform that is closest to the hose discharge of the apparatus until water is no longer discharging into the lab drain
7. Open the empty drain nearest to the hose inlet for about 15 seconds to relieve any potential air pockets in the rig
8. Use the purge valve by the water supply line to purge the air in the back half of the pressure rig. Let the water run into the drain on the lab floor for one minute
9. Close valve 2 on the pressure rig
10. Ensure that the thermocouples are not loose in the copper block, and check all electrical connections within the PID and the DAQ system
11. Prop the heating element up using a 2x4 so that the heating element is not within two inches of the top of the hose
12. Turn on the PID and begin heating up the copper block to the desired temperature
13. Run the Labview in order to monitor the pressure of the hose for the transducer and the temperature of the copper block from the thermocouples
14. Use pressure washer to get the pressure up to 150 +/ 7 psi by opening valve #3 and pulling the trigger. Close Valve 3 as soon as pressure washer trigger is released
    a. Let the pressure settle. Typically, the pressure will drop significantly from the peak pressure experienced while using the pressure washer

    b. Use Labview to verify the pressure of the hose
15. Monitor thermocouple all thermocouples using the Labview until the average temperature reaches the desired range and there is a temperature disparity not greater than 2% between any two thermocouples. Adjust the PID as needed to reach the desired temperature
    a. Run labview for 2 minutes to ensure the temperature is leveled out
16. Cover all electrical components near the apparatus with trash bags to protect them from the hose failure, and prepare a stopwatch to use to determine time to failure
17. Lower the heating element/copper block onto the charged fire hose and start the timer on the stopwatch
    a. NOTE: Make sure Labview is still running
18. Watch the hose and document time to visible leakage or catastrophic failure
19. After hose failure
    - Stop the stopwatch
    - Stop the labview
    - Unclamp the hose, shift the hose down, and cut away the failed part of the hose
    - Shift the hose down so the hose can discharge in the drain and shift garbage bags to keep the new area of hose dry

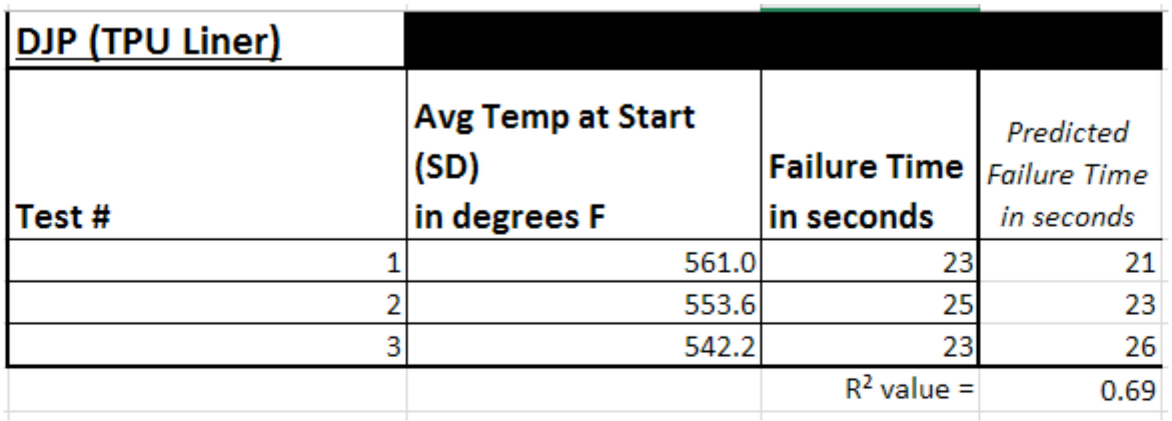
    NOTE: During the shifting of the hose, it is important that the hose does not get wet as it may affect the results of the next test.
21. Clear out water as best as possible and check all thermocouples to see if they are in place
22. Repeat steps 5-21 for more tests

Appendix B



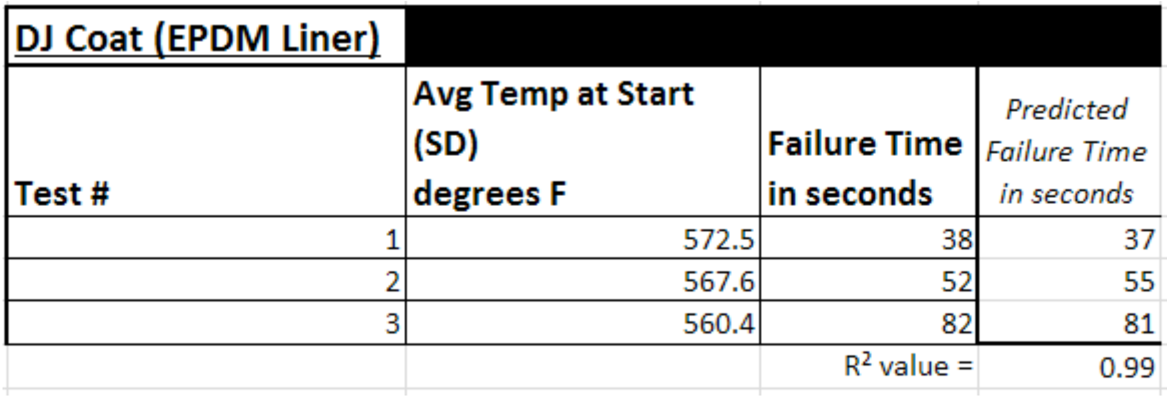
DJ (EPDM Liner)

Test #	Avg Temp at Start (SD) in degrees F	Failure Time in seconds	*Predicted Failure Time in seconds*
1	562.9	35	32
2	555.5	32	37
3	546.0	47	45
		R^2 value =	0.64



DJP (TPU Liner)

Test #	Avg Temp at Start (SD) in degrees F	Failure Time in seconds	*Predicted Failure Time in seconds*
1	561.0	23	21
2	553.6	25	23
3	542.2	23	26
		R^2 value =	0.69



DJ Coat (EPDM Liner)

Test #	Avg Temp at Start (SD) degrees F	Failure Time in seconds	*Predicted Failure Time in seconds*
1	572.5	38	37
2	567.6	52	55
3	560.4	82	81
		R^2 value =	0.99