

**Conductive, Convective, and Radiative Heat Performance Testing of Fire  
Attack Hoses**

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**The Last Call Foundation**

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## Abstract

A fire attack hose is an essential tool to control and extinguish fires and a lifeline for the firefighters manning it. In order for a firefighter to execute his or her duties in relative safety, their hoses must withstand the harsh environments of the modern day fire ground. Fire attack hoses, while rigorously tested for mechanical integrity, are not tested at a level of heat stress representative of a municipal fire ground. This study developed test methods using conductive, radiative, and flame impingement heat stresses to begin to address this issue. A selection of representative fire attack hoses used for municipal firefighting and candidate high thermal performance materials were subjected to these tests to provide groundwork for the development of a next generation fire attack hose.

## Executive Summary

An incident of hose failure at a fire in Boston on March 26, 2014 resulted in the deaths of two firefighters when the hose they were relying on failed to deliver water due to a burn-through. This and several other similar occurrences around the country suggest that currently manufactured fire attack hoses may not sufficiently withstand the levels of heat stress necessary to reliably control and extinguish fires and protect firefighter's lives on the modern day fire ground. The Last Call Foundation was founded in the wake of the Boston fire and the lives lost that day in the line of duty. Through their sponsorship, this study aimed to assess the performance of currently manufactured fire attack hoses as well as higher performing materials not presently used in fire hoses, such as those used in firefighter personal protective gear, when exposed to heat insults more representative of the environments of municipal firefighting.

This research study was conducted in two distinct parts. The first part was conducted with the goal of determining and documenting the performance of currently manufactured fire attack hoses when exposed to a higher level of conductive heat stress than they are currently tested at and when exposed to a European standard hose test involving flame-to-hose impingement. The results of this research are presented in Chapter One of this document. The second part of this study involved testing of current and potential hose materials subjected to a radiative heat stress. A comparison of the performance of jacketing materials used in the manufacture of modern fire attack hoses to the performance of "high heat resistance" materials presently used in firefighter personal protective gear via radiative heat insults is presented in Chapter Two.

### ***Chapter One: Heat Performance Testing of Currently Available Fire Attack Hose***

A market analysis was conducted which identified the materials and construction of the bulk of commercially available fire attack hose models meeting the requirements of *NFPA 1961: Standard on Fire Hoses*. A study of these hoses aided in the identification of a range of physical characteristics that may influence the performance of these hoses. These characteristics then combine to compose the "structure" of the fire attack hose. The market analysis provided an understanding of the municipal fire attack hose structure that is most common in the fire service and therefore of interest to this study.

All hose models tested were double-jacketed, lay-flat attack hoses with a 1 3/4 inch flow diameter. This is the description of the most common hose structure identified by the market analysis for use in municipal firefighting. Within this category of fire attack hose, the majority can be described by four structural components: jacket material, liner material, weight per unit length, and jacket coating. These components were set as our study variables for the first part of this research. An array of ten fire attack hose models was created based on these four study variables. In order to isolate these variables, each hose in the test matrix was chosen with at least one other hose that differed by only one variable such that performance comparisons could be made as a function of each individual study variable. Each of the ten hose models chosen for analysis is NFPA compliant and is available for purchase in the United States.

Once the array of fire attack hoses to be tested was finalized, a set of specifications for the performance tests were established. Overarching specifications included: the test hoses being pressurized to an operational pressure, automatic collection of real-time pressure data within a hose, a test with conduction-based heat transfer and higher temperatures than are required by NFPA 1961, and a test with a second form of heat insult beyond the simple conduction-based heat transfer present in NFPA 1961. A rigorous conduction test, hereby known as the "Hot Plate" test, was developed which utilized a controlled hot surface to impart a conductive heat flux on a hose. To incorporate a second form of heat insult, which involved flame impingement, a replication of the German DIN 14811 Flame Resistance Test was built in the WPI fire lab.

A total of three iterations of apparatus design were carried out for the Hot Plate test. 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. A failure analysis of the trial designs is intended to provide a stepping stone for the future continuation of fire attack hose research and development of fire attack hose performance tests. Data collected from the comparative analysis of the test matrix using the hot plate test was largely inconclusive. However, a clear correlation between the severity of hose failure and the liner material was discovered. Additionally, this portion of the study established a set of criteria with which to quantify the majority of municipal fire attack hoses and demonstrated the challenge to be faced with performance test design.

The set of hoses selected for study were then subjected to the German DIN test involving direct flame impingement. Three of the ten test hoses, e.g. 30%, failed a single trial of this test. While a minority, this failure rate indicates that the U.S. standard is less rigorous than the

German standard and that the level of rigor of the U.S. conductive heat test may not be high enough to serve as an indicator of how the hose would perform on an actual fire ground.

Recommendations for future work are focused on design of the test apparatus, improvements in the experimental procedure, and future research on fire attack hoses. The following recommendations are offered for the continuation of research initiated by this study in an effort to produce conclusive data on currently manufactured fire hose performance.

**In order to advance the third iteration hot plate test design, it is recommended that the following design changes are made. These alterations are intended to reduce sources of error and data inconsistency present in the first three Hot Plate design iterations.**

- 1. A water guard added to the sides of the frame or some other water-proofing method is suggested to prevent pre-wetting of test segments.**
- 2. A heat source without integrated electronic components should be utilized of remove the possibility of water-damage to the heat element.**

If future research were to redesign the frame apparatus, a form of water guard such as acrylic siding would be beneficial to prevent pre-wetting of hose sections. In addition, if the hot plate is kept in a reversed orientation, then the use of a different heat source is recommended, as it would eliminate the potentially damaging effects of water condensation. Specifically, a resistance heater with internal thermocouples would produce a constant surface temperature with a constant input voltage. This would negate the difficult task of shielding electrical components from steam condensation. However, a custom device would require calibration before use to ensure temperature readings of the hot surface are accurate.

**If a new design for a hose-to-hot surface apparatus is required, a cantilever mechanism is recommended over a translating rod mechanism in order to improve design simplicity.**

A cantilever mechanism would rest the hot plate onto the hose without the tight design tolerances required when utilizing translating rods and linear bearings. While rods and bearings are very precise when custom manufactured, a cantilever mechanism is more simplistic and offers comparable accuracy at a lower cost and without custom manufacturing. In the case of this study, the translating rod mechanism created for the third hot plate design iteration offered sufficient precision and repeatability when built with aluminum extrusion framing; however, custom manufacturing would have been required for optimal precision and repeatability. A

cantilever mechanism could also be built with aluminum framing and, if properly designed, could offer improved precision over a translating rod mechanism build with the same components.

**It is recommended that the number of trials in the DIN 14811: Flame Resistance Replica Test is increased to mirror the German standard exactly.**

In the DIN standard, five trials are required for each hose with a mandatory pass rate of 4/5 hoses. The replication conducted in this study included a single trial on each hose. Mirroring the number of trials specified in the DIN 14811 test would increase both the validity and insight provided in regard to hose failures and performance.

**Further Research Recommendations on the Thermal Performance of Currently Available Fire Attack Hose:**

Testing of the full matrix of representative hoses using a waterproofed test platform with the cantilevered apparatus is recommended. Investigation should include determining the impact of each study variable with intent to further verify the effects of coatings, weight per unit length, liner failure methods, and outer jacket performance. An additional recommendation is to expand testing past the original ten hose matrix to account for hose structures separate from the structure focused on in this study. This will allow a broader understanding of attack fire hose heat resistance performance in all accounts.

## ***Chapter Two: Radiative Heat Performance Testing of Materials for Application in Fire Attack Hose***

Initial research focused on materials currently being used in fire attack hose jackets. Polyester and nylon 6.6 are the two most common jacket materials in modern fire attack hoses due to their ability to withstand mold and rot. These materials were not chosen for their heat performance ability nor are they expected to withstand a significant heat stress. NFPA 1961: *Standard on Fire Hose* only calls for conduction resistance testing on currently manufactured fire attack hoses. In contrast, NFPA codes for personal protective equipment (PPE) that firefighters wear during their daily duties do contain extensive heat performance criteria. For instance, NFPA 1971: *Standard on Protective Ensembles for Structural Fire Fighting and*

*Proximity Fire Fighting* specifies a thermal performance test for assessing the abilities of PPE materials to resist a radiative heat flux. Given this fact, it was determined that testing of materials for potential application in fire attack hose jackets would begin with materials currently used in the design and manufacture of firefighter personal protective ensembles.

The four main goals of this area of research were to select candidate materials for testing, create a test methodology for conducting a radiative heat performance test of each material, perform testing on current and candidate materials, and establish performance criteria to compare materials to one another. Five candidate materials were selected based on their PPE applications: Nomex®, Kevlar®, PBI Max®, PBI Kombat Flex® and Pyrovatex® fr Cotton. Pyrovatex® fr Cotton is the only material tested that is not used in firefighter PPE but is used in PPE commonly worn in the chemical and welding industries. The cone calorimeter, a widely studied and utilized industry standard apparatus was selected as the test platform for this research. A test methodology was created that allowed the collection of data for two performance criteria: time to decomposition and time to ignition. Test procedures included multiple trials to ensure accurate data resolution.

The testing procedure specified that materials are initially subjected to a low heat flux which is progressively increased and the times at which the materials begin to thermally decompose (and in some cases ignite) are recorded. Current fire attack hose jacket materials were tested first to create a baseline against which to compare the selected candidate materials. Polyester and nylon 6.6 both reached decomposition temperatures under a heat flux exposure of 11.9 kW/m<sup>2</sup> and ignited under an exposure of 18 kW/m<sup>2</sup>. Of the two current materials, polyester performed better, decomposing and igniting at a later time than nylon 6.6 when exposed to the same heat flux. However, it is important to note that both current hose materials ignited at heat fluxes lower than a value widely accepted as an indicator of flashover (approximately 20 kW/m<sup>2</sup>). Both polyester and nylon 6.6 reached decomposition temperature at a heat flux value just slightly greater than half of the same value widely accepted as an indicator of flashover.

All candidate materials surpassed the baseline performance of the current materials. None of the candidate materials decomposed or ignited during testing at 11.9 kW/m<sup>2</sup> and only two candidate materials, 50% Kevlar®-50% Nomex® and Pyrovatex® fr Cotton, reached decomposition at 18.0 kW/m<sup>2</sup>. At a heat flux of 24.2 kW/m<sup>2</sup>, 20% higher than that indicative of flashover, PBI Max® and Kombat Flex® still did not show signs of decomposition. Testing was

continued on PBI Max® until ignition was reached at 48.4 kW/m<sup>2</sup>, a heat flux more than double that which occurs at flashover.

Given the results of radiative testing the following was concluded: current hose jacket materials do not withstand pre-flashover conditions, there are candidate materials currently being manufactured that perform better in high heat environments than current materials do, and certain candidate materials do not ignite until heat fluxes higher than those indicative of flashover. In light of these findings, it was determined that there are other materials currently being manufactured that are better suited for the high heat environment of the fire ground than the current materials being used in fire hose jackets today.

Recommendations for future work are focused on further testing of the materials selected for this research, along with searching for other materials that are suitable for this type of application.

**Continued testing on selected materials would provide a more complete set of results.**

Continued testing of these candidate materials at the desired heat fluxes of 10, 15, and 20 kW/m<sup>2</sup> is recommended. Materials used in this testing that did not ignite near these heat flux values (Kevlar®, Nomex®, PBI® Fiber and Pyrovatex® fr Cotton) should continue to be tested on the cone calorimeter by increasing the heat flux until ignition occurs. It is also important to know the decomposition point of those materials to determine what their limits are as to what heat fluxes they can withstand. As of now, it is difficult to determine which of those materials is considered to be the best candidate.

**Additional high heat performance materials should be tested following the same methodology.**

This study focused mainly on PPE materials meaning that there are other possible candidate materials that were left out. For example, this project did not look into intumescent materials or other hose configurations. Additionally, some hose models intended for wild-fires have the ability to “weep” meaning that small perforations in the hose allow water to leak out in a controlled manner and pre-wet the jacket material. This keeps the jacket material at a cooler temperature and could potentially prolong its decomposition time. A material that is highly reflective could also be an effective candidate material. If the material can reflect portions of incident heat energy instead of absorbing it, the service life of the hose can be extended.

**High heat performance materials should be tested in combinations.**

Each candidate material in this study was tested individually. The thermal resistance offered by combinations or layers of these and/or similar materials could produce enhanced performance results. Specifying different layer thicknesses or amounts of separate materials could offer greater heat resistance at a lower cost.

**A similar radiative heat insult study should be conducted on liner materials.**

Further investigation into potential “high thermal performance” materials for fire attack hose liners is recommended since this project only focused on jacket materials of municipal fire attack hoses. Current hose liners made of EPDM rubber and thermoplastic polyurethane (TPU) have never been tested under radiative heat fluxes similar to those in this study. In this light, other material may offer better performance against heat insult.

**A prototype hose made of candidate materials should be tested via a rigorous heat performance test for analysis in a large-scale scenario.**

Once the aforementioned testing is completed, and if the material passes non-heat performance testing, the creation of a prototype hose constructed from candidate materials is suggested. This prototype should then be tested according to a procedure similar to those discussed in Chapter One to analyze its applicability in a high heat environment. The results from that testing can then be compared to the results from this research to determine if the prototype displays significant improvements in performance.

***Concluding Statements***

This study provided the first methodologies and data sets for assessing the performance of fire attack hoses and candidate fire attack hose materials against conductive, radiative and flame impingement heat stresses on the scale of those found on the fire ground. It is intended that this study will raise awareness of fire attack hose thermal performance and provide a stepping stone for the continued development of fire attack hoses and the testing methodologies used to inform their design. In this light, recommendations were provided for further testing and improved procedures in order to advance the development of a fire attack hose with higher thermal performance.

## Introduction

### **Project Sponsor: The Last Call Foundation**

On March 26, 2014 a nine-alarm fire broke out in a four-story brick home in the Back Bay of Boston, Massachusetts. Strong winds drove an intense fire that continued to grow, tearing through the brownstone and resulting in unpredictable conditions. In the basement of the building were two Boston Fire Department officials, Lieutenant Edward Walsh and Firefighter Michael Kennedy. They entered the building with the intent of rescuing a possible victim from the basement. Upon reaching the bottom of the stairs, Lieutenant Walsh was recorded calling Command to request water. At this point, the Engine 33 pump operator charged the line. However, “the hose line lost its water due to the rapidly deteriorating fire conditions which compromised the hose” [1]. Tragically, neither firefighter survived the incident.

### **The Issue**

In the weeks and months following this tragedy, there were many questions asked as to why this happened. Initially, many believed that the hose failure was a fluke accident or solely the result of tactical operations. The story of a hose burning through and leaving firefighters trapped inside of a burning building was not one that many had heard before. However, as word about this incident spread, phone calls and emails from fire departments across the country were received saying that they have experienced burn-throughs of fire attack hoses. It became apparent that this was not an isolated incident. It was also revealed that neither the extent nor frequency of burn-throughs in the U.S. was documented or even known. In fact, an in-depth literature review found no research done on the heat performance of the currently available fire attack hoses. In parallel with this study, another research team at WPI created a database where the fire service could report and document fire attack hose burn-throughs [2]. Finally, a major issue that arose was that no test methods are currently in place in the United States for thermal performance testing of fire attack hoses at conditions representative of the municipal fire ground.

## Project Scope

This study was conducted in two parts, each with the high-level goal of contributing scientific data useful for the design and production of a next generation fire attack hose with high thermal performance. The focus of the first part was on understanding and documenting the performance of currently manufactured fire attack hoses when subjected to both a conductive heat insult and flame impingement. The focus of the second part was on testing new materials which are known to have high thermal resistance but are not currently used in the manufacturing of fire attack hoses. These new materials, referred to as “candidate materials”, were tested to document their performance when exposed to a range of radiation heat fluxes. The performance of these candidate materials was then compared to the performance of current jacket materials when exposed to identical radiative heat exposures.

To understand the performance of currently manufactured fire attack hoses when exposed to conductive heat insult and flame impingement, a conduction-based heat insult test and a replication of a German flame impingement test were developed. These tests allowed for the comparison of an array of ten fire attack hose models that conform to the most common design and structure of municipal fire attack hoses today. The four principle study variables that were investigated as the main distinguishing factors in the structure and performance of a fire attack hose include the liner material, jacket material, weight per unit length, and jacket coatings. The initial design of a conduction-based test focused on subjecting hose specimens to higher steady-state heat fluxes than are present in current U.S. fire attack hose standards. With this goal in mind, an iterative process of design and testing was carried out to refine the test accuracy and repeatability. Ultimately, three design iterations were carried out and a set of recommendations was given for further development of the test design and the direction of future research. Although a final satisfactory design was not reached, another research team at WPI has begun to build off of the recommendations provided.

This research also focuses on identifying candidate materials for application in a fire attack hose jacket which were then compared to the baseline radiative heat performance of materials currently used for fire attack hose jackets. Referencing the standard ASTM E1354 (which deals with test methods for measuring heat release rates) and using a widely accepted test apparatus, a methodology was created that allowed a quantitative data comparison between materials. The radiative testing was performed on a cone calorimeter at varying heat flux

exposures to accurately compare the thermal performance of these materials. Criteria were identified in order to rank the materials based on their performance during testing. From this, recommendations were made to continue testing on selected materials and to perform additional investigations into other high heat performance materials.

# Chapter 1

## Heat Performance Testing of Currently Available Fire Attack Hose

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## 1. Goal Statement

The main goals of this study were as follows:

1. Design a rigorous performance test to accurately and repeatably assess the performance of a variety of commercially available fire attack hose models subjected to a range of conduction-based heat fluxes.
2. Replicate the essential aspects of the German DIN 14811 flame resistance test to assess the performance of the same set of commercially available fire attack hoses when subjected to direct flame impingement.
3. Investigate the impact of each of the four principle structural components of a municipal fire attack hoses as it relates to a hose's overall resistance to a heat stress.

## 2. Background

### 2.1 Modern Municipal Fire Attack Hoses

Today's fire service plays an essential role in our public safety, as it has for hundreds of years. The firefighters who risk their lives for the safety of others depend on their equipment to be functioning properly to keep them out of harm's way. One of the most crucial pieces of equipment to a firefighter is the fire hose which provides a critical line of defense second only to the fire fighter's personal protective ensemble (PPE). Next to the PPE, "a fire hose surely is the firefighter's next lifeline" [2].

There are multiple types of fire hoses in the industry today that perform different functions on the fire ground, including water supply and fire attack, however, it is the fire attack hose that is the subject of this study. The purpose of a fire attack hose is to transport water from the fire pump to the firefighter, allowing him or her to extinguish flames at strategic locations anywhere on the fire ground. These hoses must be durable and reliable against the harsh conditions present on the fire ground and be able to withstand multiple years of service.

#### 2.1.1 An Overview of Hose Structure

The two main areas of structural firefighting are industrial and municipal. This study focuses on the fire attack hoses used for municipal firefighting, which involves residencies and most non-industrial occupancies. These hoses are typically "lay-flat" and non-rigid, making them easily maneuverable while empty and efficiently storable 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 [3]. 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 differences in weight between hose models are due to differences in material density and quantity.

There are the three principal lay-flat hose structures: single jacket, double jacket, and thru-the-weave extrusion. Double-jacketed hoses are the norm when fighting a municipal fire while single-jacketed hoses are common in industrial applications. Thru-the-weave extrusion hoses are seen in both fire attack and water supply applications, although they are less common in fire attack. A single layer of woven fabric bonded to an inner elastomer liner forms the modern single jacket attack hose. 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. 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 [3]. 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. This type of construction is less common but is seen in supply lines and specially manufactured fire attack lines.

### 2.1.2 Jacket Materials

The outer jacket of a fire attack hose is designed and tested to withstand pressures ranging from 300 psi to the manufacturer specification, and the outer jacket is what protects the watertight liner and/or inner jacket from heat, abrasion, and puncturing [8]. 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 manufactured today based on the current market. This being said, cotton jacketed fire attack hoses are still in use at fire stations all over the country, and though no longer manufactured, make up a significant part of the fire service's attack lines.

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 [6, 11]. Polyester fibers have a melting point temperature of approximately 250°C. 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°C [7, 11]. For both materials, their melting points allow them to survive most ambient conditions, however contact with hot gas flows, flames or hot surfaces sufficient in

duration to heat the hoses at or above these temperatures would cause material degradation / melting.

### 2.1.3 Coatings

A majority of fire attack hoses are sold with their jackets treated with a coating meant to enhance the hose performance on the fireground, as well as increase the overall lifespan by preventing unnecessary wear and tear. The exact composition of the jacket coatings vary 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 were designated by manufacturers to provide either abrasion resistance or abrasion *and* heat resistance to the hose jackets they are applied to.

### 2.1.4 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 with thermosetting synthetic rubber, such as ethylene propylene (EPDM rubber), or thermoplastic material, such as thermoplastic polyurethane (TPU). Some fire attack hoses models have liners made of nitrile, although this is less common.

On one hand, EPDM has the appearance of regular black rubber and is the most commonly manufactured synthetic rubber in municipal fire hose liners. It has a minimum service temperature of -60°C and a maximum service temperature of 300°C. This material is used in fire attack hoses due to its high elasticity and strong resistance to heat, ozone, and weather [4]. On the other hand, TPU is the most commonly utilized thermoplastic elastomer. TPU is very versatile and has a high elongation and tensile strength, as well as the ability to resist oil, solvents, chemicals, and abrasion [5]. This material has a mildly transparent appearance when used as a fire attack hose liner.

## 2.2 Double Jacketed Fire Attack Hose Manufacturing Process

While there are several types of fire attack hoses, most share a similar manufacturing process. In the case of a double-jacketed hose, the general process includes the following steps. First, each of these two jackets are woven separately, one slightly smaller than the other. They are then woven using two different types of yarn, a filler yarn and a warp yarn. The warp yarn

runs the length of the hose and is usually made out of a polyester or nylon material. The filler yarn runs a tight spiral around the circumference of the hose, crisscrossing between the warp yarns. In some cases, the jackets are then dipped in a tank of elastomeric coating, which increases abrasion and heat resistance [3].

Next, the rubber material goes through an extruding process to form the liner. During this process a mass of uncured rubber is inserted into an extruder. At this point it is warmed before being shaped into a tubular liner by a cylindrical press. The liner is soon vulcanized, which makes the rubber strong and elastic. The vulcanized liner is then passed through a rubber calendar, which wraps another thin layer of uncured rubber around it. The jackets and liners are then sent for assembly.

In the assembly process, the outer jacket is first laid out flat. The inner jacket and consecutively the liner are then pulled through, creating a loose hose. One end of the hose assembly is clamped shut and a steam nozzle is attached to the other end. This pressurizes the hose and presses the three layers against each other. The high pressure and heat cause the rubber of the lining to bond with the inner jacket. Couplings are added to the hoses through the use of an expansion mandrel, which seals the jacket between a brass ring and the coupling. The hoses are then pressurized to between 600-800 psi to test for leaks [3].

## 2.3 Current Fire Attack Hose Performance Standards

### 2.3.1. NFPA 1961

NFPA 1961: Standard on Fire Hoses, states the design, construction, inspection and testing requirements for all newly manufactured fire hoses. The code is not required; however, most manufacturers comply with it for safety purposes and buyer satisfaction. This standard includes kink tests, burst tests, and proof tests. NFPA 1961 does not explicitly define the testing method for the heat resistance test, 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 [8].

The heat resistance test set forth by UL 19 and FM 2111 is conductive and 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. Upon completion of the trial, the hose is allowed to cool and is then pressurized

to three times service test pressure. If there is no observable leakage or critical damage, the hose is considered to have passed the test [9]. This test, however, is only specific to one type of heat transfer, when all three are present in a fire environment.

### 2.3.2 The DIN 14811 Flame Resistance Test

The German Institute for Standardization has developed a fire hose performance standard that is referred to as *DIN 14811: Fire-fighting hoses – Non-percolating lay flat delivery hoses and hose assemblies for pumps and vehicles*. The standard includes a “flame resistance test” that requires a test hose to be able to perform against flame impingement and be able to self-extinguish. This test requires five trials of pressurizing a fire hose with water to 70 psi and securing a portion of it perpendicular to an open flame such that the flame impinges the hose for ten seconds. If the test hose can withstand the ten-second impingement without bursting and if the after-flame or after-glow time is no more than three seconds, the hose is considered to have passed the trial [10]. The hose must pass four out of five trials to pass the test. In comparison to the heat resistance performance test specified in NFPA 1961, the DIN 14811 test introduces a whole other form of heat insult as well as higher level of rigor. Although the trials times are 1/6 as long, the insult temperatures are at least 6 to 9 times as high.

## 3. Methodology

### 3.1 Market Analysis of Currently Available Fire Attack Hoses

To understand the range of fire attack hose models and characteristics available for purchase in the U.S., a search of multiple manufacturer websites was carried out during the early stages of this study. At the onset of the search, the only parameters that had been specified for the fire hoses to be tested were that they were:

- Intended for municipal firefighting
- Lay-flat construction
- Specified as fire attack hose
- Not specified as “large diameter”

This study is focused on municipal firefighting, which involves lay-flat hose construction as the norm since lay-flat construction allows for more efficient storage on the fire trucks. Fire hose specified and used as fire attack hose is laid out from the fire truck to the source of the fire. In contrast, large diameter hoses are laid out from the nearest hydrant to the truck and are used to supply water to the operation. Large diameter fire hoses are also impractical for most municipal fire attack operations even if the manufacturer specifies them for “fire attack”. The outcome of the search was a list of fifty-eight hose models available from eleven different hose manufacturers. All fifty-eight fire attack hoses met the four criteria stated above. An assessment of the hose list confirmed that most municipal fire attack hoses are double jacketed and have the option for nominal flow diameters of 1 ¾ and 2 ½ inches.

### 3.2 Establishment of Study Variables

Based on background research and the market analysis, the hose structure of interest was determined to be a lay-flat double-jacketed hose with a 1-¾ inch flow diameter, which is most representative of a generic fire attack hose that would likely be used by a firefighter, neglecting any specifications for couplings or nozzles. The array of lay-flat double-jacketed hose available in 1-3/4” flow diameter differed in four key variables. These included liner material, jacket material weight per unit length, and whether or not the hose was coated for abrasion and/or heat. In terms of weight, the majority of double-jacketed 1-¾ inch attack hoses ranged from 14-19 lbs per 50 feet of linear hose length with outliers as light as 12 lbs per 50ft and as heavy as 23 lbs per 50ft. All hose models from the market analysis had either polyester or nylon jackets and

the large majority had either EPDM or TPU liners. Based on these findings, the following four study variables were selected:

- Weight per 50 feet (14 -19 lbs. per 50ft)
- Jacket Material (Nylon or Polyester)
- Liner Material (EPDM Rubber or TPU)
- Jacket Coating (None, Abrasion Resistance Only, Abrasion & Heat Resistance)

### 3.3 Development of a Parametric Fire Attack Hose Test Matrix

With a set of study variables established, the next step was to develop an array of representative fire attack hose models (i.e. a “test matrix”) to analyze. The chosen models had to represent the fire attack hose structure and materials identified as commonplace in municipal firefighting. Additionally, each model was NFPA 1961 compliant in all aspects of its design and performance.

The final matrix of hoses to be evaluated is shown in Table 1. Hoses are identified by the four study variables as opposed to the particular hose manufacturer. The matrix allows for a parametric analysis of the hoses in terms of liner material, jacket material, weight, and coating. Comparisons can be made between hoses in the matrix that differ only by one variable. For example, Hose 3 and Hose 4 both weight 14 lbs per 50ft length and have nylon jackets coated for abrasion resistance. This isolates a difference in liner material that can then be analyzed.

Hose Number	Hose 1	Hose 2	Hose 3	Hose 4	Hose 5
Weight per 50ft	14	14	14	14	17
Jacket Material	Polyester	Polyester	Nylon	Nylon	Polyester
Liner Material	EPDM	TPU	EPDM	TPU	TPU
Coating	Abrasion	Abrasion	Abrasion	Abrasion	Abrasion & Heat
Hose Number	Hose 6	Hose 7	Hose 8	Hose 9	Hose 10
Weight per 50ft	17	19	15	17	14
Jacket Material	Polyester	Polyester	Nylon	Polyester	Polyester
Liner Material	TPU	EPDM	EPDM	TPU	EPDM
Coating	None	Abrasion & Heat	None	None	None

**Table 1: Hose Test Matrix**

### 3.4 Performance Test Specifications

With an array of test hoses compiled, the next step was to determine the specifications that would inform the choice of an international fire hose performance test and the design of a rigorous conduction test to be used in the parametric analysis. The two primary specifications for both tests were that they be repeatable, rigorous and realistic and that the hose specimens be uniformly pressurized during all trials. Repeatability reduces random error and helps improve data accuracy. Rigor ensures that performance in terms of time to failure can be observed. Realism governs the heat insult magnitude and modes of heat transfer such that they are comparable to what a hose would experience on the fire ground. Realism also dictates that the hose is pressurized to simulate a fire-fighting situation. A consequence of pressurizing the hoses was to define “failure” as the initial loss of constant pressure. A hose was considered to have failed during a testing trial if any loss of pressure was recorded and the failure itself could be physically observed. Other specifications for the individual tests are given below.

For the international performance test:

- The mode of heat transfer to the hose must be convection and/or radiation.
- The test must be designed for the equivalent of a municipal fire attack hose.

For the conduction test:

- The conductive heat source must be steady state and adjustable.
- Heat insult temperatures must match or exceed 260°C while remaining realistic.

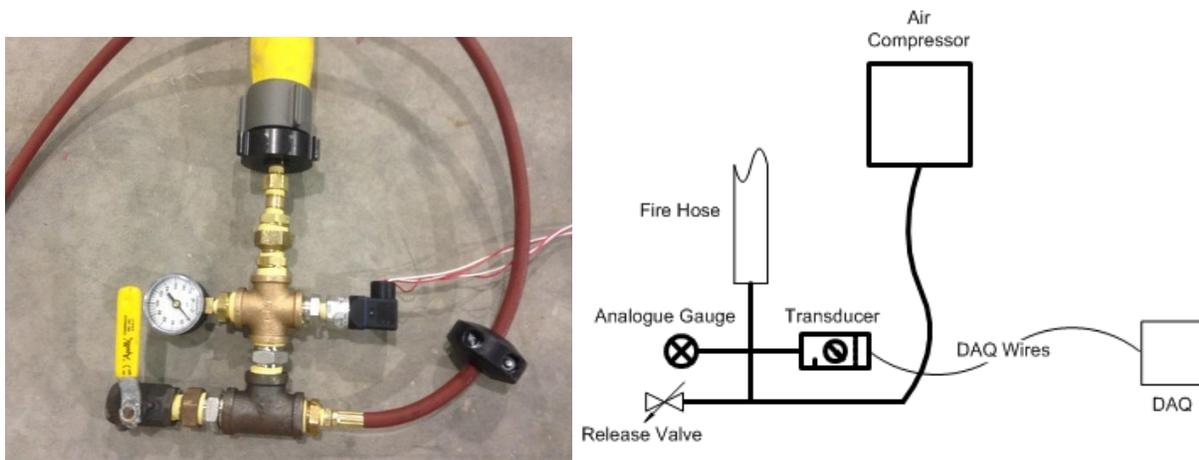
### 3.5 The Hot Plate Test

The original conduction test, which was dubbed the “Hot Plate Test”, involved draping a hose pressurized with air over a digital laboratory hot plate, supporting both ends of the hose, and recording time to initial pressure loss (See Figure 2). The hot plate was set to four successive temperatures: 350°C, 400°C, 450°C, and 500°C. There were four trials run at each temperature for each hose in the matrix. Air was the chosen medium, as it would not cause water damage to the electronic hot plate in the event of a failure. The hoses were pressurized to 110 +/- 7 psi, a realistic operational pressure for fire attack hoses. The set up for the first iteration of this design can be seen below in Figure 3. The entire procedure can be seen in Appendix C.

Initially, this test was designed with the knowledge that the failure times would not emulate those that may be seen in a fire environment since air, not water, was used to pressurize the hoses. The hot plate test was intended solely to compare the four hose variables – weight per unit length, liner material, jacket material, and coating. The effect of water as a heat sink was seen as a consistent variable that could be effectively factored out of the testing scenario.



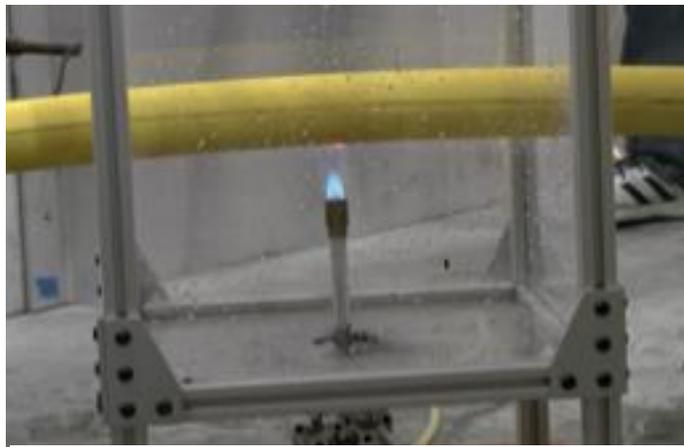
**Figure 1: First Hot Plate Iteration Design**



**Figure 2: First Iteration Pressure Rig**

### 3.6 The DIN Flame Test Replication

The German DIN 14811: 2008-01 Flame Resistance Test was the foreign standard test ultimately chosen for replication in this study. This test involves subjecting a hose to ten seconds of flame impingement. The hose specimen is considered to have passed the test if it does not ignite, burst, or if it extinguishes itself within three seconds of removing the flame. The full procedure of this test can be seen in Appendix A. While an apparatus was built to replicate that used in this standard, it was not certified as an official test. Subjecting each hose in the test matrix to a replication of the DIN Test produced a case study of how U.S. hoses perform against a rigorous foreign standard specifically designed for municipal attack hoses. The experimental setup is shown in Figure 3 below. The compartment was built based on the recommended dimensions of DIN 14811: 2008-01 [9]. The walls were made of clear acrylic and the frame of extruded aluminum. Specifications such as the use of a Bunsen burner flame and the mode of heat transfer (flame impingement) were followed exactly. The non-trivial difference between the standard requirements and the test performed for this study was the number of trials per hose. A single trial was performed per hose as opposed to the five trials required in the standard. If three or more of these trials result in failure, the hose specimen is considered to have failed the DIN 14811: 2008-01 Flame Resistance Test.



**Figure 3: Flame Chamber Test Set-Up**

Using the same test apparatus, each hose in the test matrix was also subjected to a second test, which is referred to as the "Flame Chamber Test". This involved the same set up, however the flame impingement was held constant until loss of water pressure could be observed. This "Flame Chamber Test" was intended to compare flame resistance performance among the hose array in terms of time to initial pressure loss. The testing procedure is given in Appendix B.

### 3.7 An Overview of Data Acquisition and Hose Pressurization

Automatic data collection was required for all testing instances and trials. All data was recorded through a basic data acquisition system (DAQ system). The system included a Texas Instruments DAQ chassis and analog module package for raw data collection, in addition to a LabVIEW 2013 virtual instrument (VI) program for live data collection and result output (See Figure 4).



Figure 4: DAQ System

The DAQ system was capable of measuring voltage data, which could be translated directly into pressure values. Voltage data versus time was collected via a pressure transducer and a power supply, which provided an excitation voltage to the transducer. The transducer outputted a 0-10 volt reading, which could be translated to pressure on a 0-200 psi scale (i.e. 1 Volt = 20 psi). The transducer was mounted to a “pressure rig” constructed of national pipe thread (NPT) piping that connected the pressure source to the fire hose.

By Pascal’s Law, which states that the pressure applied to a confined fluid increases the pressure throughout the fluid by the same amount, the transducer could measure the pressure in the fire hose. This being said, the compressibility of air produced inevitable minor uncertainties. The time histories of pressure within the hose for a given trial were recorded and tabulated via LabVIEW 2013. Times to failure were secondarily recorded using a stopwatch and then written

down manually. An analog gauge mounted to the pressure rig also secondarily measured pressure in the hose.

### 3.8 Third Party Quality Assurance

Before the hose array was subjected to any testing, each individual hose was removed from original packaging, checked for physical defects, pressurized to 250 psi for 5 minutes, and then checked for leaks by engine crews at the Worcester Fire Department (See Figure 5). A pressure of 250 psi is higher than any pressure achieved during actual testing. Therefore, this third party testing ensures there are no hose defects and that the quality of the hoses is sufficient prior to any data being collected.



**Figure 5: WFD Quality Assurance Testing**

### 3.9 Testing of Fire Attack Hoses

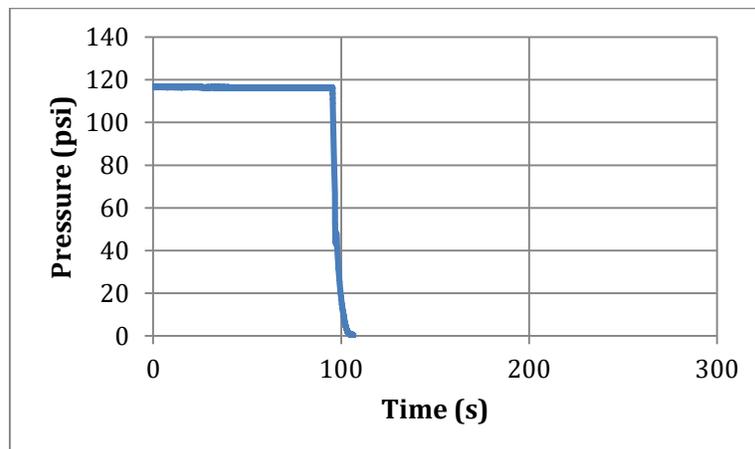
After it was confirmed that a hose specimen was in operational condition, performance testing began. Initial trials were carried out using the Hot Plate design described in Section 5.5 as well as the DIN: 14811 replication and flame chamber test as described in Section 5.6. The data collected from the testing trials and shown in the results section has been selected to show major findings. In some cases, these findings were that apparatus design changes had to be implemented and experiment improvements had to be made.

## 4. Results and Discussion

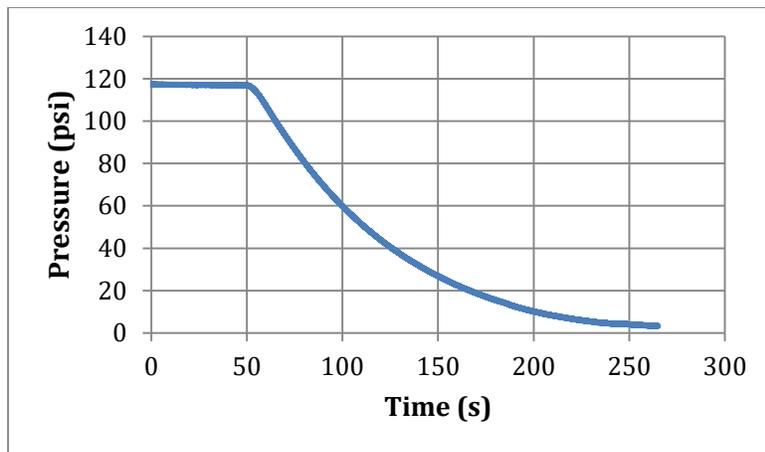
### 4.1 Test Results of the First Hot Plate Design

The first hot plate test design ultimately served as an initial step in designing a more rigorous conduction test. A full parametric analysis was not completed using this design since a series of design changes were decided upon before all hose models could be shipped to the testing site. However, enough trials were performed to reveal a connection between liner material and hose performance and to identify other potential design improvements.

During this first iteration of hot plate testing, it was found that hoses displayed two different modes of failure that were dependent on liner material (i.e. TPU or EPDM). On one hand, 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. Figures 6 and 7 below display pressure loss curves recorded from the hot plate trials of an EPDM and a TPU lined test hose, exemplifying the dissimilarity in time to total pressure loss.

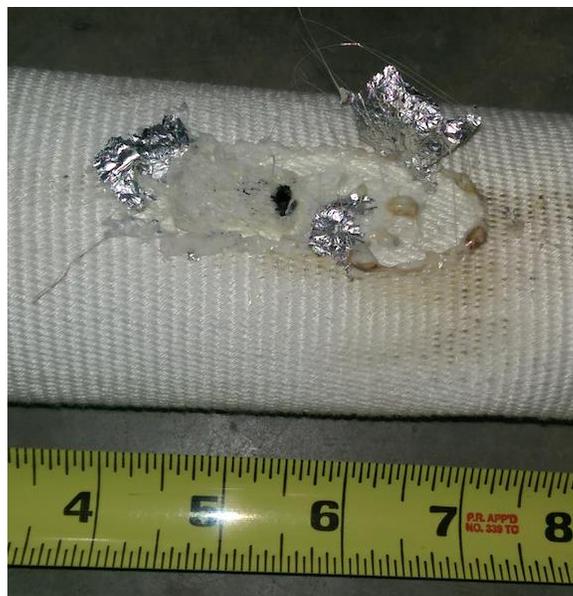


**Figure 6: Example Pressure Loss in EPDM Lined Hose Trial**



**Figure 7: Example Pressure Loss in TPU Lined Hose Trial**

These failure modes held true through all three hot plate testing iterations. Data was inconclusive as to whether EPDM or TPU hoses lasted longer until initial pressure drop; however, TPU lined hoses consistently took a longer time to reach a point of half-pressure when compared with EPDM lined hoses. The difference in failure modes is based on the thermo mechanical properties of the liner material. More specifically, EPDM is thermosetting while TPU is thermoplastic. When a heat flux is applied to the EPDM lined hoses, the outer jacket and coating are first melted away leaving the liner exposed. The application of heat caused the liner to build up interior thermal stresses until it eventually ruptures as seen in Figure 8 below. If these holes are large enough, they could render the hose incapable of delivering water to the nozzle at an adequate pressure to fight a fire.



**Figure 8: EPDM Hose Failure Example**

When the same heat flux was applied to a TPU lined hose, the jacket and coatings acted similarly by melting away and leaving the liner exposed as seen below in Figure 9. However, the liner also melted instead of building internal stresses. The pressurized water released slowly through pin-hole sized orifices that formed in the melting material at a much slower rate than any EPDM lined hose.



**Figure 9: TPU Hose Failure Example**

The conduction-based nature of the hot plate test requires that the hose be in constant contact with a solid surface. This fact possibly contributes to the failure modes observed from EPDM and TPU lined hoses. The slow-release nature of TPU lined hoses is likely assisted by the presence of a solid surface pressing against the leakage orifices, while the energetic releases of EPDM hoses are neither assisted nor significantly hindered. The same hoses subjected to a purely radiative, purely convective or combination heat insult could display different modes of failure.

Although first iteration testing was both relevant and informative, it was decided that in the interest of realism the test hoses should be pressurized with water instead of air. The addition of water would increase the complexity of the apparatus and procedural design and the hose failure times. However, the original hot plate design would differ from all other performance standard tests if the test hoses were pressurized with air. The air compressor available also initially limited the chosen operational pressure to 110 psi. Using water would allow for higher pressures.

## 4.2 The Second Hot Plate Design Iteration

A second hot plate design iteration was developed based on the findings and troubleshooting of the first iteration. Most changes were made in order to account for the heat transfer effects of static water within a fire attack hose and to streamline the testing procedure. A hose pressurized with water is more difficult to contain upon rupture; however, it is more realistic and more common among standard fire hose performance tests including those referenced in DIN 14811 and NFPA 1961. To increase rigor, the test pressure for the second iteration was increased to 150 psi, which is a high-end value of fire attack hose operational pressure. Additionally the range of temperatures the hoses were tested at (i.e. 350°C, 400°C, 450°C, 500°C) was reduced to include only 500°C. This procedure can be seen in Appendix D. Ceramic or metallic building components involved in a structural fire can reach similar temperatures and utilizing only one rigorous temperature value for conduction testing allows for a simpler parametric analysis. The added dimension that would result from varying temperature was deemed unnecessary.

The new apparatus utilized the chamber built for the DIN replication to contain water spray, which drained out a hole in the bottom of the compartment (seen in Figure 10). The hot plate was raised off the bottom of the chamber to prevent water pooling into its electrical components and to align it with the hose inlets. The hose itself was arced through the chamber such that the apex of the arc rested on the hot plate, but was smooth enough for complete contact. Both ends of the arc were supported by cinder blocks.

The pressure rig, originally intended for air, had to be redesigned to accommodate for water and a higher pressure. As shown in Figures 10 and 11, the rig consisted of a direct standpipe connection with two waterways: a pump (pressure washer) and a bypass. The bypass allowed the pressure rig and the fire hose to be quickly filled with water at a standpipe pressure of about 55 psi before the pump increased the pressure of the system to 150 psi.



Figure 10: Second Iteration Hot Plate Design

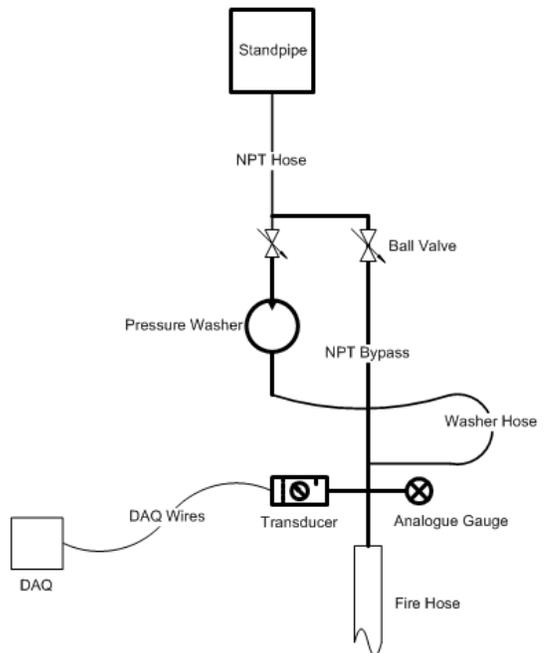


Figure 11: Second Iteration Hose Pressure Set Up

#### 4.2.1 Second Iteration Results and Discussion

Figure 12 below shows the recorded initial failure times of each test hose during the second iteration hot plate tests. A full parametric analysis was performed. There were two trials run on each hose, as represented by the pink and red bars. The resulting data presented a set of inconsistencies. Some trial sets produced similar failure times as seen for the trials of Hose 3, Hose 4 and Hose 7; however, other trial sets displayed very dissimilar failure times such as for Hose 1 and Hose 9. For instance, the Hose 9 test trials displayed a 153.6% difference in failure time even though the trials themselves were procedurally identical. The Hose 1 trials were also extreme outliers with failure times at least 20 minutes longer than those seen in any other hose trials. The physical differences between Hose 1 and the other hoses in the test matrix would not lead to such a drastic performance difference. Aside from these trial-based inconsistencies, the data as a whole could not produce conclusions related to how weight per 50ft, jacket material, or coating affected performance. The conclusion was drawn that a set of design flaws affecting data collection and accuracy must have been present. The factors most likely to have caused data inconsistencies are discussed below.

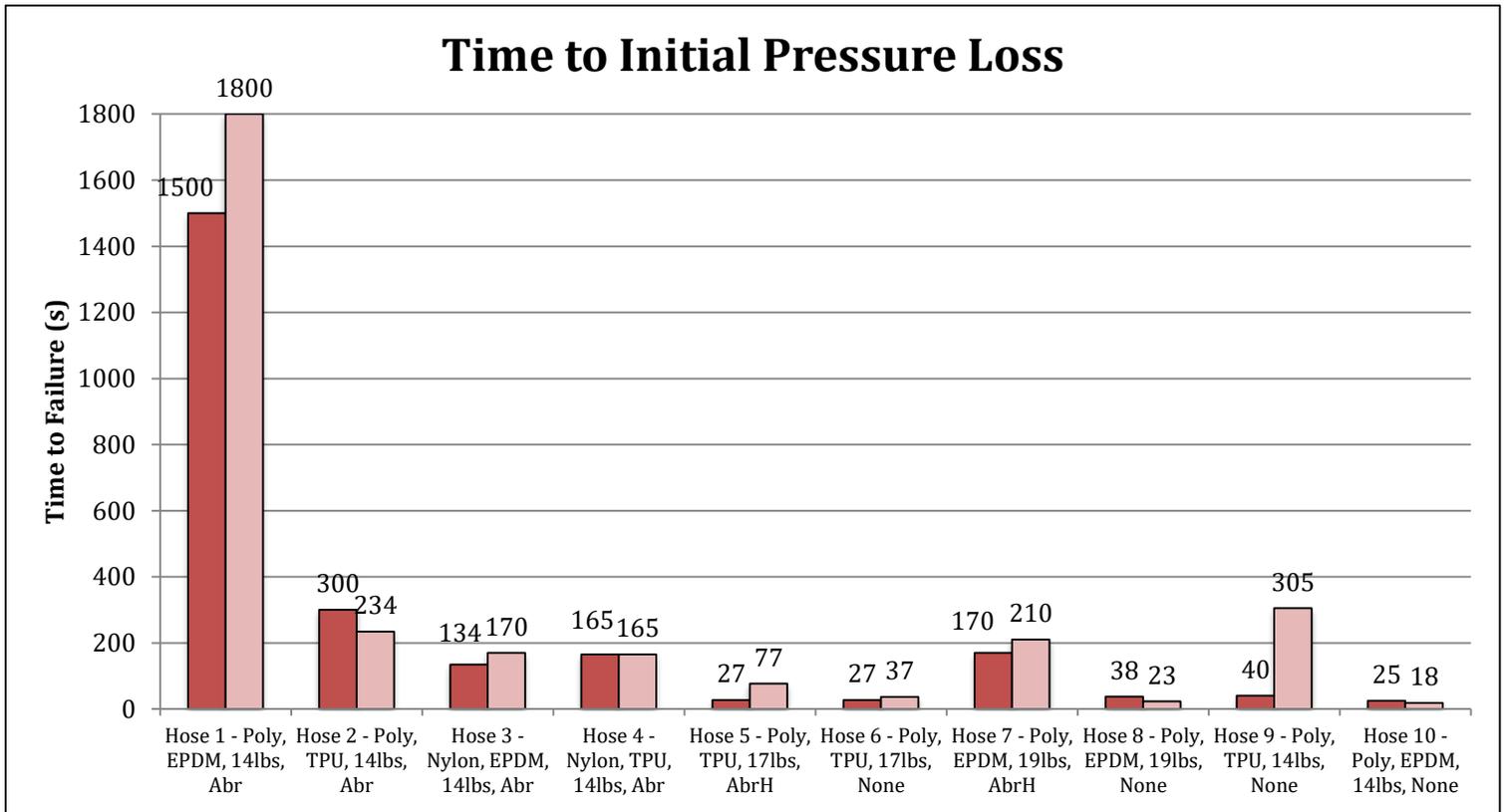


Figure 12: Second Iteration Hot Plate Initial Pressure Loss Results

## **Placement and Contact Area on the Hot Plate**

The ceramic hot plate used in the conduction test was assumed to distribute an equal heat flux across the entire surface area of the hot plate. It is possible that a slight temperature gradient exists with higher temperatures in the center of the plate and lower temperatures around the outside edges. However, the internal heating element of the hot plate is well distributed and if any gradient in present it would not be significant. With that being said, the hoses were manually placed as precisely as possible on the centerline of the plate at the beginning of each trial to ensure that the intended temperature was being applied to the hose. A more likely source of error was the actual hose contact with the hot plate. Internal stresses caused by the hose twisting along its length or by its rigidity when pressurized could have caused it to lift against its own weight when resting on the plate. This can cause variations in the hose's contact with the plate, affect the conductive heat transfer into the hose and therefore affect failure times.

## **Material Bonding**

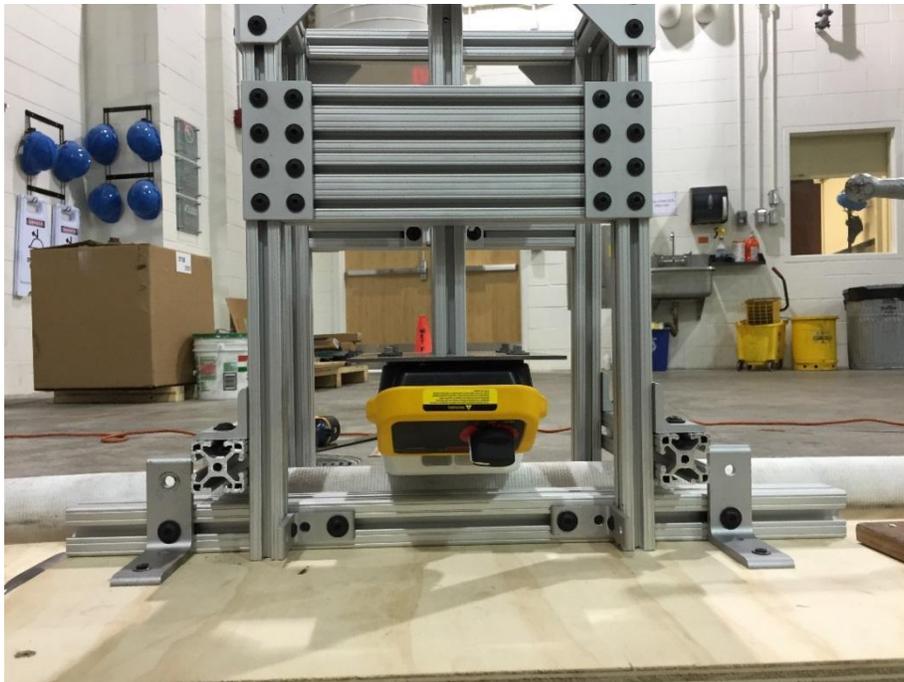
As TPU lined hoses were exposed to the heat flux of the ceramic plate; their coatings, outer jackets and liners melted. As this melting occurred, the material could seal up or shrink some of the small orifices that had developed and started leaking. This may have affected the rate at which pressure was lost from the hoses, causing the pressure loss rate to decrease. Jacket melting is less likely to have had an effect on EPDM hoses, since they experienced instantaneous and energetic failure. The hose material melting onto the plate also required it to be cleaned on a regular basis or covered with tin foil.

## **The Cooling Effect of Water**

During trials with TPU lined hoses, the slowness of the pressure loss and water leakage would allow some of the discharged water to pool onto the hot plate. Water is an excellent heat sink and can act as a coolant in a heat transfer scenario. Even though the hot plate was kept at a constant temperature, it is likely that the pooling water would absorb some of the heat energy before it transferred to the hose. The leaks caused by initial failure would supply flowing water that would absorb heat, evaporate and then be replenished. Similar to variation in hose contact with the plate, the presence of water pooling can therefore failure times as well.

### 4.3 The Third Hot Plate Design

The third and final design iteration was aimed at addressing sources of error and inaccuracies that involved hose-to-hot plate contact. These arose and were identified during second iteration testing. The pressure rig and the DAQ system remained the same. The new apparatus consisted of an aluminum frame that houses a hose guide, clamps, and a linear slider mechanism that raised and lowered the hot plate onto the hose (See Figure 13). A labeled Solidworks diagram of the frame is also shown in Figure 14. The guide bars and adjustable clamps kept the test hose flat, horizontal and in the same position relative to the hot plate. The reversed orientation of the hot plate eliminated any water pooling on the plate surface. Furthermore, the rigid geometry of the frame and the hot plate's ability to translate up and down repeatedly created consistent hose-to-plate contact between trials. This procedure can be seen in Appendix E.



**Figure 13: Third Iteration Hot Plate Design Test Set-Up**

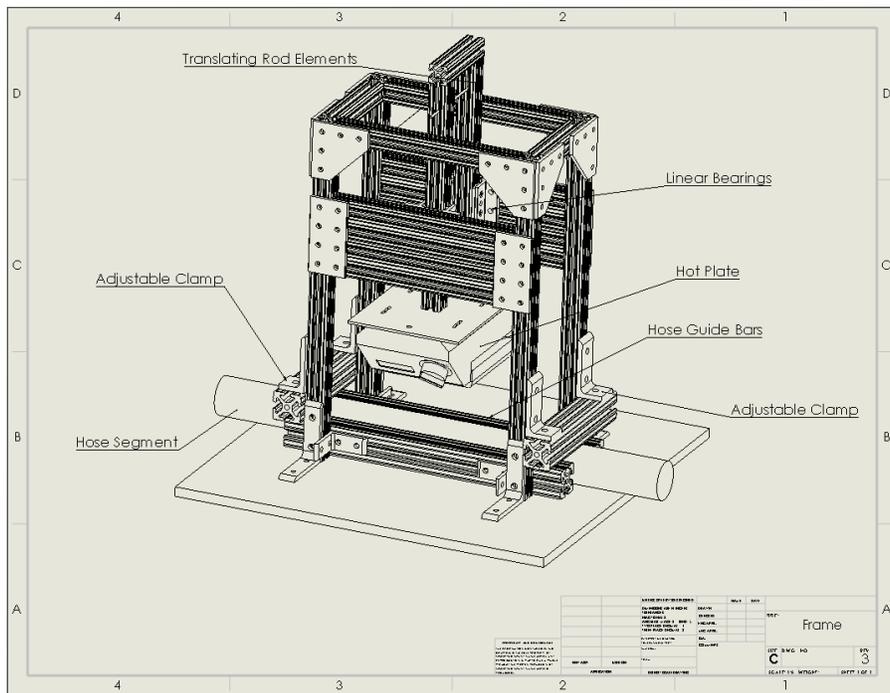


Figure 14: Third Iteration Hot Plate Design CAD File

The smoothness of translation affected the contact between the hose and the hot plate in addition to the hose guide and rigidity of the frame. The translating rods had to be able to slide through the bearings with minimum friction and no binding. The aluminum extrusions and linear bearings used in the design were not created with 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 thousandths existed between the translating rods and the bearings. To test the smoothness of translation, a load cell analysis was conducted to ensure the force on the hose among multiple iterations of raising and lowering the hot plate would remain constant. As shown in Table 2, there was only a variation range of 0.128 N among all ten trials.

Trial	1	2	3	4	5	6	7	8	9	10
Force (N)	26.568	26.627	26.656	26.607	26.578	26.538	26.636	26.627	26.568	26.666

Table 2: Load Cell Analysis

The bearing ratio of the slider mechanism as a whole was calculated as shown:

$$BR = \frac{Lef}{Def}$$

\*\*where Lef is the effective length and Def is the effective diameter.

A bearing ratio of 1 or higher is required for smooth translation and a value of 1.5 is recommended as optimal. The slider mechanism ratio is approximately 1.31. This value is less than ideal, although the data shown in Table 2 supports the claim that a ratio of 1.31 is sufficient for this application of providing consistent contact force.

#### 4.3.1 Results of Third Hot Plate Design Test

Only a limited amount of trials were performed on the third iteration design before inconclusive data patterns were observed. As seen in Figure 15 below, there were eight trials run on Hose 4 at the onset of the third iteration testing due to data inconsistency. These trials resulted in failure time data that displayed grouping. Four trials resulted in 34-37 seconds to failure while four resulted in 68-75 seconds. Three trials were also performed on Hose 3, although as shown in Figure 16 the trials resulted in three separate outcomes.

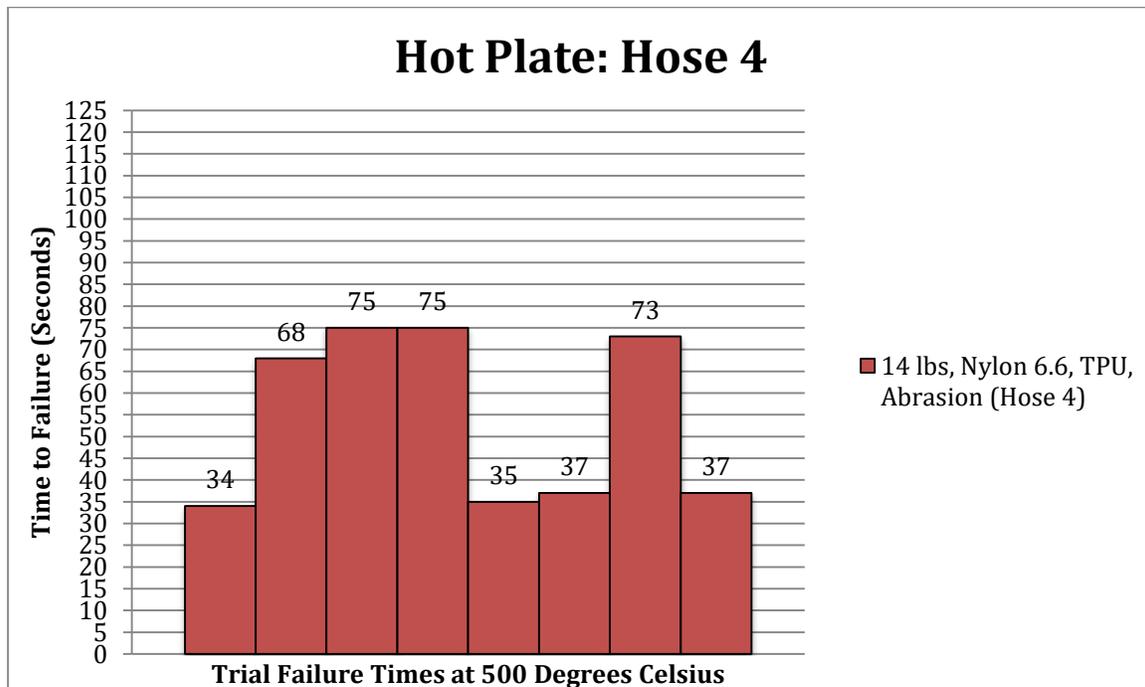


Figure 15: Third Iteration Hot Plate Test - Hose 4 Results

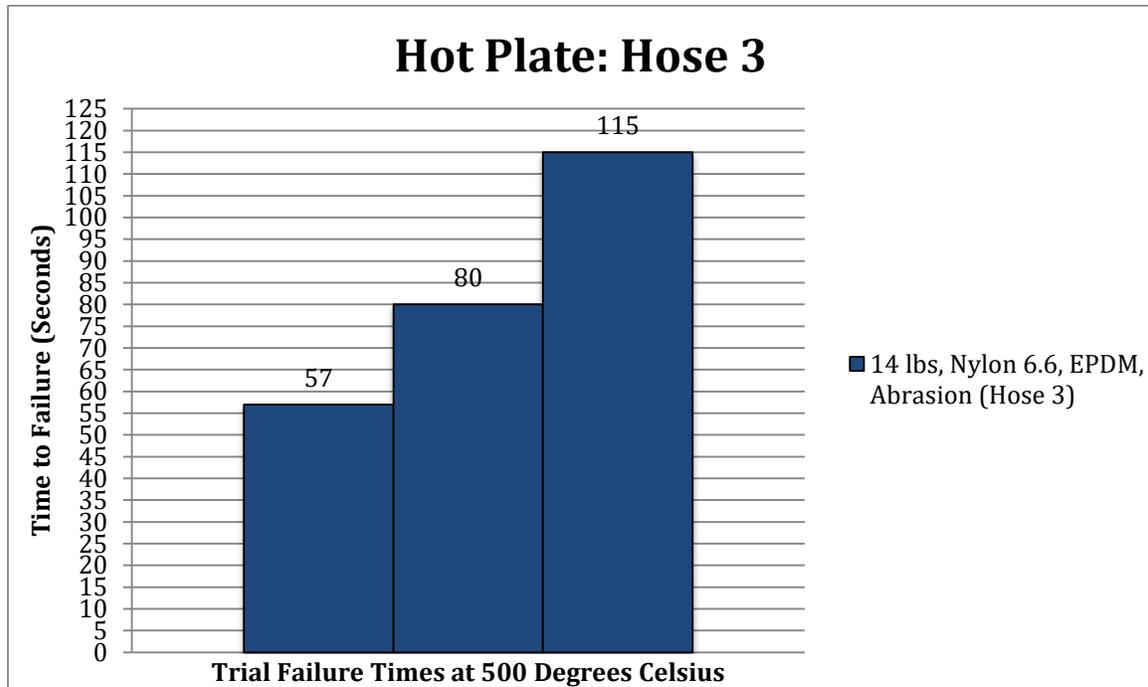


Figure 16: Third Iteration Hot Plate Test - Hose 3 Results

In spite of the issues addressed by the third design iteration, the new apparatus also developed its own unique set of problems. Primarily, the new orientation of the hot plate allowed water to spray inside the hot plate itself as opposed to on its surface after a test hose ruptured. The water was then evaporated by the internal heating element and condensed onto electrical components, causing short-circuits. Efforts were made to prevent water condensation from reaching these components after the phenomenon was first observed in initial trials; however, they were not successful. The involvement of potentially faulty circuitry led to uncertainties as to how much heat the plate was actually producing compared to the numerical value that was shown on the digital display. This uncertainty was present across all trials. Secondly, water that sprayed from the hose due to failure from each trial would pre-wet consecutive segments of the hose to be used in later trials, requiring a long intermission between trials. If the hoses were not completely dry before the next trial, the water could slow the rate at which the hose surface was heated.

#### 4.4 Hose Performance when Subjected to an International Flame Impingement Thermal Assault Test

The apparatus and the procedures of both the DIN: 14811 flame resistance test replication and the flame chamber test were kept constant throughout the course of all testing. There were no alterations made and a complete parametric analysis was performed. It should be noted that only one trial was completed per hose. In the DIN 14811 test, a hose length is subjected to flame impingement for a ten second-time period. The flame is then extinguished and hose performance is analyzed. A trial is considered to be successful if the hose does not ignite, rupture or is able to self-extinguish within three seconds. Ultimately, three of the ten hoses in the test matrix failed the DIN 14811 replication. This result suggests that the level of rigor and heat insult that the actual DIN standard requires fire attack hoses to withstand is higher than that of U.S standards on fire hoses. Table 3 shows which of hoses passed the DIN 14811 replication as well as the times to initial pressure loss during the flame chamber test.

<b>Hose (Red=Abrasion Coating, Blue=Abrasion and Heat, Green=No coating)</b>	<b>Time to Failure (seconds)</b>	<b>German Test Results (F: fail, P: pass)</b>
<b>14lbs, Polyester, EPDM, Abrasion (Hose 1)</b>	25	F
<b>14lbs, Polyester, TPU, Abrasion (Hose 2)</b>	28.5	P
<b>14lbs, Nylon 6.6, EPDM, Abrasion (Hose 3)</b>	40	P
<b>14lbs, Nylon 6.6, TPU, Abrasion (Hose 4)</b>	25	P
<b>17lbs, Polyester, TPU, Abrasion &amp; Heat (Hose 5)</b>	17	F
<b>17lbs, Polyester, TPU, No Coating (Hose 6)</b>	14	P
<b>19lbs, Polyester, EPDM, Abrasion &amp; Heat (Hose 7)</b>	14	F
<b>19lbs, Polyester, EPDM, No Coating (Hose 8)</b>	12	P
<b>14lbs, Polyester, TPU, No Coating (Hose 9)</b>	24	P
<b>14lbs, Polyester, EPDM, No Coating (Hose 10)</b>	14	P

**Table 3: DIN Replica Test and Flame Chamber Test Results**

Jacket material and jacket coating were the only two study variables that displayed significant trends within the DIN replication and flame chamber test results. To recall, there were three categories of hose jacket coatings: no coating, an abrasion coating, and an abrasion and heat coating. Although all uncoated hoses passed the DIN replication by self-extinguishing when pulled away from the flame, the hoses coated for abrasion resistance on average lasted

about 15 seconds longer than either abrasion and heat coated hoses or completely uncoated hoses when constantly subjected to flame impingement during the flame chamber test. This result can be seen in Table 3 with hoses one through four having only an abrasion coating (red shading), hoses five and seven having an abrasion and heat coating (blue shading), and hoses six, eight, nine, and ten having no coating (green shading). Also shown in Table 3, all three hoses that failed the DIN replication were polyester jacketed hoses that were also coated for either abrasion or abrasion and heat. Therefore, there are two principle findings from these results that the authors feel merit further investigation and research:

1. It appears that the outer jacket material is a factor in flame resistance as all three hoses that failed the German Standard Test had polyester outer jackets. Since the melting point temperature of nylon 6.6 is slightly higher, this might be expected, but other thermal and even structural components of the nylon jacket may also play a role in its ability to self-extinguish.
2. Uncoated hoses were more likely to self-extinguish after being moved away from direct flame impingement; however, they did not last as long as their coated counterparts during instances of constant flame impingement. This contradicted an initial hypothesis that coated hoses offered all-around superior performance against heat insult. Once flame impingement was halted, all four uncoated hoses were all able to self-extinguish while only three of the six coated hoses were able to. While this finding requires further testing in order to be confirmed, it appears that the presence of coatings does not benefit the ability of the fire attack hose to self-extinguish.

The best performing hose in this study was the nylon 6.6, EPDM lined hose with the abrasion coating (Hose 3). Note that only two hoses in this study had nylon 6.6 outer jackets, this one having a weight per unit length of 14 lbs per 50 ft. This hose lasted 40 seconds before failure in the direct flame impingement test. Based on this finding, it would be informative to test a nylon 6.6, EPDM lined hose with the abrasion coating in a heavier weight per unit length.

#### 4.4.1 A Closer Look at the Effect of Coatings on Flame Resistance

The hose comparisons made from the flame chamber test data showed that, when the other three study variables were held constant, a coated hose outperformed a counterpart hose with no coating. Coating comparisons were made between the following pairs: Hose 5 vs. Hose

6; Hose 7 vs. Hose 8; Hose 1 vs. Hose 10. While this data suggests that the coated hoses last longer until complete pressure loss under constant flame impingement than their counterparts, further testing would be necessary in order to confirm this and to determine the significance of this finding versus the idea that the uncoated hoses are superior in terms of ability for self-extinguishment.

The first comparison made, seen in Table 4 below, was between Hose 5 and Hose 6. Both of these hoses were polyester jacketed TPU lined hoses that weighted 17 lbs per 50 ft of length. The first of these, Hose 5, was coated for abrasion and heat resistance, while the other was not coated. While the failure time difference initially appeared marginal, the coated hose outperformed that with no coating by 19.3%.

Hose	Time to Initial Pressure Loss (sec)
Polyester, TPU, 17lbs, Abrasion & Heat (Hose 5)	17
Polyester, TPU, 17lbs, No Coating (Hose 6)	14

**Table 4: Hose 5 vs. Hose 6 Coating Comparison**

A second similar comparison, seen in Table 5, was then made between two polyester jacketed EPDM lined hoses that weighed 19 lbs per 50 ft. Once again, the time difference appeared to be marginal but the hose coated for abrasion and heat outperformed that with no coating by 15.5%.

Hose	Time to Initial Pressure Loss (sec)
Polyester, EPDM, 19lbs, Abrasion & Heat (Hose 7)	14
Polyester, EPDM, 19lbs, No Coating (Hose 8)	12

**Table 5: Hose 7 vs. Hose 8 Coating Comparison**

A third and final comparison is shown in Table 6 between two polyester jacketed EPDM lined hoses that weighed 19lbs per 50ft. In this case, however, the comparison included a hose with a coating designed strictly for abrasion resistance. Following the same trend as the two

previous coating comparisons, the coated hose resulted in a 56.4% longer time to failure than the hose without any coating.

<b>Hose</b>	<b>Time to Initial Pressure Loss (sec)</b>
Polyester, EPDM, 14lbs, Abrasion (Hose 1)	25
Polyester, EPDM, 14lbs, No Coating (Hose 10)	14

**Table 6: Hose 1 vs. Hose 10 Coating Comparison**

There is limited understanding as to why there are seemingly significant differences in time to initial pressure loss between coated and uncoated hoses within the flame chamber test. The compositional differences between a coating that provides “abrasion resistance” or one that provides “abrasion and heat resistance” cannot be fully determined because not all hoses came from the same manufacturer and therefore are not likely manufactured the same way. Therefore, the performances variations caused by different types of coatings cannot be clearly distinguished. This being said, the presence of a coating adds a layer of material that must be destroyed before the hose fails. This insulating effect can increase the endurance of the hose during constant flame impingement.

## 5. Conclusion

This study took first steps towards understanding the thermal performance of NFPA 1961 compliant municipal fire attack hoses that are currently manufactured and sold in the United States. In order to protect the firefighters manning these fire attack hoses from serious injury or death, the hoses must be able to maintain full functionality during all fire ground operations, including, but not limited to maintaining structural integrity against intense heat insults. In order to obtain scientific data on hose failure due to burn-through, an array of ten hoses was selected to represent the most common municipal fire attack hose structure as well as the key variables that differentiate these hoses, inform purchase, and outline performance.

Assessment of each hose model in the test matrix using the three design iterations of a conduction-based performance test revealed a connection between liner material and pressurized hose failure in addition to setting the groundwork for the development and improvement of further performance tests. Additionally, a replication of a foreign fire attack hose performance standard was utilized to demonstrate that American versions do not possess the same rigor and that hose jacket material and coating may have an impact on flame resistance. In light of these findings, the research goals established at the beginning of this study were accomplished. Although this study was by nature preliminary, it contributes to the initiative of improving firefighter apparatus and develops the foundation for creating a next generation of fire attack hoses.

## 6. Future Work and Recommendations

Recommendations for future work are focused on design of the test apparatus, improvements in the experimental procedure, and future research on fire attack hoses. The following recommendations are offered for the continuation of research initiated by this study in an effort to produce conclusive data on currently manufactured fire hose performance.

**In order to advance the third iteration hot plate test design, it is recommended that the following design changes are made. These alterations are intended to reduce sources of error and data inconsistency present in the first three Hot Plate design iterations.**

- 1. A water guard added to the sides of the frame or some other water-proofing method is suggested to prevent pre-wetting of test segments.**
- 2. A heat source without integrated electronic components should be utilized of remove the possibility of water-damage to the heat element.**

If future research were to redesign the frame apparatus, a form of water guard such as acrylic siding would be beneficial to prevent pre-wetting of hose sections. In addition, if the hot plate is kept in a reversed orientation, then the use of a different heat source is recommended, as it would eliminate the potentially damaging effects of water condensation. Specifically, a resistance heater with internal thermocouples would produce a constant surface temperature with a constant input voltage. This would negate the difficult task of shielding electrical components from steam condensation. However, a custom device would require calibration before use to ensure temperature readings of the hot surface are accurate.

**If a new design for a hose-to-hot surface apparatus is required, a cantilever mechanism is recommended over a translating rod mechanism in order to improve design simplicity.**

A cantilever mechanism would rest the hot plate onto the hose without the tight design tolerances required when utilizing translating rods and linear bearings. While rods and bearings are very precise when custom manufactured, a cantilever mechanism is more simplistic and offers comparable accuracy at a lower cost and without custom manufacturing. In the case of this study, the translating rod mechanism created for the third hot plate design iteration offered sufficient precision and repeatability when built with aluminum extrusion framing; however,

custom manufacturing would have been required for optimal precision and repeatability. A cantilever mechanism could also be built with aluminum framing and, if properly designed, could offer improved precision over a translating rod mechanism build with the same components.

**It is recommended that the number of trials in the DIN 14811: Flame Resistance Replica Test is increased to mirror the German standard exactly.**

In the original DIN standard, five trials are required for each hose. The replication conducted in this study included a single trial on each hose. Mirroring the number of trials specified in the DIN 14811 test would increase both the validity and insight provided in regard to hose failures and performance.

**Further Research Recommendations on the Thermal Performance of Currently Available Fire Attack Hose:**

Testing of the full matrix of representative hoses using a waterproofed test platform with the cantilevered apparatus is recommended. Investigation should include determining the impact of each study variable with intent to further verify the effects of coatings, weight per unit length, liner failure methods, and outer jacket performance. An additional recommendation is to expand testing past the original ten hose matrix to account for hose structures separate from the structure focused on in this study. This will allow a broader understanding of attack fire hose heat resistance performance in all accounts.

## 7. Appendices

### Appendix A –German DIN: 14811 Replication Procedure

**Failure Definition:** The hose bursts in less than ten seconds or did not self-extinguish within 3 seconds of the propane source being cut.

**Procedure:**

1. Connect a 50ft length fire attack hose specimen to the pressure rig consisting of a booster pump and bypass attached to the laboratory standpipe.
2. Ensure the pressure transducer (which is mounted to read the pressure within the pressure rig and hose) is wired to a power supply and the data acquisition software.
3. Run the hose through the openings in the walls of the compartment built to the specifications of DIN 14811: 2008-01
4. Connect the Bunsen burner to the propane tank via rubber tubing
5. Place the Bunsen burner through the hole at the bottom of the compartment
6. Clamp the hose on the side farthest from the pressure source.
7. Pressurize the hose to roughly 70 psi utilizing the analog pressure gauge also connected to the WPR. To ensure a static pressure, loosen the clamp for a moment to allow air to escape then re-clamp the hose.
8. Light the Bunsen burner so that the flame impinges on the hose surface while simultaneously starting the timer
9. Allow flame to burn for 10 seconds before cutting the propane source
10. Wait 3 seconds to determine if the hose self-extinguishes or stops glowing.
11. Record observations

## Appendix B - Flame Chamber Procedure

**Failure Definition:** The point at which the hose begins to lose pressure.

**Procedure:**

1. Connect a 50ft length fire attack hose specimen to the pressure rig consisting of a booster pump and bypass attached to the laboratory standpipe.
2. Ensure the pressure transducer (which is mounted to read the pressure within the pressure rig and hose) is wired to a power supply and the data acquisition software.
3. Run the hose through the openings in the walls of the compartment built to the specifications of DIN 14811: 2008-01
4. Connect the Bunsen burner to a pressurized propane tank via rubber tubing and the proper valves.
5. Place the Bunsen burner through the hole at the bottom of the compartment
6. Clamp the hose on the side farthest from the pressure source.
7. Pressurize the hose to a roughly 70 psi utilizing the analog pressure gauge also connected to the pressure rig. To ensure a static pressure, loosen the clamp for a moment to allow air to escape then re-clamp the hose.
8. Light the Bunsen burner so that the flame impinges on the hose surface while simultaneously starting the timer
9. Observe the hose until failure (measured through visual observation and a drop in pressure on the LabVIEW live data output)
10. Record observations upon failure

## Appendix C – Hot Plate – First Iteration Procedure

**Failure Definition:** The point at which the hose begins to lose pressure.

**Secondary Point of Interest:** The point at which the pressure in the hose reaches half its initial value.

### **Procedure:**

1. Connect a 50ft length fire attack hose specimen to the pressure rig consisting of an NPT module and analog pressure gauge connected to an air compressor.
2. Ensure the pressure transducer (which is mounted to read the pressure within the pressure rig and hose) is wired to a power supply and the data acquisition software.
3. Place the hot plate on directly between two cinder blocks, which are placed four feet apart.
4. Run hose through the two cinder blocks such that it may be arced over the hot plate and rested on its surface
5. Clamp the hose on the side farthest from the pressure source
6. Pressurize the hose to 100 +/- 7 psi (tolerance included to account for air compressor accuracy and the compressibility of air)
7. Place aluminum foil over the hot plate to protect it from melted material build up, yet still allow heat conduction.
8. Set the hot plate to 350°C, allow it to reach temperature and rest the pressurized hose on the center of the hot plate surface.
9. Record time to both definitions of failure for three trials at 350°C, utilizing an undamaged section of hose for each trial.
10. Repeat 7-8 for hot plate temperatures 400°C, 450°C, and 500°C

## Appendix D – Hot Plate – Second Iteration Procedure

**Failure Definition:** The point at which the hose begins to lose pressure.

**Secondary Point of Interest:** The point at which the pressure in the hose reaches half its initial value.

### **Procedure:**

1. Connect a 50ft length fire attack hose specimen to the pressure rig consisting of a booster pump and bypass attached to the laboratory standpipe.
2. Ensure the pressure transducer (which is mounted to read the pressure within the pressure rig and hose) is wired to a power supply and the data acquisition software.
3. Ensure the hot plate electronics are waterproofed through the use of plastic wrap and aluminum tape, while assuring the waterproofing does not interfere with the ceramic plate itself.
4. Mount the hot plate in the bottom of the compartment built to mimic the specifications of DIN 14811: 2008-01
5. Run the hose through the holes on either side of the compartment, so that it rests above the hot plate but does not yet touch it
6. Clamp the hose on the side farthest from the pressure source.
7. Begin to pressurize the hose to 150 psi utilizing the analog pressure gauge also connected to the WPR. To ensure a static pressure, loosen the clamp for a moment to allow air to escape then re-pressurize until the water pressure remains stable at 150 psi.
8. Lay the pressurized hose through the compartment such that 23 inches of hose exist between both sides of the compartment and cinder blocks supporting the hose arc. Ideally, the hose will then drape to the floor before and after the cinder blocks, creating a smooth arc over the hot plate. However, if insufficient hose length is available as trials progress, the clamp is then raised off the floor such that the hose still follows the same arc curve. The idea here is for the hose to sit with approximately the same pressure on each of the cinder blocks.
9. Place aluminum foil over the hot plate to protect it from melted material build up, yet still allow heat conduction. Turn on the hot plate and allow it to heat to 500 °C.

10. Place the hose on the center of the hot plate, ensuring that the hose is not resting on a fold crease. Then close the sliding walls of the compartment and simultaneously start the trial timer
11. The hose should press up against the top of the holes in the sliding walls, which in turn press the hose to the hot plate.
12. Continue monitoring pressure – record the time at which the pressure is initially lost, and the time at which it reaches half of its initial pressure
13. At half pressure, stop the timer and remove the hose from the compartment
14. Slide down the hose to a new location and repeat
15. Repeat this procedure 3 times at 500 °C

## Appendix E – Hot Plate – Third Iteration Procedure

**Failure Definition:** The point at which the hose begins to lose pressure.

**Secondary Point of Interest:** The point at which the pressure in the hose reaches half its initial value.

### **Procedure:**

1. Connect a 50ft length of coupled fire attack hose to the pressure rig, i.e. a pump and bypass attached to the laboratory standpipe.
2. Ensure the pressure transducer (which is mounted to read the pressure within the pressure rig and hose) is wired to a power supply and the data acquisition software.
3. Run the deflated hose through either side of the precision frame, so that it rests within the hose guide.
4. Clamp the free end of the hose at a distance such that maximum hose length is saved for later tests.
5. Begin to pressurize the hose to 150 psi utilizing the analog pressure gauge also connected to the pressure rig. To ensure a static pressure, loosen the clamp for a moment to allow air to escape then re-pressurize until the water pressure remains stable at 150 psi
6. Lower and lock the hose clamp bars such that the hose is resting flat and true between the hose guide with minimal bowing
7. Turn on the hot plate and allow it to reach 500°C
8. Release the mechanism holding the hot plate off of the hose and allow it to be lowered onto the hose
9. Once the hose and hot plate contact each other, begin the timer for the trial.
10. Continue monitoring pressure – record the time at which the pressure is initially lost, and the time at which it reaches half of its initial pressure
11. At half pressure, stop the timer, stop the DAQ, and raise the hot plate off of the hose
12. Slide the hose through the hose guide to a new location, clamp off the damaged section from the previous test (if applicable)
13. Perform five iterations (trials) of this procedure for each of the ten hose specimens.

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# **Chapter 2**

## **Radiative Heat Performance Testing of Materials for Application in a Fire Attack Hose**

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## 1. Introduction

A fire attack hose is an essential tool used by firefighters to combat and suppress fires and to provide a line of safety. However, the hoses are not always recognized for their other important role on the fire ground: serving as an additional line of defense for firefighters. From this, one would assume that these hoses would be able to withstand the harsh conditions of the fire ground. There are multiple documented accounts of firefighters being left stranded inside burning buildings without an adequate water supply due to fire attack hose burn throughs. According to the National Institute of Occupational Health and Safety, “in 2008, two firefighters in North Carolina and one firefighter in Alabama died when an attack hose burned through and in 2010, an Illinois firefighter was killed when a hose failed” [1]. More recently in Boston’s Back Bay, two firefighters lost their lives “when they lost their water supply after their hose burned through” [1].

It seems that the materials being used in fire hoses today are cannot reliably withstand the exposure levels at the scene of a fire creating a demand for the discovery of new materials that can. This research will identify materials used in PPE that could be applied to the jackets of a fire hose in order to: create a test method that will test current and candidate materials in a radiative heat environment, perform this testing on the selected materials, and quantify the time to decomposition and ignition of these materials as compared to current fire hose materials. This research serves to test the hypothesis that there are materials being manufactured that are better suited for the high heat environment of the fire scene than the current materials being used in fire hose jackets today.

## 2. Literature Review

During the earliest recorded firefighting operations in the United States, buckets of water were carried from a water source to the fire in an attempt to extinguish it. This method was inefficient, unreliable and labor intensive. With the invention of the hand pump, water was more efficiently directed towards a burning structure; however, the firefighting was still carried out with buckets. It was not until 1807 when two Philadelphia firefighters fashioned leather and metal rivets into a long tube shaped object that the idea of a fire hose was created. At the time, “one hundred feet of hose was the equivalent of sixty men with buckets” [2].

The idea was incredibly successful, however the leather was not. It would dry out, crack and burst when exposed to high pressure and heat. While the metal rivets solved some of these problems, hoses were still required to be regularly oiled and maintained to keep them in working order. In 1821, a rubber-lined hose made of cotton webbing was introduced to the fire service along with an entire industry invested in creating different sizes and shapes of fire hose. For many years afterward, cotton was the standard material for the fabrication of fire hoses as it was stronger, lighter, and easier to roll and handle than leather [2].

### 2.1 Current Hose Materials

The introduction of polyester, nylon, and reinforced plastic to the fire hose industry occurred in the late 1900's. These materials became the new standard for jacket materials while rubber continuing to be used as a liner material. These jacket materials were seen to be superior over cotton solely for their ability to withstand mold and rot [3]. These materials had not been chosen for application in the jacket of a fire hose primarily for their performance characteristics against heat insult. This is alarming since the fire attack hose is considered to be the second line of defense for a firefighter behind only their personal protective equipment.

Most fire attack hoses being used by fire departments today have jackets weaved from polyester or nylon 6.6. These materials are typically found in household applications, especially in clothing and furniture. They do not have high heat applications besides use in fire attack hoses. Table 1 below compares the characteristics of polyester and nylon 6.6 [4].

Material	Burns?	Melts?	Drips?	Decomposition Temperature
Polyester	Yes	Yes	Yes	265°C
Nylon 6.6	Yes	Yes	Yes	250-260°C

**Table 1: Characteristics of Current Fire Hose Materials**

Today, the National Fire Protection Association (NFPA) codes outline the specifications and performance capabilities required for fire hoses. More specifically, NFPA 1961: *Standard on Fire Hose* defines all performance tests that current fire hoses must meet [5]. These tests for hose certification involve an elongation test, a burst test, a tensile strength test, and a flexibility and compressibility test among others. The only heat resistance test required is a conduction-based heat resistance test. This test requires a 2 ½” x 1 ½” x 8” steel block to be heated to 260 °C and stamped on a fire hose for 60 seconds. The hose is then hydrostatically pressurized to three times the service test pressure to identify any leaks. NFPA 1961 currently contains no radiative heat performance test.

## 2.2 Personal Protection Equipment Material

NFPA codes do contain radiative heat performance testing criteria for the personal protective equipment (PPE) that firefighters wear during their daily duties. NFPA 1971 Section 8.10 specifies that PPE must be tested in accordance with ISO 17492 for its thermal protective performance through a series of tests where the material is exposed to a heat flux of 84 kW/m<sup>2</sup> +/- 2 kW/m<sup>2</sup> [6]. A thermal protective performance (TPP) will be calculated and a value of 35 must be achieved for the material to pass the test. The firefighters’ personal protective equipment is made of material that is expected to withstand the hottest temperatures of the fire scene and could potentially be well suited for application in a fire attack hose jacket.

High-heat performance materials are typically classified by the type of characteristics they possess. The two terms that classify these materials are fire resistant and fire retardant. Fire resistant materials are those that will not ignite upon exposure to flames and do not melt or drip under high radiant heat exposures upwards of 600 °C. Fire retardant materials may catch fire and could suffer a burn through; however, they will self-extinguish when removed from direct flame

contact [7]. Both of these types of materials are used in the fire service for firefighter's personal protection against high heat conditions.

A selection of fire resistant and fire retardant materials, all of which are utilized in firefighter PPE and could potentially have application in fire attack hoses were selected for testing. However, this selection is by no means an exhaustive set of all fire resistant and fire retardant materials. DuPont manufactures two of the materials: Nomex®, known for its flame-resistance is used in turnout gear and accessories and Kevlar®, known for its thermal protection, durability, and strength is used in turnout gear as outer shells and thermal liners [8]. PBI® fiber is manufactured by PBI, Inc. and is known for its strength and thermal protection that is woven into a fabric used to create the outer shell of turnout gear [9]. PBI was first synthesized in 1961 and began being used by the New York City Fire Department and other areas within the U.S. fire service industry in 1994. Two specific weaves of the PBI® fiber were selected: PBI® Max and PBI® Kombat Flex. PBI Max is 70% PBI fiber and 30% Kevlar® filaments while PBI® Kombat Flex is 36% PBI fiber and 64% Kevlar® filaments [10][11].

While not tested to the same standard that firefighter turnout gear is tested, the chemical industry also has personal protective equipment. Pyrovatex® fr Cotton was selected for testing to represent materials used in this industry. Pyrovatex® fr Cotton is actually a coating applied to pure cotton material, used as protective apparel in both the chemical and welding industries for its fire resistive properties [12].

Previous test data on the performance of current fire hose jacket materials when exposed to a known radiative heat flux could not be found. Therefore, this research will serve to create a test methodology and to document the performance of current fire attack hose and PPE materials

### 3. Methodology

The overall goal of this portion of the study was to identify candidate materials to be compared to current materials for application in a fire attack hose. This research:

1. Selected candidate materials for testing
2. Created a test methodology for quantifying the radiative heat performance of each material
3. Performed testing on current and candidate materials
4. Established performance criteria to compare materials

Before the test procedure was created and the testing occurred, candidate materials were identified based on their application in industry as personal protection equipment. The heat related characteristics of the current and candidate materials were documented and compared.

#### 3.1 Objective #1: Select Candidate Materials for Testing

Five materials were selected as candidate materials to test the hypothesis that there are other materials that exist that perform better in a high heat environment than the current fire hose jacket materials. The burning, melting, and dripping properties as well as decomposition temperatures of the materials can be found in Table 2 [13][14][15].

<b>Material</b>	<b>Burn?</b>	<b>Melt?</b>	<b>Drip?</b>	<b>Decomposition Temperature</b>
Nomex®	Yes	No	No	425°C
Kevlar®		No	No	450-480°C
PBI Max®	No	No	No	676°C
PBI Kombat Flex®	No	No	No	676°C
Pyrovatex® fr Cotton		No	No	250°C

**Table 2: Characteristics of Potential Candidate Materials**

Based on the properties identified above, these materials were selected for testing. As all of these materials have high heat applications, they were expected to perform better than the current materials.

## 3.2 Objective #2: Create Test Methodology for Radiative Heat

To test the performance of current hose jacket materials and the candidate materials, a test methodology needed to be created. The test needed to include a means of quantifying heat resistance under a controlled, uniform radiative heat source in a repeatable and concise fashion as well as allow comparison between materials. A testing apparatus called the cone calorimeter fit these criteria and was chosen as the principle apparatus of this portion of the study.

### 3.2.1 The Cone Calorimeter

The cone calorimeter has a radiant cone-shaped heater that provides a constant irradiance to the surface of the sample being tested. The heat flux from this heater ranges from 0-110 kW/m<sup>2</sup> [16]. This apparatus is used to determine “the ignitability, heat release rates, mass loss rates, effective heat of combustion and visible smoke development of materials and products” [17]. It also allows an effective means to calculate the time to ignition. While the cone calorimeter can provide information on toxic gas production and heat release rate calculations, these capabilities were not required for this research. This study utilized the cone heater as a radiative heat source and the built-in thermocouples to record the temperature time histories of the top and bottom surfaces of the samples during each test.

### 3.2.2 Data Collection

The temperature data recorded by the calorimeter thermocouples allowed the determination of the time required for the material samples to reach their listed decomposition temperature. This time data was used as a comparison to determine which materials could withstand radiative heat the longest. The time to ignition and flame extinction, if applicable, was also used in this manner. The time to ignition or ignitability under a constant heat flux was defined as the “measurement of time from initial exposure to time of sustained flaming” [17]. Overall, materials that could withstand a specified heat source for a longer time were favored. The time to decomposition, or time to failure, was defined as the time when the top thermocouple on the sample reaches the decomposition temperature of the material. Current jacket hose materials were tested first in order to create a baseline against which to compare the performance of the candidate materials. In order to prove the initial hypothesis, candidate materials needed to surpass the performance baseline set by the current host materials.

### 3.2.3 Test Procedure

A procedure for testing all of the selected materials needed to be created so that test results were consistent and repeatable. While this type of testing had not been done on hose materials, a general cone calorimeter sample testing procedure has. Section 6 of the *User's Guide for the Cone Calorimeter* created by the National Institute of Standards and Technology (NIST) lists preparative procedures for sample testing that should be applied "as needed to assure adequate preparation for actual testing" [18].

Before any experiments could be performed, test materials were cut into 100mm x 100mm samples, then labeled and measured for thickness and weight. Shears, razor blades and a band saw were used to cut the materials to size. Extraneous threads were removed to prevent inconsistent results. After being cut, each sample was wrapped with aluminum foil and fitted with an edge frame to prevent edge burning, a phenomenon that can lead to two-dimensional burning and alter results. A wire grid was also used to prevent two-dimensional burning which is common with thin materials like those being tested. To record the results of each test, thermocouples were placed above and below the test sample, between the wire grid and the top surface of the sample and between the bottom surface of the sample and the aluminum foil. Thermally insulated cement was coated onto the aluminum foil in the area where the thermocouple was placed to prevent the thermocouple from misreading. This cement forced the thermocouple to read the surface temperature of the material and not of the aluminum foil.

The testing apparatus was prepared by placing a ceramic fiber blanket into the specimen holder. The sample, wrapped in aluminum foil with the thermocouples, was placed on top of the ceramic fiber blanket. The wire grid was then situated on top of the sample and finally the edge frame was positioned on top to hold everything in place. This entire apparatus was subjected to heat fluxes from the cone heater. Insulated gloves were used to handle the apparatus and samples at the end of each test.

The cone heater was positioned in the horizontal orientation as this is the most common arrangement according to ASTM E1354 Section 1.4, "independent of whether the end-use application involves a horizontal or vertical orientation" [17]. This orientation also ensures that materials that may melt or drip are held in the same location and therefore are accurately tested [16]. Before each test was run, the distance from the top surface of the sample to the cone heater was measured and adjusted so that there was a gap of approximately one inch or twenty-five millimeters.

Once the sample was properly prepared, testing was ready to begin. Each test was run identically and following the subsequent procedure:

1. Clean air was run through the cone calorimeter for three minutes (180 seconds)
2. The testing apparatus was placed on the sample mount assembly
3. The spark igniter was moved into place and the shutters were opened
4. The testing apparatus was exposed to the predetermined heat flux for 15 minutes (900 seconds) or until ignition and self-extinguishment of the sample
5. The testing apparatus was removed, the spark igniter moved out of place and the shutter closed
6. Three minutes (180 seconds) of clean air was run through the cone calorimeter once more

During each test, the length of clean air before and after the test was recorded along with the time to ignition and flame self-extinguishment if applicable. The time to failure was calculated after the test was complete. Failure was defined as the time when the thermocouple on the top of the sample reached the decomposition temperature of the material. If the sample did not ignite, it was exposed for fifteen minutes as this allows enough time for the material to reach the maximum temperature possible from the heat flux given. When ignition does not occur, this means that the temperature of ignition of the material was higher than the maximum temperature reached.

### 3.3 Objective #3: Perform Testing on Materials

Each test (material and heat flux combination) was run twice to remove any potential inconsistencies. If the time to ignition or time to decomposition had a percent error of higher than 20%, the test was repeated. Trials were repeated as well if there was a thermocouple failure during testing.

Materials were tested at heat fluxes intended to start at  $10 \text{ kW/m}^2$  and then increasing by  $5 \text{ kW/m}^2$  until the material showed signs of decomposition. It is important to note that the heat flux of  $20 \text{ kW/m}^2$  closely represents the heat flux at the floor during a compartment fire at flashover [19]. The heat flux of  $10 \text{ kW/m}^2$  was chosen as it represents pre-flashover conditions.

### 3.3.1 Heater Thermocouple Calibration

After testing had concluded, the heater thermocouple calibration was performed. According to the *User's Guide for the Cone Calorimeter*, this calibration should be performed once a month to ensure that the cone heater is producing the desired flux [18]. All testing was performed using the original calibration table of heater temperatures and corresponding heat fluxes; however, a new table was generated after testing had concluded and it was discovered that the actual heat fluxes to the samples were different than the original desired fluxes.

The heater thermocouple calibration is performed using a heat flux gauge positioned where the specimen would be during normal testing. The set point on the temperature controller was changed until the heat flux gauge read the desired flux. The temperature reading was recorded and the temperature controller changed for the next desired heat flux. According to the *User's Guide for the Cone Calorimeter*, this calibration should be performed at 10, 25, 35, 75, and 100 kW/m<sup>2</sup> [18]. These heat fluxes provide enough data to make an appropriate curve in which to accurately predict the heat flux based on the set point on the temperature controller.

Figure 1 below shows the cone temperature heat flux curves for the cone heater used in this testing prior to and after calibration. As shown, the new values found after the calibration yield a higher heat flux per cone temperature than the original values. For example, a set point of 392 degrees Celsius on the old curve would yield a heat flux of 10 kW/m<sup>2</sup>, while on the new curve it yields a heat flux of 11.9 kW/m<sup>2</sup>. The equations of the lines were used to calculate the heat fluxes that were actually used during testing.

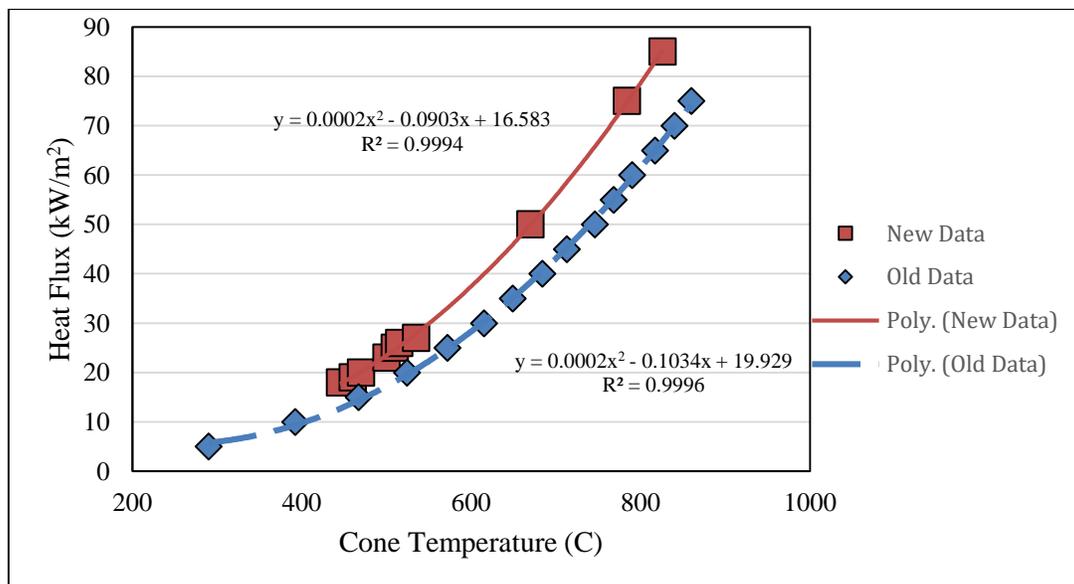


Figure 1: Old vs. New Cone Temperature Heat Flux Curves

Heat fluxes were incremented by 5 kW/m<sup>2</sup> using the old calibration scale. See Table 3 below for a conversion from the old calibration scale to the new calibration scale.

<b>Old Calibration Scale</b> [kW/m <sup>2</sup> ]	<b>New Calibration Scale</b> [kW/m <sup>2</sup> ]
10	11.9
15	18.0
20	24.2
25	30.4
30	36.7
35	42.2
40	48.4

**Table 3: Calibration Conversion Table**

### 3.4 Objective #4: Establish performance criteria based on current materials

The experimental plan stated above includes the testing of current materials used in fire hose jackets and candidate materials that are being testing for their application in a fire hose. Current hoses and hose material were tested to create a baseline on which to compare the candidate materials. As this project is focusing on improving the materials within the design of a fire hose, the candidate materials are expected to surpass the benchmarks set by the current materials. The current and candidate materials were first ranked by the highest heat flux they withstood without igniting and then by decomposition and ignition. This allowed a direct comparison between the current and candidate materials. The materials with longer times to decomposition and ignition at the higher heat fluxes performed better.

## 4. Results

Time to decomposition and time to ignition were selected as the properties to evaluate each material's performance. These characteristics (if applicable) allow for a comparison of each material's properties against a variety of high radiative heat fluxes. Materials that can withstand higher heat fluxes are better suited for the fire ground. The time to failure is defined as the time when the top surface of the test sample reaches the decomposition temperature of the material. This was chosen as it is an estimate of the beginning of degradation of the material. Materials with longer times to decomposition and ignition are desired.

### 4.1 Current Materials

Initial research focused on current materials used in fire attack hose jackets to identify a baseline on which to compare candidate materials. The following two metrics, time to decomposition and time to ignition, were chosen as the criteria for documentation and comparison of the performance of each material. Polyester and nylon 6.6 both withstood a heat flux of 11.9 kW/m<sup>2</sup> without ignition over the fifteen minute duration of each test. The time to decomposition for both polyester and nylon 6.6 subjected to a heat flux of 11.9 kW/m<sup>2</sup> are presented in Table 4. To reiterate, the time to decomposition is defined as the time when the top surface of the test sample reached the decomposition temperature of the material.

<b>Material</b>	<b>Decomposition Trial 1 [seconds]</b>	<b>Decomposition Trial 2 [seconds]</b>
Polyester	132	129
Nylon 6.6	22	172

**Table 4: Testing Results for Current Materials at 11.9 kW/m<sup>2</sup>**

While further testing would be needed to reduce the uncertainty in the time to decomposition of nylon 6.6, it is clear that both materials reach the decomposition temperature at less than three minutes, even when subjected to a very moderate heat flux. Because neither material ignited at 11.9 kW/m<sup>2</sup>, the heat flux was increased to 18.0 kW/m<sup>2</sup>. Both current jacket materials ignited at this heat flux and the results from this testing are presented in Table 5.

<b>Material</b>	<b>Decomposition Trial 1 [seconds]</b>	<b>Decomposition Trial 2 [seconds]</b>	<b>Ignition Trial 1 [seconds]</b>	<b>Ignition Trial 2 [seconds]</b>
Polyester	45	46	256	260
Nylon 6.6	22	16	214	223

**Table 5: Testing Results for Current Materials at 18.0 kW/m<sup>2</sup>**

The polyester and nylon 6.6 samples both decomposed and ignited at a heat flux of 18.0 kW/m<sup>2</sup>. It is important to note that this heat flux is indicative of pre-flashover conditions [19]. Both samples decomposed around one minute and ignited around four minutes of exposure to this heat flux. The nylon 6.6 sample ignited after 214-223 seconds of exposure to these conditions (18 kW/m<sup>2</sup>, 467°C), where the polyester sample did not ignite until 256-260 seconds of exposure to the same conditions. Both samples ignited after approximately four minutes of exposure to a heat flux that is approaching but below flashover conditions. This is alarming as these materials are currently being used every day by the fire service. In the meantime, it appears that hoses made of polyester material may last longer when exposed to heat fluxes on the fire scene.

From this information, the following conclusions can be made: the current fire hose jacket materials are not suitable for high heat environments as they decompose in under a minute and ignite in about four minutes when exposed to pre-flashover conditions, and polyester may be the better performing material in terms of time to decomposition and time to ignition.

## 4.2 Candidate Materials

There were five candidate materials tested for application in a fire hose jacket: 50% Kevlar®-50% Nomex®, 90% Nomex®, PBI Max®, PBI Kombat Flex®, and Pyrovatex® fr Cotton. None of the candidate materials reached decomposition or ignition temperatures when exposed to 11.9 kW/m<sup>2</sup> as compared to both current materials tested, which both reached their decomposition temperatures under exposure to this heat flux.

Results were analyzed for the materials tested at a radiant heat flux of 18 kW/m<sup>2</sup> and are shown in Table below.

<b>Material</b>	<b>Decomposition Trial 1 [seconds]</b>	<b>Decomposition Trial 2 [seconds]</b>
50% Kevlar®-50% Nomex®	511	--
90% Nomex®	--	--
PBI Max®	--	--
PBI Kombat Flex®	--	--
Pyrovatex® fr Cotton	56	64

**Table 6: Testing Results for Candidate Materials at 18.0 kW/m<sup>2</sup>**

At a radiant heat flux of 18.0 kW/ m<sup>2</sup>, 50% Kevlar®-50% Nomex® and Pyrovatex® fr Cotton reached their decomposition temperatures in 511 and 56-64 seconds respectively. Like the current materials, Pyrovatex® fr Cotton decomposed after about one minute, however the differentiating factor is that it did not ignite while current materials did. Table 6 above shows a decomposition temperature for 50% Kevlar®-50% Nomex® in one of the trials occurring in about 8.5 minutes. In the other trial, the decomposition temperature was not reached within the 15-minute duration that the test was run. Therefore it was concluded that this heat flux is close to the failure range of this material. From this testing alone, the hypothesis that there are other materials being manufactured that are better suited in fire hose jacket performance on the fire scene than the current materials being used has been proved to be true.

Testing did continue as none of the candidate materials ignited at 18.0 kW/m<sup>2</sup> and the heat flux was increased to 24.2 kW/m<sup>2</sup>. Data on the time to decomposition for trials run at 24.2 kW/m<sup>2</sup> are shown in Table 7 below. None of the candidate materials ignited at this heat flux, which is 20% higher than that indicative of flashover.

<b>Material</b>	<b>Decomposition Trial 1 [seconds]</b>	<b>Decomposition Trial 2 [seconds]</b>
50% Kevlar®-50% Nomex®	54	166
90% Nomex®	145	117
PBI Max®	--	--
PBI Kombat Flex®	--	--
Pyrovatex® fr Cotton	50	50

**Table 7: Testing Results for Candidate Materials at 24.2 kW/m<sup>2</sup>**

The 50% Kevlar®-50% Nomex® and Pyrovatex® fr Cotton once again reached their decomposition temperatures and more quickly under this heat flux. The 90% Nomex® also reached its decomposition temperature. While it is clear that further testing would be needed to reduce the uncertainties in the decomposition times, it is also apparent that the 50% Kevlar®-50% Nomex®, 90% Nomex®, and Pyrovatex® fr Cotton begin to decompose in less than three minutes under exposure to a heat flux of 24.2 kW/m<sup>2</sup>. This compares to the current materials tested which also reached decomposition in less than three minutes but under exposure to a heat flux 25% less than the candidate materials. Pyrovatex® fr Cotton is used for PPE in the chemical and welding industry but not for PPE in the firefighting industry. Both PBI Max® and PBI Kombat Flex® withstood exposure to 24.2 kW/m<sup>2</sup> radiant flux for a duration of 15 minutes without reaching their thermal decomposition temperatures. From this, PBI Max® was selected for testing at higher heat fluxes of 36.7 kW/m<sup>2</sup> and 48.4 kW/m<sup>2</sup>. The results from this testing are shown below in Table 8.

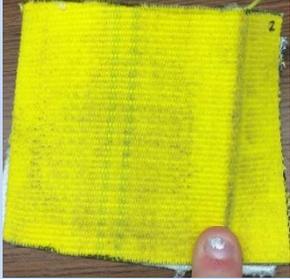
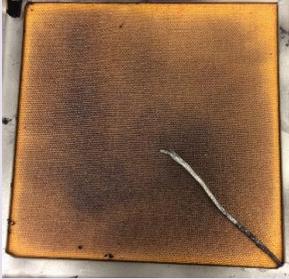
<b>Material</b>	<b>Heat Flux [kW/m<sup>2</sup>]</b>	<b>Decomposition Trial 1 [seconds]</b>	<b>Decomposition Trial 2 [seconds]</b>	<b>Ignition Trial 1 [seconds]</b>	<b>Ignition Trial 2 [seconds]</b>
PBI Max®	36.7	---	414	--	--
	48.4	83	106	85	110

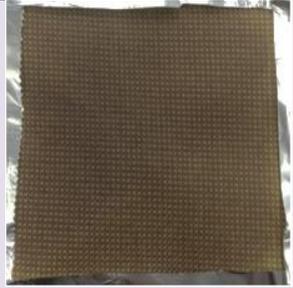
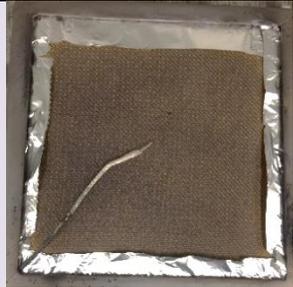
**Table 8: Testing Results for PBI Max® at 36.7 and 48.4 kW/m<sup>2</sup>**

It was not until a heat flux of 36.7 kW/m<sup>2</sup> did the material decompose and 48.4 kW/m<sup>2</sup> that PBI Max® began to ignite. However, it can be said that both materials made of PBI fiber withstood heat flux the best of the materials tested during this research.

### 4.3 Comparison of Current and Candidate Materials

Images of test samples of each material exposed to 18 kW/m<sup>2</sup> are shown in Table 9. In addition to the quantitative data presented above, the photographs visually demonstrate that the candidate materials perform better in high-heat environments. A heat flux of 18 kW/m<sup>2</sup> was chosen for this comparison as a point of interest because it represents the stage in a fire that is approaching flashover.

Material	Before Testing at 18 kW/m <sup>2</sup>	After Testing at 18 kW/m <sup>2</sup>
Polyester (Current)		
Nylon 6.6 (Current)		
50% Kevlar®-50% Nomex® (Candidate)		

<p>90% Nomex® (Candidate)</p>		
<p>PBI Max® (Candidate)</p>		
<p>PBI Kombat Flex® (Candidate)</p>		
<p>Pyrovatex® fr Cotton (Candidate)</p>		

**Table 9: Before and After Photo Comparison of Samples at 18.0 kW/m<sup>2</sup>**

Looking at the images displayed in Table 9 above, it is clear that the candidate materials are better suited for high-heat environments as all remain intact without signs of holes or cracks forming. While some discoloring occurred, none of the candidate materials showed signs of charring or burning. Also, all candidate materials were able to easily be removed from the testing apparatus without damage and still remained flexible. The candidate materials did not appear to lose their material-like qualities while the current materials did, changing into hardened plastic mounds before burning up completely into ash and dust piles.

Results of this research are summarized visually below in Table 10 and Table 11 where the red box indicates decomposition or ignition and the green box indicates no decomposition or ignition.

Material	11.9 kW/m <sup>2</sup>		18 kW/m <sup>2</sup>		24.2 kW/m <sup>2</sup>	
	<u>Decomposition</u>	<u>Ignition</u>	<u>Decomposition</u>	<u>Ignition</u>	<u>Decomposition</u>	<u>Ignition</u>
Polyester	Yes	No	Yes	Yes	--	--
Nylon 6.6	Yes	No	Yes	Yes	--	--

Table 10: Current Material Comparison

Material	11.9 kW/m <sup>2</sup>		18 kW/m <sup>2</sup>		24.2 kW/m <sup>2</sup>	
	<u>Decomposition</u>	<u>Ignition</u>	<u>Decomposition</u>	<u>Ignition</u>	<u>Decomposition</u>	<u>Ignition</u>
Pyrovatex® coated Cotton	No	No	Yes	No	Yes	No
50% Kevlar®- 50% Nomex®	No	No	Yes	No	Yes	No
90% Nomex®	No	No	No	No	Yes	No
PBI Max®	No	No	No	No	No	No
PBI Kombat Flex®	No	No	No	No	No	No

Table 11: Candidate Material Comparison

From this table, the following can be concluded: current hose jacket materials do not withstand pre-flashover conditions, there are candidate materials currently being manufactured that perform better in high heat conditions than current materials do, and certain candidate materials do not ignite until heat fluxes higher than those that commonly occur in flashover.

## 5. Conclusions

This research accomplished four things: identified candidate materials used in PPE for application for the jacket of a fire hose, created a test method useful for testing current and candidate materials in a radiative heat environment, performed the aforementioned test methodology using the cone calorimeter and quantified the time to decomposition and ignition of current and candidate materials under a range of heat fluxes. This research proved the hypothesis to be true that there are other materials being manufactured that are better suited in fire hose jacket performance on the fire scene than the current materials being used.

The project tested the two main materials currently being used in fire attack hose jackets, polyester and nylon 6.6, to create a baseline on which to compare candidate materials. Five different materials currently used in PPE were identified as being suitable for application in a fire attack hose jacket: 50% Kevlar®-50% Nomex®, 90% Nomex®, PBI Max®, PBI Kombat Flex® and Pyrovatex® fr Cotton. A test method was created using a cone calorimeter to provide a radiant heat flux that was reliable, consistent and repeatable. This method allowed the following information to be gathered about each sample if applicable: time to decomposition and time to ignition.

Based on the data collected, it is evident that there are candidate materials that perform better than the current materials when exposed to the same radiative conditions. The current materials both reached decomposition temperature when exposed to a radiant heat of  $11.9 \text{ kW/m}^2$ , a heat flux comparable to pre-flashover conditions. As testing continued, it was found that current jacket materials began to ignite at  $18.0 \text{ kW/m}^2$  (still pre-flashover conditions), while a majority of the candidate materials were not even close to reaching their decomposition temperatures.

Testing was continued on PBI Max® until it reached ignition. It was not until the material was exposed to a radiant heat flux of  $36.7 \text{ kW/m}^2$  and  $48.4 \text{ kW/m}^2$ , which is double the heat flux indicative of flashover, that it began to burn. This evidence proves the research hypothesis that there are materials currently used in firefighter PPE that perform better when exposed to a radiant heat source than the current materials being used in fire attack hoses. PBI Max® and PBI Kombat Flex® both withstood a heat flux higher than that considered to be indicative of flashover.

## 6. Recommendations and Future Work

Recommendations for future work are focused on further testing of the materials selected for this research, along with searching for other materials that are suitable for this type of application.

### **Continued testing on selected materials would provide a more complete set of results.**

Continued testing of these candidate materials at the desired heat fluxes of 10, 15, and 20 kW/m<sup>2</sup> is recommended. Materials used in this testing that did not ignite near these heat flux values (Kevlar®, Nomex®, PBI® Fiber and Pyrovatex® fr Cotton) should continue to be tested on the cone calorimeter by increasing the heat flux until ignition occurs. It is also important to know the decomposition point of those materials to determine what their limits are as to what heat fluxes they can withstand. As of now, it is difficult to determine which of those materials is considered to be the best candidate.

### **Additional high heat performance materials should be tested following the same methodology.**

This study focused mainly on PPE materials meaning that there are other possible candidate materials that were left out. For example, this project did not look into intumescent materials or other hose configurations. Additionally, some hose models intended for wild-fires have the ability to “weep” meaning that small perforations in the hose allow water to leak out in a controlled manner and pre-wet the jacket material. This keeps the jacket material at a cooler temperature and could potentially prolong its decomposition time. A material that is highly reflective could also be an effective candidate material. If the material can reflect portions of incident heat energy instead of absorbing it, the service life of the hose can be extended.

### **High heat performance materials should be tested in combinations.**

Each candidate material in this study was tested individually. The thermal resistance offered by combinations or layers of these and/or similar materials could produce enhanced performance results. Specifying different layer thicknesses or amounts of separate materials could offer greater heat resistance at a lower cost.

**A similar radiative heat insult study should be conducted on liner materials.**

Further investigation into potential “high thermal performance” materials for fire attack hose liners is recommended since this project only focused on jacket materials of municipal fire attack hoses. Current hose liners made of EPDM rubber and thermoplastic polyurethane (TPU) have never been tested under radiative heat fluxes similar to those in this study. In this light, other material may offer better performance against heat insult.

**A prototype hose made of candidate materials should be tested via a rigorous heat performance test for analysis in a large-scale scenario.**

Once the aforementioned testing is completed, and if the material passes non-heat performance testing, the creation of a prototype hose constructed from candidate materials is suggested. This prototype should then be tested according to a procedure similar to those discussed in Chapter One to analyze its applicability in a high heat environment. The results from that testing can then be compared to the results from this research to determine if the prototype displays significant improvements in performance.

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## Glossary

**Candidate Material** – refers to a material that is currently used in Personal Protective Equipment and being tested in this research for application in a fire attack hose jacket

**Current Material** – refers to a material that is already being used to manufacture fire attack hose jackets

**Fire Resistant** - will not ignite upon exposure to flames and do not melt or drip under high radiant heat exposure upwards of 600 degrees Celsius

**Fire Retardant** – chemically treated to self-extinguish after flame exposure

**Time to Decomposition** – the length of time from when the sample was first introduced to a heat flux to the moment when the surface of the sample reached its temperature of decomposition

**Time to Ignition** – the length of time from when the sample was first introduced to a heat flux to the moment flaming combustion occurred