Thermomechanical Performance of Fire-Hose Materials

A Major Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.

Submitted by:

Amy Misera ________________________

Tiago Olijnik ________________________

Submitted to: Project Advisor: Nima Rahbar ___________________

April 28, 2016

Abstract

Fire hoses are a firefighter's main line of defense and offense during an emergency. The durability and strength of the materials are the key parameters that guaranty the hose material withstand all conditions during its lifecycle. This project studied the tensile strength of six double jacket fire attack hose materials by performing tensile tests at three different elevated temperatures using a custom designed ceramic cup furnace.

Authorship

This Major Qualifying Project was created and compiled by the shared contributions of both group members. Each member satisfied their required responsibilities as well as attended group meetings, conducted research, and accomplished the required narratives involved for the finalization of this document.

Amy Misera was responsible for the all of the simulations and the subsequent write ups of simulation methodology, results and conclusions. Amy also wrote the visual observation results and conclusions. As part of the team, Amy participated in all of the tensile tests and contributed to the writing and formatting of the introduction, background, and executive summary.

Tiago Olijnik was responsible for the ceramic cup design and the subsequent write up of the ceramic cup methodology. Tiago participated in all of the tensile tests, created the graphical figures related to testing and wrote the results, analysis and conclusions for the tensile testing. In addition, Tiago was responsible for the poster design.

Capstone Design Experience Statement

In accordance with the Major Qualifying Project requirements, the goal of this project was to create initial finite element simulations in order to design a reliable fire hose material. The simulations were created based on the thermomechanical properties that are experimentally measured during the project. This project establishes a design and simulation process that can be used to test several different materials. Considerations in this design included the health and safety of fire fighters using the hoses and the performance of the hose materials. The design involved testing the stresses in fire hose jacket materials when a constant pressure and temperature equal to the conditions of water used during a fire extinguish at high temperatures. Creating finite element simulations allowed for the computation of stresses in the materials as a function of parameters such as hose thicknesses and temperatures, while also generating uniform conditions that can be reproduced indefinitely. Lastly, the results of this project can significantly help future developments in NFPA code, as the current code is lacking completely physics-based evaluation criteria.

Acknowledgments

We would like the express our appreciation to Professor Nima Rahbar for his valuable and constructive advice and suggestions through the entire project. His continuous leadership and guidance helped navigate and overcome the difficulties encountered.

We would also like to thank Russell Lang for his continuous help through the entire testing process. His assistance and expertise allowed us to fully utilize the resources available in the Civil Department laboratory and his creative mind helped devise unique methods and tools to address various challenges faced while testing.

We acknowledge the indispensable participation of Jinqiang Ning in the design and construction of the ceramic cup and selecting effective components.

We would like to thank Jessica Rosewitz and Sina Askarinejad for their assistance and support when learning how to use the finite element software.

Lastly, we would like the thank Last Call Foundation for funding our project, so we could research and help design a fire resistant fire hose.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

To be a firefighter, one must assume a certain amount of risk and understanding that every fire has the possibility of being the last. Intensive training and safety gear offer protection, but what if the trusted equipment responsible for extinguishing the fire poses its own threat?

Firefighters successfully extinguish fires from a distance, however certain circumstances require firefighters to enter a burning structure. The atmosphere inside subjects' firefighters and their protective equipment to serious danger, which intensifies with prolonged and repeated exposed. The protective gear and equipment are designed to withstand certain elements, but due to advanced materials used in products today, fires develop quicker, become hotter and fully envelope structures faster than they did ten years ago (Kerber,2011). These new threats have forced the modification of safety gear and equipment such as hoses, and the establishment of tests which are performed to ensure equipment is still viable. Fire is unpredictable, in the moment circumstances can change and despite best efforts, equipment can still fail. Unfortunately, the unforeseen hazards and failures often lead to injury or death.

1.1 Back Bay Fire

On March 26, 2014 the Boston Fire Department responded to a fire in the area of Boston commonly known as Back Bay. When the first responders arrived most entered the building to rescue residents on the upper floors. Lt. Edward Walsh and Michael Kennedy took their hose and headed to the basement where they believed the fire had originated. Soon after entering the basement, the men realized they were trapped and placed a distress call. Despite the immediate reaction to the call for help, it took thirty minutes for firefighters to reach the basement, find and evacuate Michael Kennedy. Kennedy was rushed to the hospital, where he was later pronounced dead due to smoke inhalation. It was not until later that evening when firefighters were able to locate Lieutenant Walsh, who was pronounced deceased at the scene. While trying to extinguish the fire and rescue the trapped men, firefighters had to deal with heavy winds fueling the fire, and an unexpected blast in the stairwell which knocked down and injured firefights as they tried to reach the men in the basement. Overall, the fire took four hours to fully extinguish, claimed two lives and injured thirteen firefighters and five civilians. In the aftermath, an investigation discovered that the fire hose used by Walsh and Kennedy had burned through preventing the water from reaching the target (US Fire Administration, 2015). As a result of this tragedy, the mother of Michael Kennedy decided to take action. The Last Call Foundation was created and committed to providing funding, education and research to advance the safety needs of firefighters, to save lives and to help prevent a future tragedy. In 2015, The Last Call Foundation awarded WPI a grant to fund the Next Generation Fire Hose Project, which is a culmination of various projects working to design a fire resistant fire hose that meets the diverse needs of the fire service during fire ground operations (Last Call Foundation, 2014).

1.2 Next Generation Fire Attack Hose Project

This project is one of six groups associated with the grant funded Next Generation Fire Hose Project. The various projects address different aspects to increase the research and testing to ensure the best design. The current project began in late 2014, where a group of students preformed tensile testing on fire hoses in room temperature. That series of tests was used as a baseline and has been continued in this current project, with the addition of applied heat during the tensile testing.

1.3 Goal Statement

This project was designed to test the tensile strength of current on the market fire hoses in higher temperature situations using a designed ceramic chamber with heating coils in order to recommend a different combination or design a new hose that will be more fire resistant and still meet all specifications.

2.0 Background

Before making radical changes to current fire hoses, it is crucial to cover every step that has led to here. Learning the history of fire hoses, all the way back to the first design and understanding the codes and tests performed on current hoses lay the ground work for the next larger steps.

2.1 Fire Hose History

In the late 1670's the first public American Fire department was established in Boston. The members of this colonial fire extinguishing unit employed buckets since the use of fire-hose was not yet prevalent. The first iteration of the fire hose designed in 1821, was very primitive in its nature. James Boyd patented the design for a rubber lined fire hose with a woven cotton outer structure (Jones, 2010). Though innovative, this early design had many flaws, leaks were a common occurrence and often the 50-foot leather hoses burst due to excess pressure.

In the 1800's advances were made in fire hose material development. Instead of sewing, James Sellars and Abraham Pennock of the Philadelphia Hose Company administered metal rivets and couplings to bind the leather hoses (Hashagen, 1998). These hoses were still extremely heavy and hard to work. Lining the hose with rubber to withstand great pressures and using seamless cotton mesh on the exterior allowed for greater durability and flexibility. The combination generated an efficient and lightweight hose that could be used on fire engines and easily handled by the members of the fire department.

2.2 National Fire Protection Agency

The National Fire Protection Agency is the head organization for all standards and codes related to fire safety. The origin of the organization can be traced to the development of the automatic sprinkler in the 19th century. In 1895, a group of men with various interests in sprinklers and fire insurance met to discuss the inconsistencies with the standards in the industries. The single meeting spurred into many other larger meetings, and lead to a final meeting in March of 1896. The end product of the meetings was the ‘Report of Committee on Automatic Sprinkler Protection’. The committee soon grew and by 1897 it was titled NFPA and was made up of members from 20 different companies.

The NFPA produces various code books on all aspects of fire protection. NFPA 1961 has the standards for fire hose. Originally named NFPA 196, the first issue was created in 1934 as *Standard Specifications for Cotton Rubber-Lined Fire Hose for Public and Price Fire Department Use.* This was the standard that was used until 1958 and the committee updated the requirements, issuing the official standard in 1960. Small changes were made through the years, and a completely revised copy was issues in 2002, this issue included changes regarding alternating pressures, hose lengths and inspections (Grant, 1995). The NFPA makes changes to the standards every couple of years to account for changing technologies and new findings that improve the quality of hoses used (NFPA, 2007).

2.3 Fire Hoses and Codes

The current NFPA 1961 includes all standards regarding current on the market fire hoses and the tests performed. There are various types of fire hoses that are used for different scenarios and emergencies. NFPA 1961 provides standard definitions for a fire hose and six specific types of hoses (NFPA, 2007).

Fire Hose: A flexible conduit used to convey water.

Large Diameter Hose: A hose of 3 ½ in. (90mm) or larger size.

Attack Hose: Hose designed to be used by trained fire fighters and fire brigade members to combat fires beyond the incipient stage.

Forestry Fire Hose: A hose designed to meet specialized requirements for fighting wildland fires.

Occupant Use Hose: Fire hose designed to be used by the building’s occupants to fight incipient fires prior to the arrival of trained fire fighters or fire brigade members.

Suction Hose: A hose that is designed to prevent collapse under vacuum conditions so that is can be used for drafting water from below the pump (lakes, rivers, wells, etc.)

Supply Hose: Hose design for the purpose of moving water between a pressurized water source and a pump that is supplying attack line

This particular project focused on double jacket fire attack hoses. A 2012 report investigated the available double jacket fires hoses and found that out of the 33 types of attack hoses available, 23 have a synthetic polyester jacket and only 9 have a nylon jacket. In addition, 14 of the hoses have an EPDM liner and 10 have TPU elastomer (Scheffey, 2013). For this project, six different hoses were analyzed. The hoses used in this project have a Nylon 6.6 or Polyester outer jacket, and a TPU or EPDM rubber lined inner jacket.

Table 1: List of Fire Hoses Used

Hose	Outer Jacket	Inner Jacket
1	Polyester	EPDM
2	Polyester	TPU
3	Polyester	EPDM
4	Polyester	TPU
5	Nylon 6.6	EPDM
6	Nylon 6.6	TPU

Each hose must follow general standards and ones specific to its purpose. In addition, there are codes set for testing and inspection of the hoses. Chapter 6 of NFPA 1961 describes 12 different testing method codes, including tests such as kink, burst, tensile strength and elongation, cold bending, etc. The tests performed in this project were modeled after NFPA 1961 6.7 Tensile Strength and Elongation. The code describes the procedure to test the tensile strength of hose materials in room temperature in accordance with ASTM D 412 *Standard Test methods for vulcanized Rubber and Thermoplastic Elastomers – Tension Method A (ASTM, 1998).*

A previous project, tested the same hoses in room temperature using the standards set in 6.7, and this project served as a continuation using the addition condition of applied heat to further understand the thermomechanical properties of the fire hose materials.

2.4 Abaqus

To support results, computer programs are used to simulate experiments with finite elements. Abaqus, a computer software originally released in 1978 is widely used for finite element analysis and computer-aided engineering. Abaqus is a multi-faceted program with five main core software products, each designed for specific uses and vary in intricacy. Abaqus can be used to test things such as car collisions, beam bending, material deformation and many other things. All Abaqus programs allow users to recreate tests, including sample elements, material properties and applied conditions. Figure 1 shows the design of a testing element used during the room temperature tests. The dimensions are identical to the physical samples.

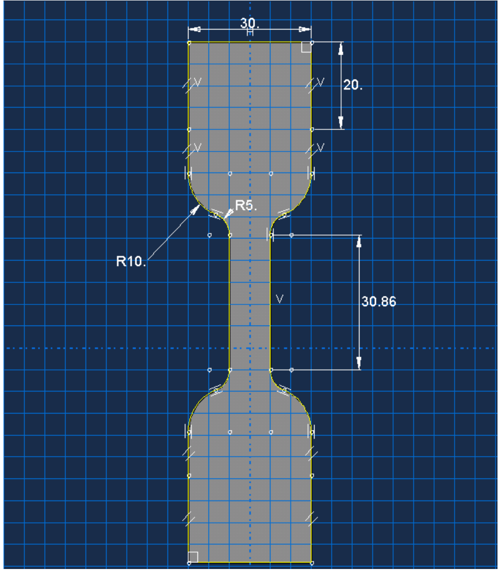
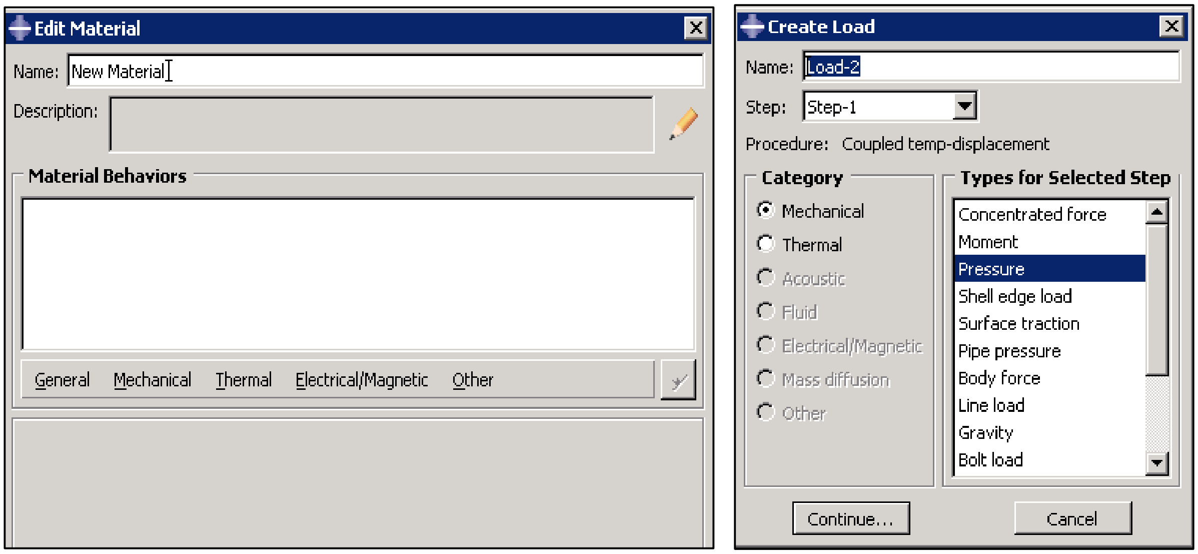


Figure 1: Sketch of Sample in Abaqus

To run a proper simulation the necessary property materials must be entered. The user can personalize the material and input all relevant properties and apply certain boundary conditions and applied loads. Figure 2 below show the dialog boxes where the material properties and applied loads are entered.



Name: New Material

Name: Load-2

Step: Step-1

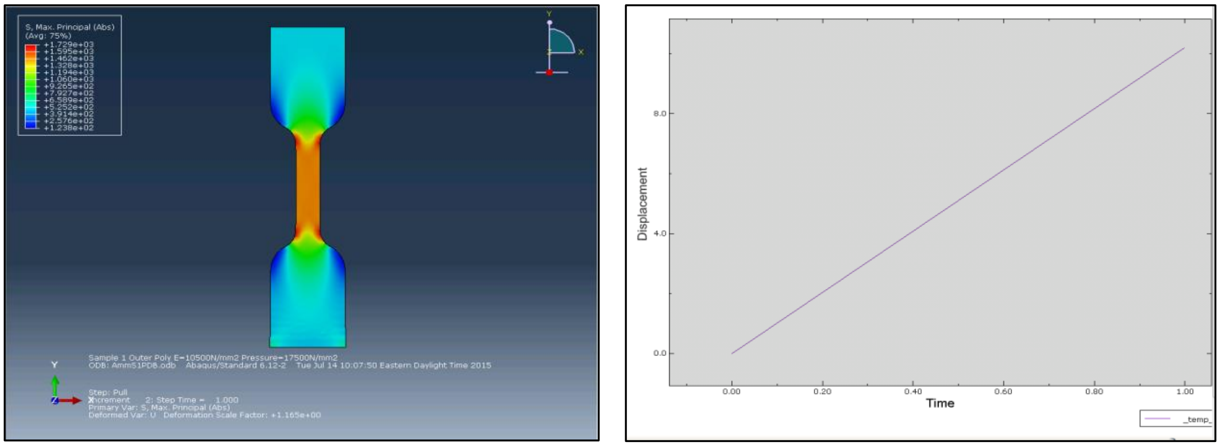
Procedure: Coupled temp-displacement

Category: ● Mechanical

Types for Selected Step: Pressure

Figure 2: Dialog Boxes in Abaqus

After the conditions have been applied, the parts and properties must be meshed before running the test. The mesh separates the part into individual nodes which will be used later when analyzing the results. Once the simulation has been run, the visual results can be viewed. The images display the visualization of a sample after a tensile test and the XY plot. This visualization shows the elongation and displacement values of the sample. Underneath the sample the material properties and other important information is listed.



```
Sample 1 Outer Poly E=10500N/mm2 Pressure=17500N/mm2
ODB: Amm51PD8.odb    Abaqus/Standard 6.12-2    Tue Jul 14 10:07:50 Eastern Daylight Time 2015

Step: Pull
Increment      2: Step Time =    1.000
Primary Var: S, Max. Principal (Abs)
Deformed Var: U   Deformation Scale Factor: +1.165e+00
```

Figure 3: Example of Abaqus Results

Depending on the type of simulation run various results can be collected. Different visualizations of the results can be seen but analytical data can also be collected by creating an XY plot from results. If a certain small area of the sample is needed to be analyzed, those specific nodes can be selected or a full surface if required. To accommodate all possible tests, Abaqus works uses 1 second steps to track the simulation results. The leads to the X axis of the graphs to go from zero to one unless otherwise defined, but this represents the results from zero force to full force of the simulation.

Not only can Abaqus be used to recreate experiments, it can be used to speculate conditions not yet tests or that are unable to be tested. By allowing the customization of applied forces and boundary conditions, expected results of how a sample would behave in various situations are able to be obtained without having to actually execute the physical test. This can allow for the creation of design criteria and limits.

3.0 Methodology

3.1 Introduction

Tensile testing with applied heat was chosen as the ideal testing method to find the thermomechanical material properties of the selected fire hoses. Both physical experiments and simulation testing were used find results and analyze the fire hose materials. According to the NFPA code book, applying heat while testing is not a typical test so the regulations for the room temperature tensile test were followed. A ceramic cup was designed and used for the test because a hand held heating device would not reach the necessary temperatures and there was no access to a standard heating chamber that could be used while testing the hoses.

The completion of this project required fulfilling three objectives.

1) Design and build a ceramic cup for testing
2) Preform applied heat tensile testing at 50°C, 100°C, and 150°C on the inner and outer jackets of six current on the market fire attack hoses
3) Create simulations to analyze the capabilities of the fire hoses using information collected during physical testing

After completing the objectives, conclusions and recommendations could be made.

3.2 Objective 1: Ceramic Cup Design

Fire hoses undergo thermal strain tests as they are to be applied in instances where heat is a crucial factor in its performance. In order to test various fire hose materials under both thermal and mechanical strain, a heat resistant "cup" was designed and built, that acted as a miniature furnace. The cup was small enough so that it could be suspended about the Instron, to allow for mechanical strain tests to run whilst the samples were simultaneously subjected to high heat.

The materials chosen for the furnace were two different types of Alumina-Silica ceramics, due to their high resistance to heat. For the structure itself ZIRCAR Ceramics Alumina-Silica Insulation Types ECO-1200B was used. ECO-1200B is a utility grade ceramic fiber insulation board; it is made of high temperature ceramic fibers and high-purity inorganic binders that can withstand temperatures of 1260°C. This gives ECO-1200B the strong, rigid, and refractory structure; it's above average thermal shock resistance, low thermal conductivity and makes it a perfect thermal insulator for this project. A large, 1" thick sheet of ECO-1200B was purchased and cut into six rings of 5" outer diameter and 3" inner diameter, and two cylindrical plates of 5" diameter.

Alumina-Silica Insulation Type AX Moldable is the second ceramic used for building the furnace, it was used to layer and cement the rings of ECO-1200B into a rigid structure employed in the mechanical stress testing. This Alumina-Silica insulation is made of similar alumina silica fibers as the rigid ECO-1200B dispersed in water as the refractory binder; this makes AX Moldable act almost like a putty making it easy to apply to the surface of ECO-1200B insulation and dries to become a smooth but hard surface coat. The AX Moldable was chosen for this purpose for many reasons, but mainly due to its superb insulation and adhesive properties; other important characteristics include low shrinkage and a very high strength. This ceramic was prepared by mixing hot water (100°C) with a proportional amount of Alumina-Silica powder and applied in thin layers to the Eco-1200B rings first then used to “glue” the rings to one another; the top-lid feature of the ceramic cup was left unattached so that the furnace could be opened and closed when necessary. No more than ½” layers were applied at one time, and each layer was allowed to cool for a day (sometimes less due to forced drying).

The dimensions of the cup were 8” high, 3” inner diameter, 5” outer diameter, and 1” in wall thickness while the cap on the upper section added 2” in height and had a 1” x ½“ slot through the center so that the sample, thermistor and coil can be fed through. The structure was made from various ring shaped pieces of insulation that were concreted together via ceramic paste, allowing for a rigid structure that can withstand high temperatures for thermal testing. Profiles of the various features and complete assembly of the furnace are shown below.

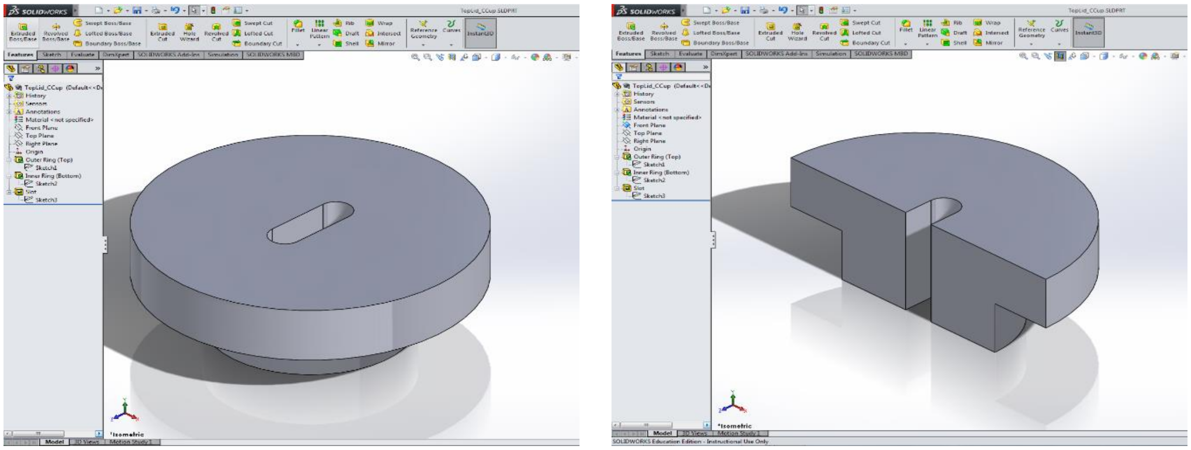


Figure 4: Ceramic Cup Lid Full and Section View

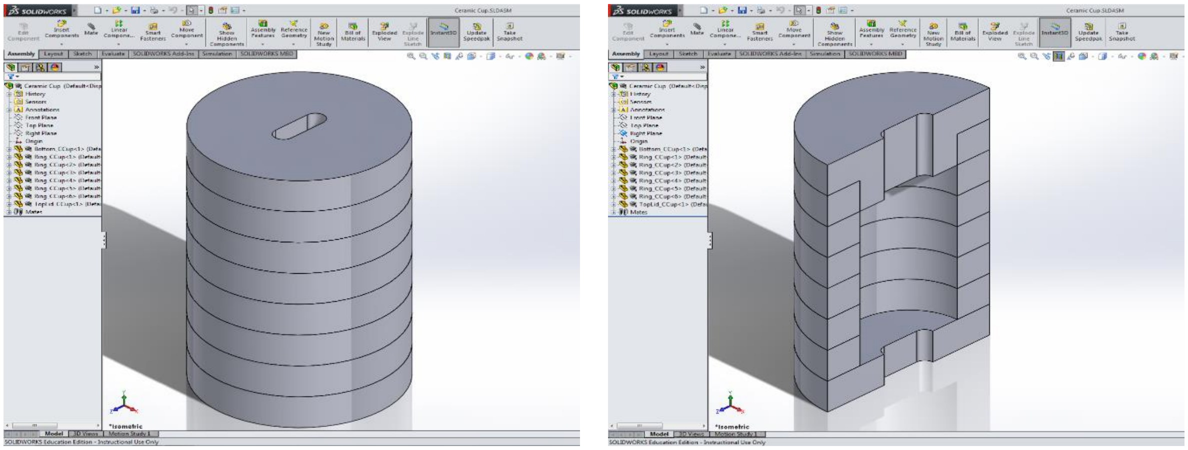


Figure 5: Ceramic Cup Full and Section View

The coil (“heat cable”) that was wrapped around the inside of the ceramics cup was made from fiberglass yarn, powered by 120V AC and could withstand temperatures from -50° to 900°F. The cable was extremely flexible and easily contoured to the surface of the AX Moldable Alumina-Silica painted onto the ECO-1200B allowing for great space efficiency within the cup.

In order to accurately control and power the ceramics cup – coil system, we are employing as splash resistant adjustable temperature switch; this remote also runs 120V AC with a current of 30 Amps. The LED display and portable nature of the device allows for the testing equipment to be handles precisely and act as a makeshift furnace station. The remote performs at a slightly shorter temperature range of -4°Fto 742°F; this still allows for the proper temperature to be reached for testing.

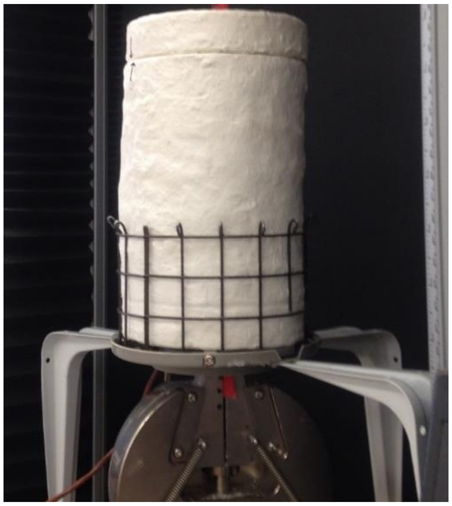


Figure 6: Photo of Ceramic Cup and Stand

3.3 Objective 2: Tensile Test with Applied Heat

In accordance with ASTM D 412, the hose samples were cut into dog bone shapes. The standard dimensions for length were modified to fit the ceramic cup but the gage width remained the same. Three samples of each hose jacket were cut for all temperatures tested. To avoid confusion and create uniformity a labeling system was used, example for the first sample of hose 1 outer jacket at 50°C, the sample was labeled 50S1-1. Once the heating device had reached the testing temperature, the sample was to be inserted into the ceramic cup and the test started in under 90 seconds. The strict timeframe was due to the heat loss in the ceramic cup due to the lid being removed. On either side of the ceramic cup the sample was clamped by the Instron machine, and the top clamp raised at a rate of 15 mm/min. The tests was automatically stopped after the sample reached the maximum load or in the higher temperatures broke. Occasionally samples slipped from the clamp grip and caused the testing to end. All inner and outer jacket hose samples were tested in one temperature before starting the next temperature. During and after each test the hose performance was observed and recorded.

3.4 Objective 3: Finite Element Simulation

For this project, Abaqus/CAE was used to simulate finite element tensile testing and the stress vs strain relationships of the hose materials. Based on the physical tests and stress vs strain values calculated, the hose simulations were able to be created. An original set of simulations were created to produce strain values that resembled with the calculated values. After completing the preliminary simulations, the design stage could begin.

The design stage used Abaqus to simulate a section of hose under the conditions experienced when pressure tested and when water is flowing through the hose. The preliminary simulations tested the materials when exposed to 50°C, focusing on the material allowed the use of a rectangular test element oppose to the dog bone shape used in the physical experiment. The element tested was the same for every material resulting in the creation of Model-1, which was a simple rectangular test element.

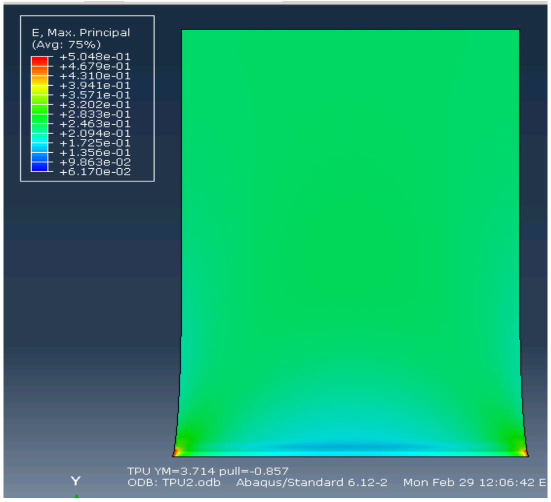


Figure 7: Visualization of Model-1 in Abaqus

The data from the preliminary simulations was often referred to during the design stage. In the design stage, one inner and outer jacket material were used in the hose model to create a guideline for future tests. The hose was simulated using the minimum operating pressure of 275 psi or 1.89 MPa to the inside of the hose, a temperature of 50°C, 100°C and 150°C were applied to the outside of the hose and a temperature of 5°C was applied to the inside to simulate water temperature (Scheffey, 2013). The pressure applied to the inside of the hose produced different stress values on the inside and outside of the hose. The hoses were also simulated at different jacket thicknesses to examine how thickness effects the stress of the material at all three temperatures.

4.0 Results and Analysis

4.1 Introduction

During this project, three different types of results were collected and each set of results helped to form the sets that followed. First, was observing the hose performance during the physical tensile. Second, the results from the tensile testing were analyzed and the mechanical properties of the fire hose materials were found. Lastly, the material properties were used to create finite element simulations and apply the findings in a hose structure with the appropriate conditions. Each set of results provides valuable information to design a more fire resistant fire hose.

4.2 Test Observations

The mechanical property values of the samples are fundamental in understanding how the materials behave and can help predict the longevity of the hoses. Similarly it is important to observe how the materials physically preform when direct heat is applied. Knowing how a hose performs to higher temperatures can be useful during physical examinations after a fire has been extinguished. If the warning signs of a compromised hose are recognized, the problem can be addressed before a critical error occurs.

As the temperature increased the material performance decreased. Starting with the 50°C testing raised concerns due to the lack of change in the materials and samples repeatedly slipping from the machine grips. However, it created a base level of material performance and knowledge of how to handle the samples. During the 50°C tests there was a noticeable difference between the outer and inner jacket material. The outer jacket materials experienced fraying, mostly contained on the edges of the middle but some spread along the entire sample. The polyester hoses experienced more fraying overall than the nylon hoses. When testing the inner jackets, there was very little change except for hose 1 where the EPDM rubber began to separate from the fabric backing. As previously stated, many samples slipped from the machine grips due to the relatively small thickness and the large load being applied. On average, the 50°C tests lasted 109 seconds, with the maximum length being 200 seconds and the minimum 43 seconds.

Figure 8: Hoses 1-6 After 50°C Testing. Outer Jackets on Right, Inner Jackets on Left

To address the amount of slippage during the previous tests, longer samples were cut and used for the remainder of testing. The raised temperature required a quick insertion of the sample into the chamber to prevent the loss of samples due to shrinkage or prolonged expose to heat prior to the physical test. The 100°C tests produced more physical material changes in all six samples, with shrinkage of the outer jacket materials being the most common physical change. Half of the polyester samples frayed but all shrunk while exposed to the heat and continued to shrink after removed. The two nylon samples performed very differently. Hose 5 shrunk due to the heat but sustained minimal damage, unlike sample 6 experienced smoking, burning, fraying and breaking in half. The difference between the inner jackets became evident during this round of tests. The EPDM samples separated from their fabric liner and the liners shortened, causing the samples to buckle. One of the EPDM samples began smoking within the first minute of the test but did not burn. The TPU samples did not separate from their backings but melted then hardened when removed from the heat. Some of the fabric backings on the TPU samples experienced fraying and shrinkage. The 100°C tests lasted an average of 119 seconds, the longest test was 243 seconds and the shortest was 35 seconds.

Figure 9: Hoses 1-6 After 100°C Testing. Outer Jackets on Right, Inner Jackets on Left

Figure 10: Addition Pictures from 100°C Testing.
1) Hose 5 smoking during testing, 2) Disfigured Hose 2 inner jacket, 3) Broken Hose 6 Outer Jacket

The final round of testing produced interesting results. Similar to the 100°C testing, the speed of the sample insertion into the camber was an important factor and also became more difficult due to skin expose and the potential of burns at 150°C. The occasional use of a protective glove and long nose tweezers were found to be useful tools to quicken the process. The 150°C tests resulted in many broken or melted samples. Three of the four polyester outer jackets broke during the test. All four experienced narrowing of the middle, melting and hardening when removed from the heat. Again, the two nylon samples performed differently. Sample 5 broke in half similar to the polyester material, but did not experience as much melting. Sample 6 remained in one piece and the only damage was narrowing and frayed edges of the middle. All EPDM samples separated from the fabric backings which broke once separated. The fabric backings also melted then hardened when removed from the heat. The TPU samples did separate from the fabric backings but they did melt and almost or completely broke in half. The testing length average dropped to 52 seconds, the longest test lasted 177 seconds and the shortest was 2 seconds.

Figure 11: Hoses 1-6 After 150°C Testing. Outer Jackets on Right, Inner Jackets on Left

4.3 Material Properties

4.3.1 Introduction

In order to obtain vital information about the performance and mechanical properties of conventionally employed fire hose materials, a servo hydraulic Instron machine facilitated the acquisition of the necessary data/figures to properly analyze the materials’ tendencies. Samples were first cut into the typical dog-bone shape so that proper ASTM standards for testing these types of materials (elastomers & vulcanized rubber) could be followed in order to procure trustworthy and scientifically sound results for our experiment. The force vs elongation data provided by the Instron was used to find the stress-strain curves for six fire-hoses each with different outer and inner jacket material; samples were tested at four different temperatures, room, 50, 100, and 150 degrees Celsius, to observe the adverse effects of heat on a non-pressurized fire-hose material. From these stress-strain curves one can derive valuable information about the mechanical performance such as: tensile strength, toughness, modulus (stiffness) and ductility.

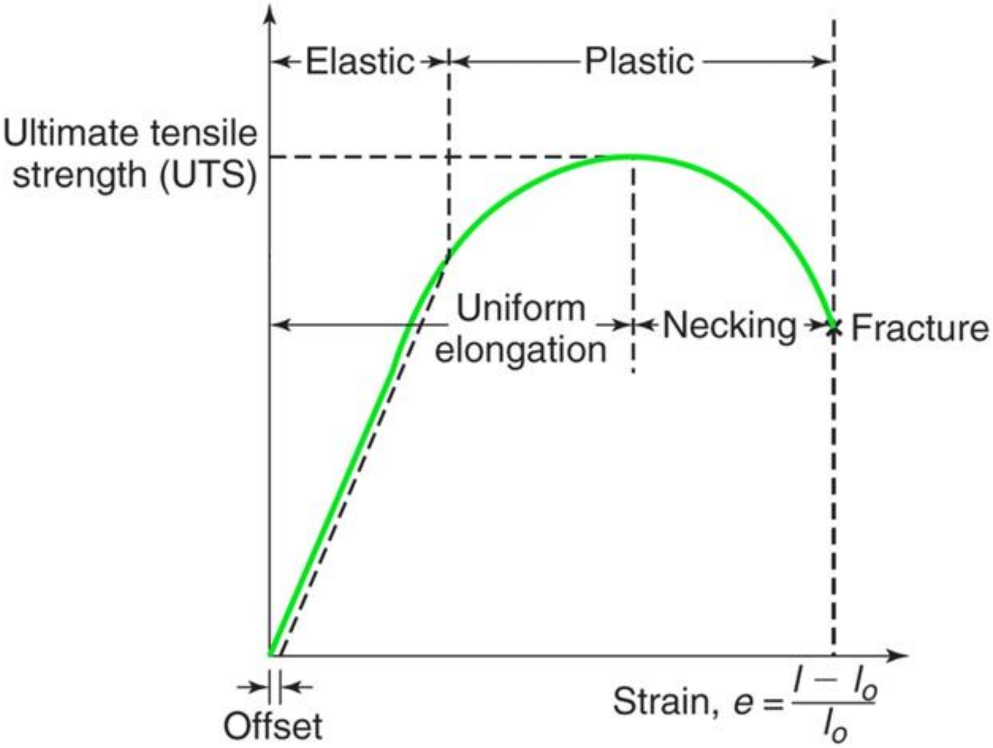


Figure 12: Mechanical Properties Graph

Mechanical Properties Observed:

1. **(Tensile)Strength**: UTS is a material’s/structure’s capacity to withstand loads that elongate (as compressive strength is to compressing loads). The tensile strength is measured by the maximum stress that a material can tolerate while being stretched or pulled before necking or breaking. Stress=Force/Cross Sectional Area

2. **Ductility**: Ductility, or Elastic Strain to failure, is better described as the extent of plastic deformation that the material undergoes, due to tensile stress, before fracture. It is measured by the amount of elongation/strain prior to breaking.
3. **Elastic Modulus (Young's Modulus)**: Defines the relationship between stress and strain during elastic deformation where it is a measure of how much stress, along the axis of strain, a material can withstand and return to its original state. Modulus of Elasticity = Stress/Strain, in other words the slope of the linear portion of the stress strain curve.
4. **Toughness**: Is a material's resistance to fracture when a stress is applied. Toughness is defined as the amount of energy per unit volume (Joules/meter^3) that a material can absorb before rupturing. Toughness is important in this study because, having a tough material requires a balance of strength and ductility; in Figure 12 above toughness can be measured as the area under the curve prior to breaking.

The sample data (graphs) presented is separated into inner and outer hose performance so that the different layers can be compared to its "competitor" in a different kind of hose. Each graph presents the stress/strain curves for that material at 50-150 with data acquired through testing. First the inner jackets will be analyzed.

4.3.2 Inner Jacket Analysis

4.3.2.1 Inner Jacket 50°C

If we begin by looking at the stress strain curves for all the materials heated up to 50 °C, it is fair to say all samples continue to show ordinary behaviors for thermoplastic elastomers; although varying for specific strength, toughness and strain to failure.

Table 2: Average Results Inner Jacket at 50°C

AVG Strength	730.0 kPa
AVG Ductility	29.8%
AVG Stiffness	2.59 MPa
AVG Toughness	120.7 kJ/m^3

As indicated by the graphed values, TPU^4 material has the lowest strength of around 458.3 kPa, while EPDM^5 demonstrated the highest strength of 900 kPa. TPU^2 and EPDM^3 have very similar strength and strain to failure with 743.3 kPa and 20% strain to failure and 739.7 kPa and 28% strain to failure respectively; however TPU^2 is stiffer with a modulus of 3.62 MPa while EPDM^3's modulus is at 2.55 MPa. In terms of elastic modulus and stiffness TPU^2 has the greatest resistance to elastic deformation, with a modulus of 3.62 MPa, while TPU^6 demonstrated the lowest modulus of 1.61 MPa. EPDM^1 and TPU^6 were both very ductile with strain to failure 41.5% and 40.3% elongation; however EPDM^1 had a much better strength value with 889.7 kPa in comparison to 651.7 kPa. The strain to failure values for EPDM^3 and EPDM^5 were also similar at roughly 30% elongation; the strengths were also comparable: hose 3 strength of 739.7 kPa and hose 5's 750 kPa. TPU^2 and TPU^4 had well under average toughness with 84.5 kJ/m^3 and 54.8 kJ/m^3 respectively, the other being EPDM^3 with 114.3 kJ/m^3 while EPDM^1 had the best toughness rating of 188.5 kJ/m^3.

If one compares the mechanical properties in order to select the inner jacket that performs best at 50°C, EPDM (specifically Hose 5) is the only material that had better than average (in the group tested) values for all four categories of strength, modulus, toughness and ductility.

4.3.2.2 Inner Jacket 100°C

At 100°C there is still enough data prior to failure to conclude that these materials continue to behave as thermoplastic elastomers should. From the average results, one may already observe that there was a general decrease in all categories.

Table 3: Average Results Inner Jacket at 100°C

AVG Strength	442.5 kPa
AVG Ductility	24.2%
AVG Stiffness	1.55 MPa
AVG Toughness	71.79 kJ/m^3

TPU^4 continues to demonstrate the lowest strength, now with 341.7 kPa showing a 100+ kPa decrease. . TPU^6 has strength of 628.3 kPa comparing to the highest strengths of EPDM^1 and EPDM^3 with strength of 597.9 kPa and 668.0 kPa. Hoses 2 and 5 were found to have very similar tensile strengths at 100°C with roughly 525 kPa each. Although the strength was the same TPU^2 has a 24% strain to failure while EPDM^5 is at 29.5%. In this case, there were two different pairs of values with comparable strain to failure values, TPU^2 and TPU^4 at 24% and 20% respectively and EPDM^3 and EPDM^5 at 31% and 29.5% respectively; as observed the EPDM hoses showed more ductility than the TPU. The exception being TPU^6 had a staggering 56% strain to failure value while still retaining an above average strength, this material seems to perform well at temperature 100°C and below; in other words TPU^6 remains strong but becomes more ductile at 100 °C in comparison to the results at 50 °C. In terms of modulus, TPU^2 was again the stiffest sample to be tested with a modulus of 2.2 MPa at 100°C, but not much stiffer than EPDM^3 which has a modulus of 2.1 MPa; while TPU^6 had the least resistance to elastic deformation with a modulus of 1.18 MPa at 100°C. TPU^4 and EPDM^5 had similar moduli, each at 1.72 MPa and 1.76 MPa respectively, although TPU^4 still falls short on strength, ductility and toughness. In terms of toughness, TPU^2 and TPU^4 fall short of the average for all the hoses, with

63.5 kJ/m^3 and 46.9 kJ/m^3 strain energy values. While EPDM^5 had an above average strain energy rating of 89 kJ/m^3, it did not compare to the values for EPDM^1, EPDM^3 and TPU^6 (respective values: 113.7 kJ/m^3; 117.6 kJ/m^3; 183.3 kJ/m^3).

When these values are contrasted with each other, we find that, at 100°C the EPDM material used performed the best in the four categories; however TPU^6 also had excellent mechanical results at 100°C in comparison to other samples. If one required a more ductile, rather than stiff, inner jacket TPU^6 could be chosen over EPDM.

4.3.2.3 Inner Jacket 150°C

At 150°C during most trials the fire-hose materials being tested began deforming due to heat, many times, before mechanical stress was applied. This lead to a vast decrease across all three categories being analyzed, therefore the assumption can be made that inner jacket material is not designed to perform optimally much above 100°C. Again there is still enough data prior to failure to conclude that these materials continue to behave as thermoplastic elastomers should. However certain sample trials ruptured before an adequate amount of data could be gathered; these discrepancies will be mentioned when/if necessary.

Table 4: Average Results Inner Jacket at 150°C

AVG Strength	313.2 kPa
AVG Ductility	22.4%
AVG Stiffness	1.20 MPa
AVG Toughness	52.2 kJ/m^3

For the data of the samples tested at 150°C EPDM^5 was an obvious outlier, the strength, stiffness, ductility and toughness were far greater than any other hose jackets and the average with values of 550 kPa, 1.85 MPa, 29.7%, and 77.8 kJ/m^3 respectively. TPU^4 for all three temperatures demonstrated the lowest tensile strength, for this instance 71 kPa. Not considering EPDM^5, the hose with highest strength was EPDM^1 with a 227 kPa tensile strength. TPU^2 and

EPDM[3] also had high strengths: of 146 kPa and 139 kPa, however their strains to failure fell below 20% in comparison to EPDM[5]'s 29% ductility. EPDM[1] had a 25% strain to failure, but in this case had a lower tensile strength and modulus of 227 kPa in comparison to EPDM[5]'s 550 kPa strength and 1.85 MPa modulus of elasticity. All other hoses (exception of 1 and 5) had strain to failure values below 20%, meaning most samples failed before elongating past 20% of their original length showing the intense effects of heat on the inner linings of fire-hose materials. Now observing the moduli, again not considering EPDM[5], hovered for most samples around 900 kPa. EPDM[1], although having some of the better mechanical properties of the inner jackets tested at 150 °C, had the lowest modulus of 819.8 kPa; however this is not much stiffer than EPDM[3] with a modulus of 873.2 kPa. TPU[2] remained very stiff having a modulus of 1.1 MPa and only elongating a further 13% of its original length. Lastly the toughness, most hoses hovered around 20 kJ/m^3, again with the exception of EPDM[5] which had an extremely high value (for 150°C) of 77.8 kJ/m^3.

4.3.3 Outer Jacket Analysis

4.3.3.1 Outer Jacket 50°C

Table 5: Average Results Outer Jacket at 50°C

AVG Strength	547 kPa
AVG Ductility	29.1%
AVG Stiffness	1.82 MPa
AVG Toughness	106.2 kJ/m^3

At 50 °C, the results indicate that Polyester[4] is the outer jacket with the lowest tensile strength at 125 kPa while Polyester[1] showed the highest strength of 1.0 MPa, about five times stronger than Polyester[4] and Nylon[6] with strengths of 188.3 kPa and 213.3 kPa. Polyester[1] and Polyester[2] had the highest strain to failure values, of 56% and 44% respectively, although Polyester[1] had ~200kPa more tensile strength than Polyester[2]; their strengths were 1.0 MPa and

783.9 kPa respectively. The hose with the highest elastic modulus was Polyester[3], with 2.9 MPa and Nylon[6] also had the lowest modulus of 1.1 MPa. Polyester[4] showed the lowest values for all categories, this trend has not been limited to the inner or outer layers. It is interesting to note that Polyester[2] and Polyester[3] demonstrated very similar tensile strengths of 783.9 kPa and 822.0 kPa. Polyester[2] is a much more ductile in comparison to Polyester[3] which is stiffer demonstrating a ductility of 28% and modulus of 2.9 MPa. For the outer jackets at 50°C there seems to be 3 tiers of toughness ratings: where Polyester[1] and Polyester[2] are the toughest (much higher than the average, about 200 kJ/m^3 each), Polyester[3] and Polyester[4] are slightly above average around 115 kJ/m^3 each, and Nylon[5] and Nylon[6] were well below average both sitting at 20 kJ/m^3.

The outer jacket material that performed best at 50°C is Polyester. If we single out each specimen, Polyester[1] had 1 MPa strength, 56% strain to failure, a 1.8 MPa modulus of elasticity, and the highest toughness of 292.5 kJ/m^3; the only other hose with similar results was Nylon[5] which also boasted a greater modulus.

4.3.3.2 Outer Jacket 100°C

The increase in temperature of 100°C from 50°C indicates a sharp drop in average tensile strength and toughness with a slight decrease in strain to failure and moduli; in other the words the samples are remaining as ductile but fail at lower values of stress.

Table 6: Average Results Outer Jacket at 100°C

AVG Strength	274.9 kPa
AVG Ductility	25.7%
AVG Stiffness	1.01MPa
AVG Toughness	43.3 kJ/m^3

With a tensile strength of 90.0 kPa at 50°C Polyester[4] once again has the lowest strength, while Polyester[2]'s outer jacket was the strongest with a 523.9 kPa tensile strength. For both tensile strength and strain to failure Polyester[1] and Polyester[4] had similar results; the tensile strengths were 137.9kPa and 90 kPa and the strain to failure values were 17% and 12.5% respectively boasting some of the lowest values at 100°C. Polyester[1] has a higher modulus of 1.0 MPa in comparison to 4's 781 kPa, the lowest elastic modulus when tested at 100°C. The outer jacket with greatest young's modulus was Polyester[3], twice as great as Polyester[4]with a value of 1.56MPa. Polyester[3] is also more than twice as strong as Polyester[4], but only a bit more ductile; 3 had a strain to failure of 20% and strength of 320 kPa in comparison to hose 4's 90 kPa tensile strength and 12.5% strain to failure. The average strain to failure of the 100°C outer jacket group has a greater standard deviation than the inner jackets, this is due to greater changes in the values from the mean; two hoses had values for strain to failure lower than 20% while two had values higher than 40%, only one sample average showed a value close to the 25.7% percent average which was Nylon[6] with a 25% strain to failure. Polyester[2] and Nylon[5] had very similar and above average moduli, both at about 1.2 MPa as well as the two highest strengths when performing at 100°C of 523.9 kPa and 413.3 kPa respectively. If one were to not consider the toughness, Hoses 2, 3 and, 5 would seem like the best choices for this section; but Polyester[3] showed a poor balance between strength and ductility leading to a strain energy value of 32.4 kJ/m^3, which is below average and comparable to Nylon[6]. This leaves hoses 2 and 5 as the only worthy options with toughness's of 106.4 kJ/m^3 and 73.9 respectively.

The best performing material at 100°C, polyester, is easily distinguishable between the samples; Polyester[2] had the greatest strength and ductility of any inner jacket, its modulus is only less than Polyester[3]. Polyester not only had the greatest values for strength and ductility, but also demonstrated that is has the best balance of the two properties at 100°C.

4.3.3.3 Outer Jacket 150°C

There are drastic decreases in all three averages from 100°C to 150°C, this again is due to early failure due to high temperatures of the furnace. The ductility for the outer hose materials at 150°C is less than half of the value of the previous strain to fail average meaning samples failed twice as fast as the same hoses at 100°C.

Table 7: Average Results Outer Jacket at 150°C

AVG Strength	60.6 kPa
AVG Ductility	8.9%
AVG Stiffness	751.0 kPa
AVG Toughness	8.98 kJ/m^3

The data shows that Nylon[5] has the lowest tensile strength of 18 kPa and lowest strain to failure of 2% at 150°C, whose values are comparable to Polyester[4] with strength of 29 kPa with a 6% strain to failure; these extremely low values are a result of the plastic deformation of the sample material due to heat before failing mechanically. Another hose material with a below average ductility is Nylon[6], also sitting at 6% strain to failure; Nylon[5] however was the stiffest of the hoses with a modulus of 1.21 MPa. Polyester[1] had the greatest tensile strength of 137.9 kPa at 150°C, its strain to failure was also the highest with a value of 17.7%; Polyester[3] was the second most ductile material at 150°C with 11.7% strain to failure. Hoses Polyester[4], Nylon[5] and Nylon[6] all failed before reaching the 8.9% average strain to failure, further demonstrating how great of an impact the heat of the system has on the mechanical properties. Polyester[2] and Polyester[4] both had similar yet below average moduli of 532.6 kPa and 487 kPa. In terms of the toughness, or how balanced the strength and ductility of these hoses were, only 2 specimens had above average strain energy values: Polyester[1] and Polyester[3]. Polyester[1] had a toughness of 19.6 kJ/m^3 and hose 3 at 15.8 kJ/m^3; while Polyester[4] was the least tough with a value of 1.87 kJ/m^3.

The most efficient outer jacket fire-hose material when performing at 150°C is Polyester (1 and 3), bolstering the best values for all categories of mechanical performance except modulus of elasticity where it fell short of Nylon (5 and 6).

4.4 Simulations

Based on the thermomechanical properties that were experimentally measured during the project, a polyester outer jacket and EPDM inner jacket were simulated in the design stage. Three different jacket thicknesses were simulated for each material at all three temperatures. A constant pressure was applied to the inside of the hose, and the stress distributions were found. Due to the unit less platform of the program, the thicknesses have been labeled as thin, regular and thick. The regular thickness was meant to simulate the current hose thickness, and the thick and thin were meant to create alternate options, with the thin being half as thick as the regular, and the thick hose double the size of the regular. Similarly, the stress values are not measured in MPa as they were in the experiment, instead the values are solely used to compare finite element performance. For each material, the maximum stress for each thickness were graphed, to compare the change of stress due to temperature. The linear correlation between each temperature and stress values increases as the thickness decreased.

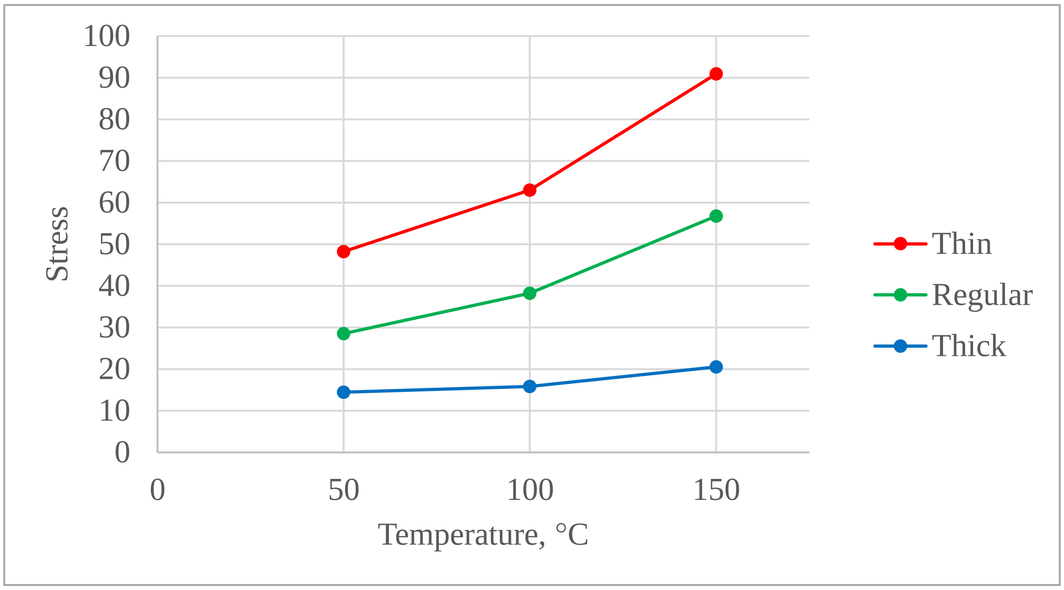


Figure 13: EPDM Stress Distribution vs. Temperature for Varying Thicknesses

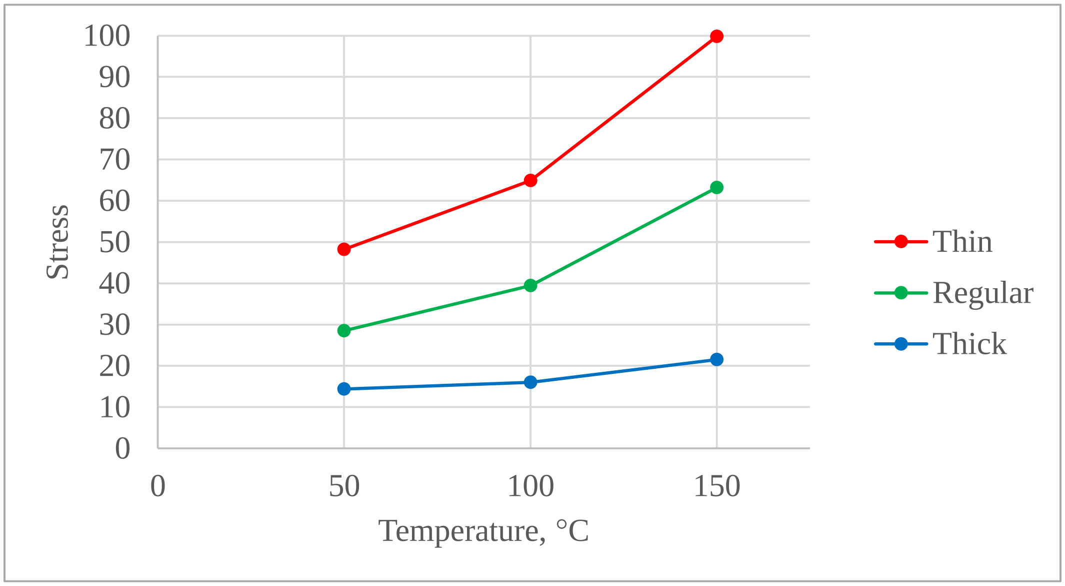


Figure 14: Polyester Stress Distribution vs. Temperature for Varying Thicknesses

The EPDM and Polyester jacket materials behaved similarly for each thickness. The thick hose had very low stress values for each temperature, ranging from around 14 at 50°C and only reaching around 20 at 150°C. The thin hose reached stress levels of over 90 at 150°C for both materials, a large increase from the stress level of 60 reached during the 100°C simulations.

5.0 Conclusions

5.1 Introduction

All three results provide different aspects of how the fire hose materials performed when tested for tensile strength with applied heat. Various conclusions were made and used to make recommendations of better inner and outer jacket material combinations.

5.2 Observation Conclusions

Through all three temperature tests some of the materials stood out in their resistance to the heat. For the outer jackets, the nylon of hose 5 was able to withstand the heat and experience minimum damage. Though it did start to melt when the temperature reached 150°C and ended up breaking, for the most part it remained intact with very little damage. For the polyester outer jackets, hose 1 outperformed the other three hoses. In all three temperature tests, it experienced the least amount of fraying. It is most noticeable in during the 150°C tests, while the other polyester samples all melted and shrunk in the middle sample one maintained its shape and simply broke into two pieces. Coincidentally, both of these outer jackets are yellow but that does not affect their ability to withstand heat. The inner jackets experienced the most damage due to the rubber materials and the fabric backings. Despite the damage in all inner liners, two performed better than the rest. For the EPDM material, hose 3 performed the best under all temperatures. Unlike the two other EPDM samples hose 3 did not separate from the fabric lining until 150°C. Even when it did separate, the fabric backing melted but remained intact. Out of the three TPU inner jackets, hose 4 outperformed the others almost tenfold. Hose 4 had zero damage during the 50°C tests, partially melted when the heat was raised to 100, and melted and broke in half during the 150°C tests. The other TPU samples all frayed and melted causing the samples to become disfigured in both 100 and 150° tests. The conditions of this test do not exactly mimic those experienced when extinguishing a fire from a safe distance but it is possible for hoses to be in close contact with high temperatures when firefighters enter a burning building.

The specialized type of tensile test with directly applied heat has never been performed on fire hoses, so there is nothing to compare the procedure or results to. Thus, all of results come with an accepted level of error. Using the designed ceramic cup oppose to a standard heating chamber provided challenges throughout the testing stage. The biggest challenge was dealing with the cup size. The 8 inch ceramic cup and supporting stand totaled 10 inches and the sample sizes cut were at most 12 inches, leaving minimal room for the grips to securely hold. In addition, the slot to fit the sample through was 1 ¾ inches long and less than half an inch thick. This presented a challenge when inserting the samples because there was no way to guide the flimsy material to a similar slot 8 inches below and have it take no more than one minute. The minute time limit was required to minimize loss of samples from shrinkage due to heat prior to testing and at 150°C the obvious dangers of prolonged skin expose. While the ceramic cup was capable of maintaining temperatures when sealed, the temperature would plunge when the lid was removed. To compensate for expected heat loss when inserting the sample, the temperature was generally set 10-20° higher than the specified testing temperature. A few times the temperature dropped lower than preferred and required more time to reach the set temperature, so some trials experienced large temperature changes which could have effected their performance. Overall, the results fulfill their purpose and provide visual representation of material reactions to possible conditions experienced during a fire extinguish.

5.3 Testing Conclusions

In order to have a more in depth analysis of the effects of temperature of firefighting hoses, graphs of the mechanical properties (Strength, Ductility etc.) plotted against the temperature were also examined. These graphs are also used to enforce/reiterate the findings analyzed in the previous sections as a form of summarization of the results and serve to outline the trends that mechanical properties have as temperature is increased.

5.3.1. Inner Jacket Analysis

Strength: EPDM^1, TPU^2 and TPU^4 show an almost linear (constant) decreasing slope when moving from 50°C to 150°C, while EPDM^3 and TPU^6 show a slowly accelerating decrease; EPDM^5 depicts an almost logarithmic decrease over the 3 temperatures. In terms of how much stress can be withstood until fracture TPU^4 can be discarded first from observing Figure 15 as it had the lowest strength at all three temperatures. EPDM^5 in this case shows the best strength at both 50°C and 150°C while maintaining an average strength at 100°C; its decelerating decreasing slope is also a good indicator that it maintains its strength more easily than the other samples.

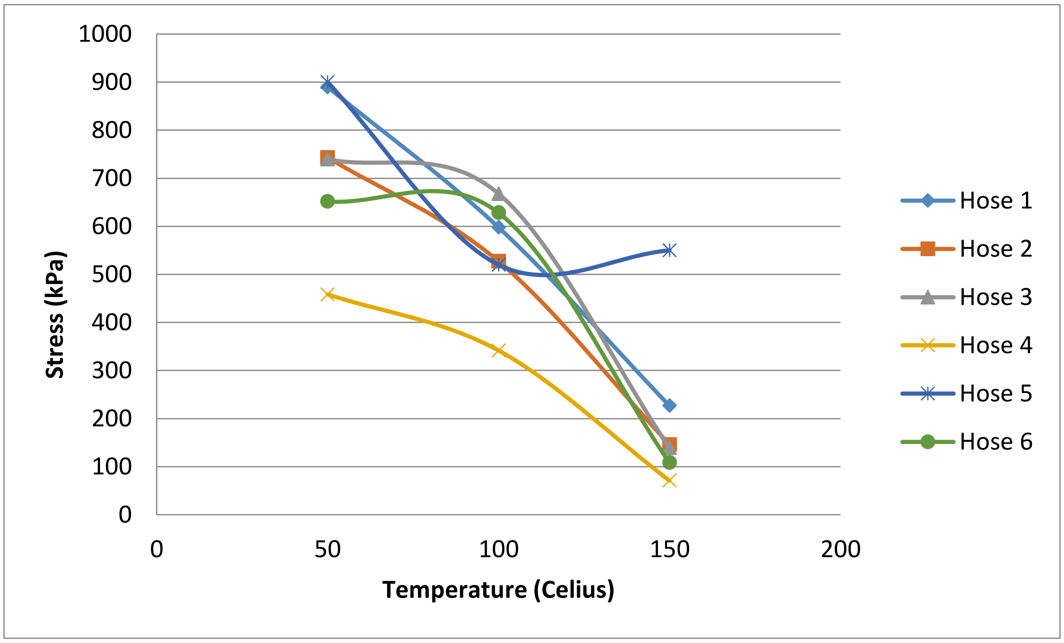


Figure 15: Inner Jackets Stress vs. Temperature

Ductility: TPU^2, EPDM^3, TPU^4, and TPU^6 all share an interesting trend, where when the temperature was increased from 50°C to 100°C the ductility of the fire hose material rose slightly before falling drastically at 150°C. This means that for a short interval, before reaching 150°C, the hose material is able to deform (in this case stretch) a greater length before ripping; the heat made the material slightly more ductile in trade for a lower strength. EPDM[1] did not increase in ductility, rather it had a very small drop in ductility from 50°C to 100°C; from 100°C to 150°C the hose material had a linear decrease in ductility remaining the second most ductile material. EPDM[5] was the biggest outlier here; the material seems to show very little change in ductility when exposed to heat, it's ductility remaining almost constant throughout the 3 temperatures.

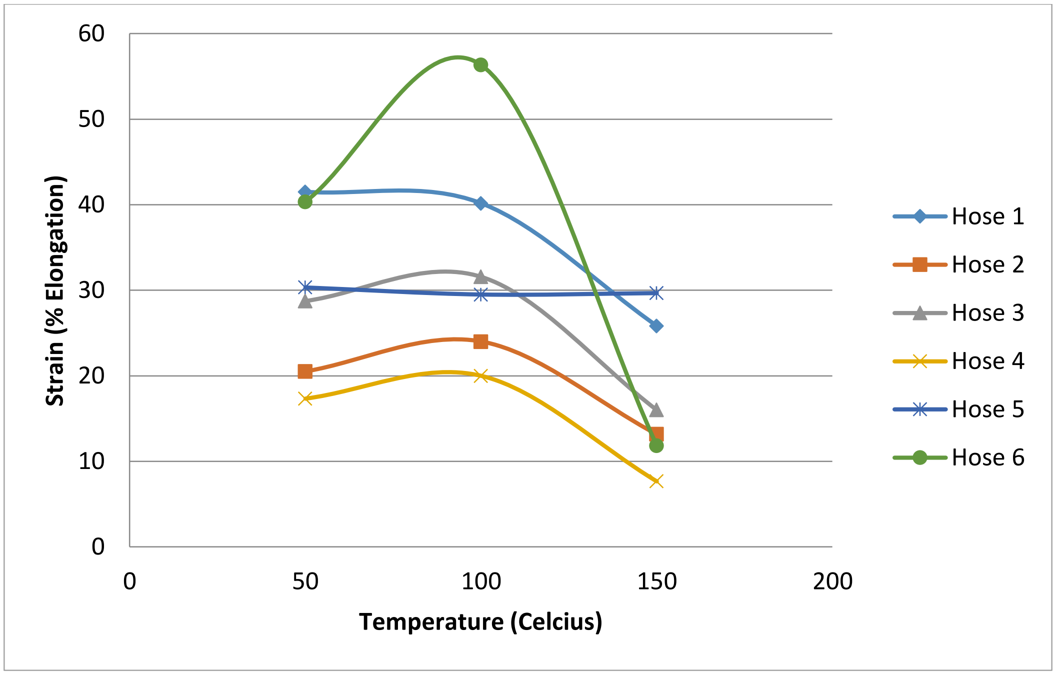


Figure 16: Inner Jackets Ductility vs. Temperature

Modulus: EPDM[1], TPU[2], TPU[4], and TPU[6] all show a steady (mostly linear) decrease in modulus as temperature is increased. EPDM[3] showed an accelerating decrease in modulus as the temperature increased, meaning that as the modulus stays around the same value until completely succumbing to the heat and losing all stiffness. EPDM[5] had a trend line that resembled an exponential decrease, in other words the modulus/stiffness of the hose is lost when exposed to heat above 50°C but shows little effect when increased from 100°C to 150°C. In this case, TPU[2] or EPDM[5]'s modulus resisted heat the best; TPU[2] had above average moduli at 50°C and 100°C but it constantly decreases as temperature is increased whereas EPDM[5] is a better candidate if the temperature where to be above 100°C.

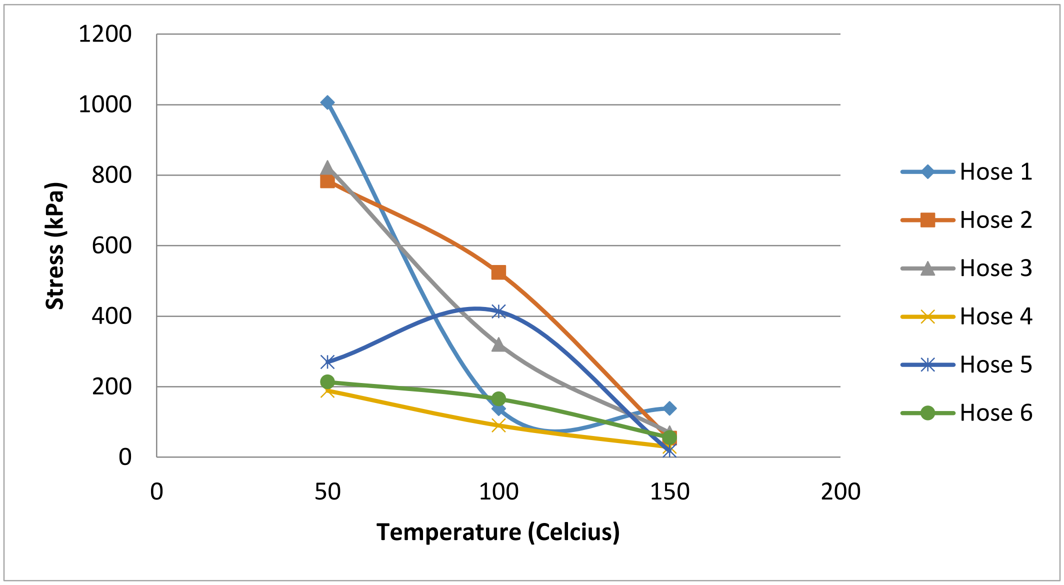


Figure 17: Inner Jackets Young's Modulus vs. Temperature

Toughness: Every specimen with the exception of EPDM[3] and TPU[6] decreased in toughness as the temperature rose from 50°C to 100°C; both of these materials rose in toughness during the first interval but demonstrated a sharp decrease from 100°C to 150°C, sharper than the other hoses. EPDM[1], TPU[2], and TPU[4] demonstrated an accelerating decrease for the three

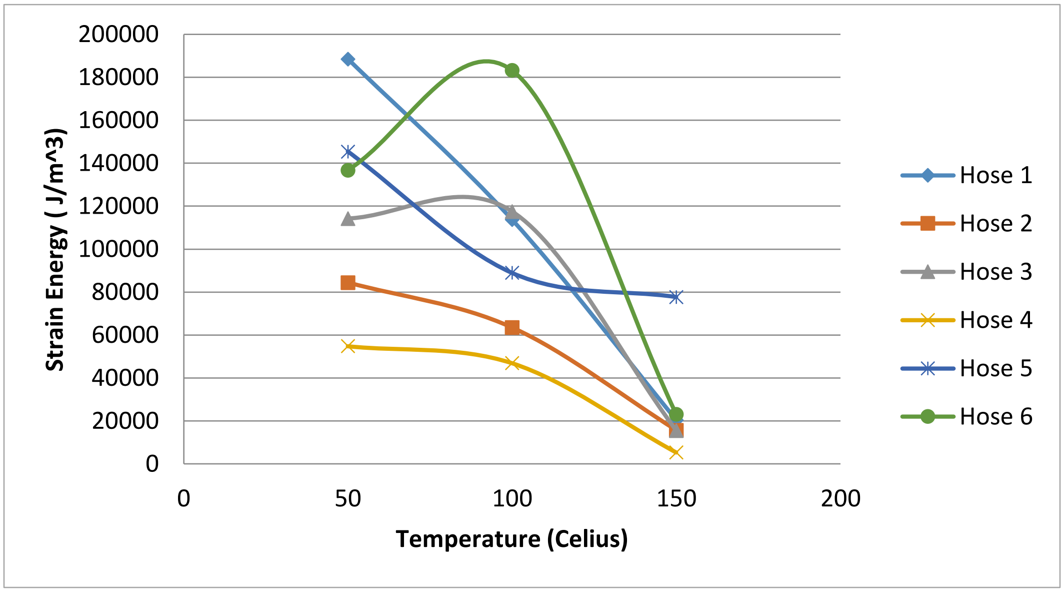


Figure 18: Inner Jackets Toughness vs. Temperature

intervals, where the slope was not as negative between 50°C and 100°C as it was between 100°C and 150°C; therefore these materials can better withstand temperature below 100°C, more closely maintaining the original toughness, than when the temperature rises above 100°C. EPDM[5] continues to demonstrate a more exponential decrease as seen in the previous graphs, where it shows a similar linear decrease as the other hoses between temperatures of 50°C and 100°C, but better maintaining its toughness above 100°C than other materials. Not only this, EPDM[5] had above average results at 50°C and 150°C while having average toughness at 100°C, which depicts better mechanical properties than its counterparts.

5.3.2 Outer Jacket Analysis

Strength: From Figure 19 one may observe that all hoses except Nylon[5] show a general decrease in strength as the temperature increases; Nylon[5] however slightly increases in strength when the temperature increased from 50°C to 100°C before sharply falling from 100°C to 150°C. This is a strange phenomenon due to the fact that most elastomeric materials' strength and stiffness degrades as temperature increases. For the hoses that show a gradual decrease, Polyester[1], Polyester[3], and Polyester[4] there is a sharper fall in strength from 50°C to 100°C in comparison to the slope from 100°C to 150°C; Polyester[1] is the most dramatic of these three specimens where it demonstrated the highest strength at 50°C but one of the lowest at 100°C. Polyester[2] and Nylon[6] show a slowly accelerating decrease, where the fall in strength from 50°C to 100°C is not as sharp as the one seen from 100°C to 150°C. Polyester[2] demonstrated the best strength and maintained it better when heat is applied.

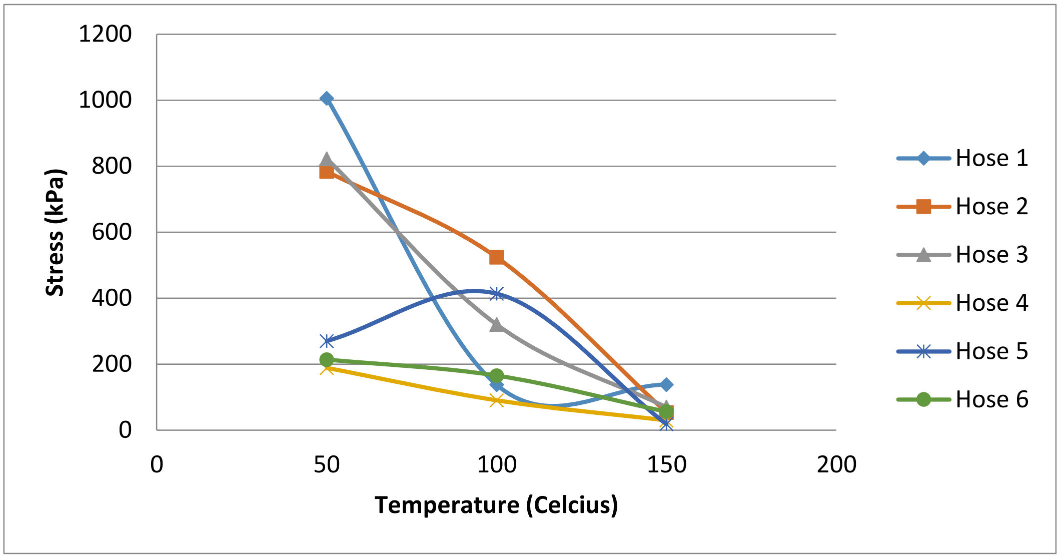


Figure 19: Outer Jackets Stress vs. Temperature

Ductility: All the hoses, as seen in Figure 20, became more ductile from 50°C to 100°C with the exception of Polyester[1] and Polyester[3]; this trend is acceptable seeing as since heat reduces the materials' resistance to deformation. Polyester[1] had the greatest ductility of the specimens when tested at 50°C but was severely stifled when temperatures rose to 100°C and above although the drop was less drastic when rising from 100°C to 150°C.

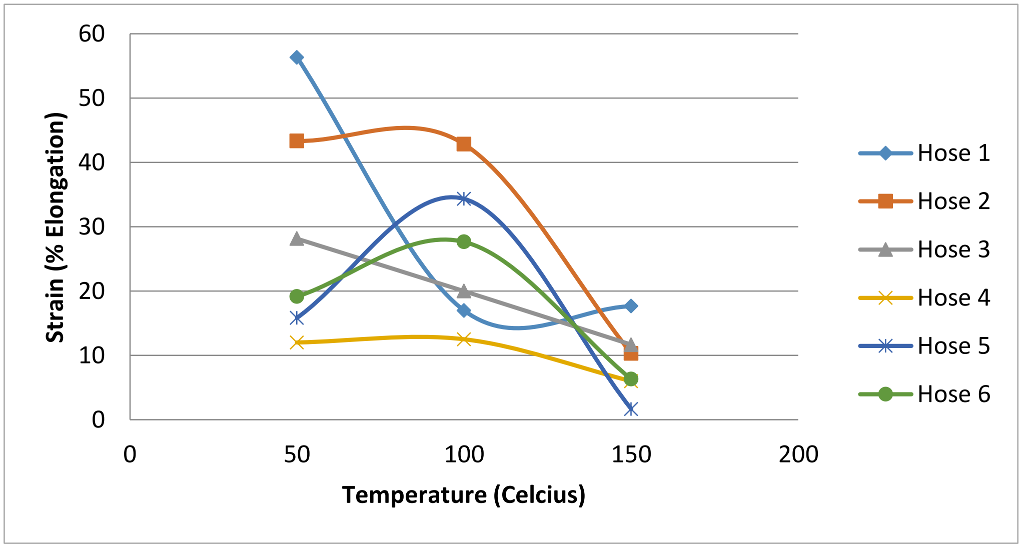


Figure 20: Outer Jackets Ductility vs. Temperature

Although Polyester[3] did not follow the trend of the majority, it had very good ductility at 50°C and 150°C while remaining somewhat average at 100°C; this specimen demonstrated a linear, slowly decreasing ductility as the temperature rose making it a much more predictable material under heat. Polyester^4 showed very little change throughout and had unimpressive results at every temperature. Polyester^2 again shows the best overall mechanical behavior when exposed to heat, it had above average values at all three temperatures and distinguished them among the other specimens.

Modulus: By analyzing Figure 21, one can conclude that there are 2 distinguishable trends taking place between modulus and the increase in temperature, the first being Polyester^2 and Polyester^3 with steady (mostly linear) decreases in elastic modulus/stiffness as the temperature rose. Polyester^1, Polyester^4, Nylon^5, and Nylon^6 demonstrated a decrease in stiffness when the temperature was brought up from 50°C to 100°C, but remained as stiff or showed very little change from 100°C to 150°C. During the experiment some of the outer jackets began to melt/smoke and even harden when exposed 150°C air of the furnace which may explain their retaining on some stiffness; while some strands of the yarn would break/rip those left intact could harden and stiffen the remaining specimen. For the outer hoses, when exposed to increasing temperatures, Polyester^3 retained the best modulus of elasticity throughout. The modulus at 50°C and 100°C for Polyester^3 was above average and the trend was fairly constant (thus predictable) as the temperature rose making it an ideal hose in terms of stiffness.

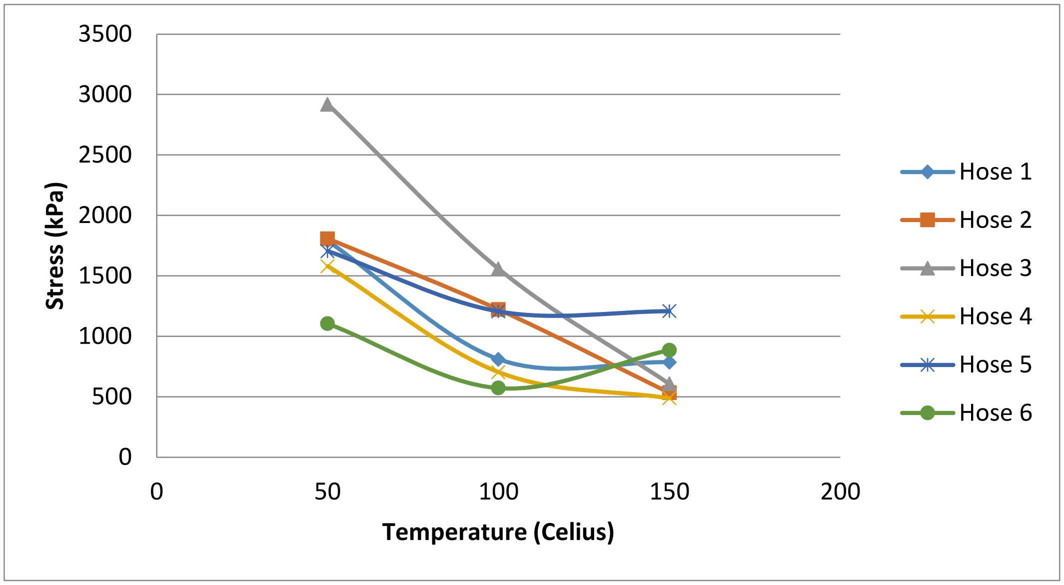


Figure 21: Outer Jackets Young's Modulus vs. Temperature

Toughness: In Figure 22 all the hoses with the exception of Nylon[6] decreased in toughness from 50°C to 100°C; the line for Nylon[6] depicts a slight increase in toughness, probably due to its drastic rise in ductility at that temperature versus a not so rapid decrease in strength. Polyester[1] had the greatest balance of strength and ductility at 50°C but demonstrated the poorest balance at 100°C returning to an average toughness at 150°C; a change as extreme as this is not desirable for a hose that will be used at various high temperatures daily.

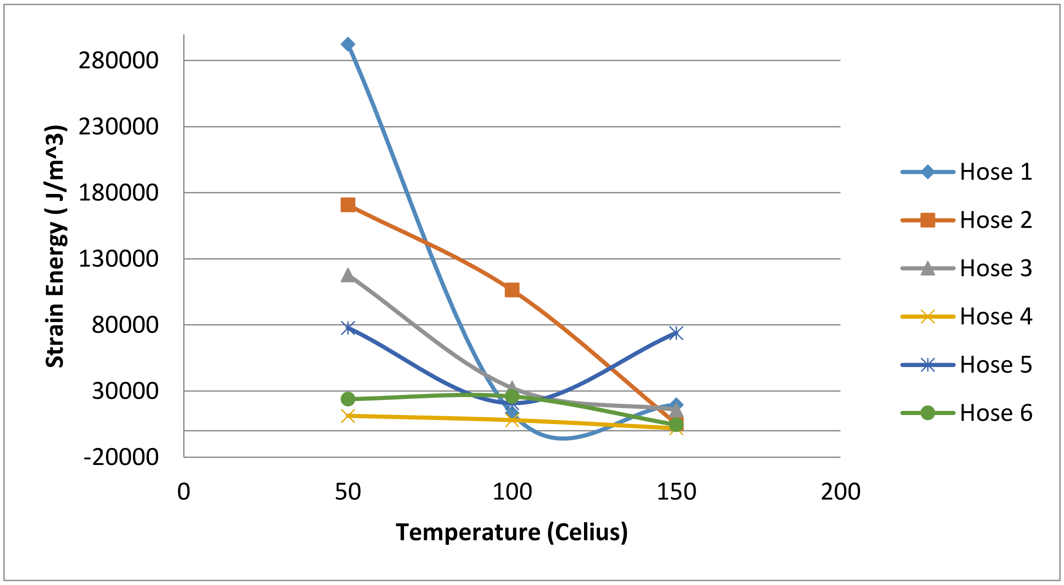


Figure 22: Outer Jackets Toughness vs. Temperature

Nylon[5] showed a peculiar increase in toughness from 100°C to 150°C shared with no other hose material; this does not signify a better strength or higher ductility that the other hoses at that temperature but a more balanced blend of both properties when under stress at that temperature. Polyester[2] had the most consistent balance between strength and ductility between all other outer jackets during the experimentation; the toughness here is important because it incorporates both the strength and ductility further implicating Polyester[2] as the most sound material for the outer jacket.

In conclusion, the two materials that performed best at all three temperatures were found to be EPDM and Polyester for the inner and outer jackets respectively. These materials demonstrated that they retain their mechanical properties more effectively when exposed to heat and that their Strength, Ductility, Stiffness and Toughness do not degrade as sharply as TPU and Nylon.

5.4 Finite Element Simulation Conclusions

The finite element simulations confirmed the findings from the tensile testing. For each jacket thickness, the stress distribution increased with temperature. In all simulation results, it is important to recognize this is an idealized situation without any exterior conditions. With that in mind, the simulations were used to determine if changing the hose thickness is a possible adjustment. As shown in Figure 18 and 19 above, the thick hose had the best stress distribution, but in practical use a thick hose would create problems while firefighting. A thicker fire hose would add weight and reduce the flexibility. The thinnest hose had poor stress distribution, which leads to the conclusions that the hose would be unable to withstand the heat and would result in more burn-throughs. In terms of hose thickness, the final conclusion was that changing the hose thickness is not a plausible adjustment. Beyond testing hose thickness and stress distribution, the simulations were designed to be used in the future. The simulations were created as a template to allow different hose jacket materials to be tested without having to redesign the object. This created the option for future tests of current or new materials.

5.5 Future Studies

These tests did not produce the end results for fire hose testing, by testing six different hoses, the data collected created a baseline for tests in the future. Both the modified tensile testing method and the simulations can be used to test any type of hose material. To create a greater understanding of current fire hoses the most commonly used hoses could be tested to find specific attributes worth maintaining and those to be improved on in order for design improvement can be made. New materials, different yarn weaving techniques, or better vulcanization of the inner hose could be researched and studied to further advance the next generation fire hose. With the simulation model, based on the characteristics found in physical testing, it is possible to test new materials such as Kevlar, or nanofibers without having to purchase, assemble, and physically test samples. The simulation would create a general understanding of how the material would perform under these circumstances, and if a material passed basic tests, it could then be purchased and applied in the field.

Additionally, we hope that modifications are made to the NFPA testing code book, to confirm the importance of these properties and how crucial they may be for improving the performance and safety of the urban fire-hose. As material technologies advance, the codes and tests must adjust to stay valid and pertinent to the field.

6.0 Sources Cited

Administration, U. S. F. (2014). *Fire-Related Firefighter Injuries Reported to the National Fire Incident Reporting System (2010-2012)*. Retrieved from Maryland:

Administration, U. S. F. (2015). *Firefighter Fatalities in the United States in 2014*. Retrieved from https://www.usfa.fema.gov/downloads/pdf/publications/ff_fat14.pdf

Agency, N. F. P. (2007). NFPA 1961: Standard on Fire Hose.

ASTM. (1998). Annual book of ASTM Standards *ASTM D412-98a: Standard Test Methods for vulcanized rubber and thermoplastic elastomers - tension* (pp. 43-55). Philadelphia.

Foundation, L. C. (2014). Foundation Overview. Retrieved from http://lastcallfoundation.org/about/overview/

Grant, C. (1995). Movers and Shakers: The Men Who Made the NFPA. *NFPA Journal, 89*(3), 97–102.

Hashagen, P. (1998). The Development of Fire Hose. *Firehouse Magazine*.

Jones, C. (2010). *Dictionary of Fire Protection Engineering*. Dunbeath, GBR: Whittles Publishing.

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

Lewis, J. G. (2003). Fire Fighting *Dictionary of American History* (Vol. 3, pp. 371-373). New York: Charles Scribner's Sons.

Scheffey, J. L., Forssell, E. W., & Benfer, M. E. (2013). *Determination of Fire Hose Friction Loss Characteristics*.

"High Temperature Refractory Ceramic Materials." *High Temperature Refractory Ceramic Materials: Zircar*. Zircar Ceramics, Inc., 2004. Web. July-Aug. 2015

Appendix A: Characteristics and Properties of Materials used in Ceramic Cup

ZIRCAR Ceramics Alumina-Silica Insulation Types

TYPE	**ECO-1200A**	**ECO-1200B**
Typical Composition, %		
Al_2O_3	33	35
SiO_2	61	64
Other Metal Oxides, %	1	
Organic Content, %	5	0
Bulk Density, gm/cc (pcf)	0.31 (20)	0.30 (19)
Color	Off White	White
Maximum Use Temp., °C (°F)	1200 (2192)	
Linear Shrinkage, %		
24 hrs at 760°C (1400°F)	0.5	
24 hrs at 1000°C (1832°F)	2.5‡, 3.5**	
24 hrs at 1200°C (2192°F)	4.0‡, 6.0**	
Loss On Ignition, %	5	0
Flexural Strength**, MPa (psi)		
MOR at room temp.		
as received	0.66 (100)	0.23 (35)
24 hrs at 760°C (1400°F)	0.23 (35)	
24 hrs at 1200°C (2192°F)	0.21 (30)	
Compressive Strength**, MPa (psi) at 10% compression	0.17 (25)	0.07 (10)
Thermal Conductivity,** W/mK (BTU/hr ft^2 °F/in)		
200°C (392°F)	0.055 (.40)	
600°C (1112°F)	0.110 (.85)	
1000°C (1832°F)	0.205 (1.40)	
Dielectric Strength (volts/mil)	27	

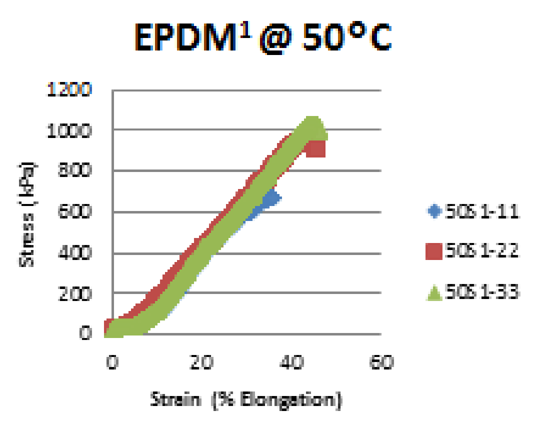
*	Maximum use temperature is dependent on variables such as stresses, both thermal and mechanical, and the chemical environment that the material experiences.
**	Properties expressed parallel to thickness.
‡	Properties expressed perpendicular to thickness.

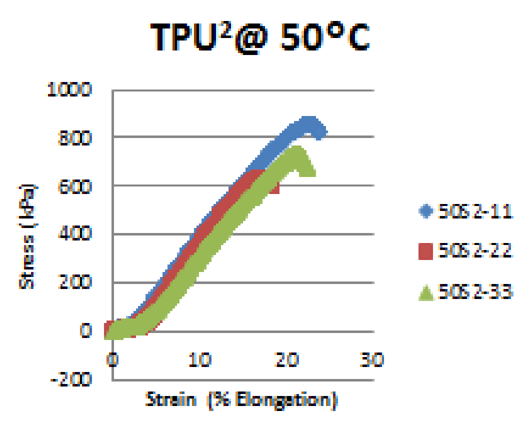
Alumina-Silica Insulation Type AX Moldable

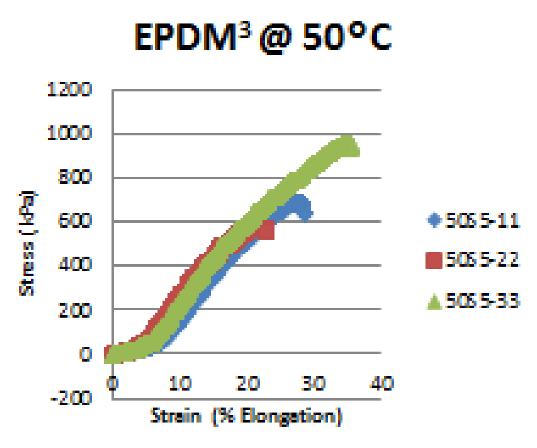
Nominal Composition, wt.% Solids	55
Wet Density, g/cc (pcf)	1.36 (85)
Dry Density, g/cc (pcf)	0.80 (50)
Maximum Use Temperature*, °C (°F)	1260 (2300)
Color	White
Modulus of Rupture, dry (psi)	400
Thermal Conductivity, Wm°K (BTU-in/ft^2 hr °F)	
204°C(400°F)	0.082 (0.57)
427°C(800°F)	0.137 (0.95)
649°C(1200°F)	0.185 (1.28)
871°C(1600°F)	0.221 (1.53)
Shrinkage, % after 24 hrs at 1093°C (2000°F)	4
Loss on Ignition, %	5

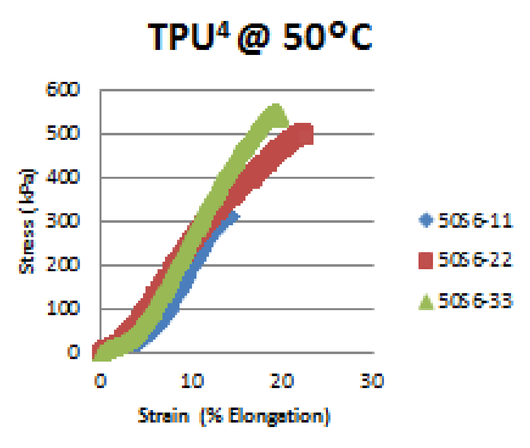
*Maximum use temperature is dependent on variables such as stresses, both thermal and mechanical, and the chemical environment that the material experiences.

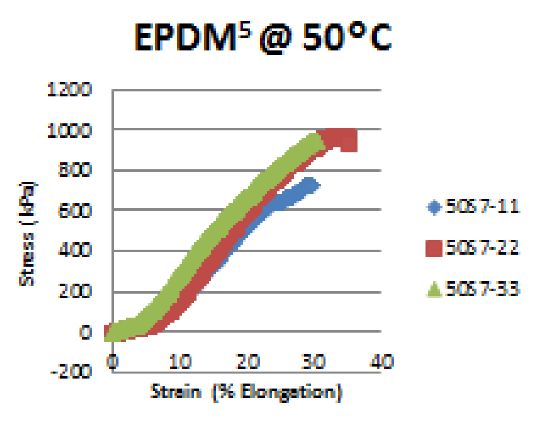
Appendix B: Inner Jacket Graphs

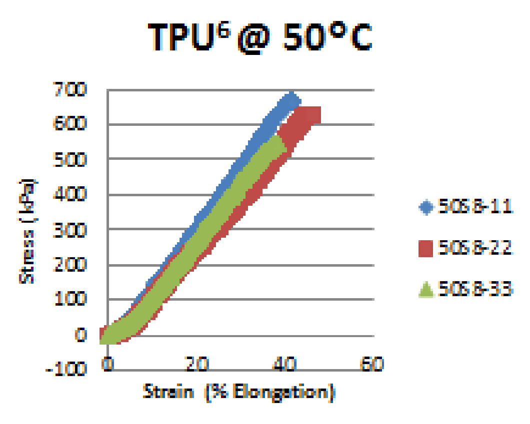


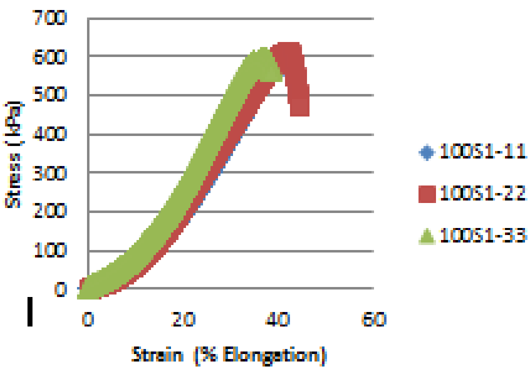


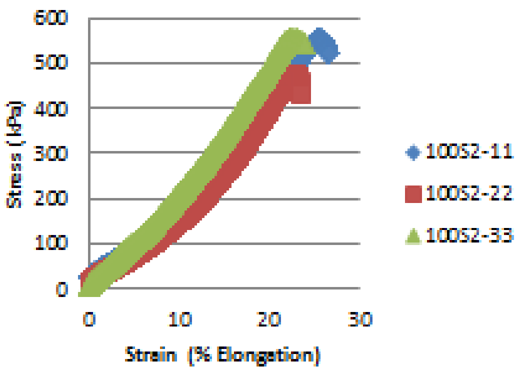


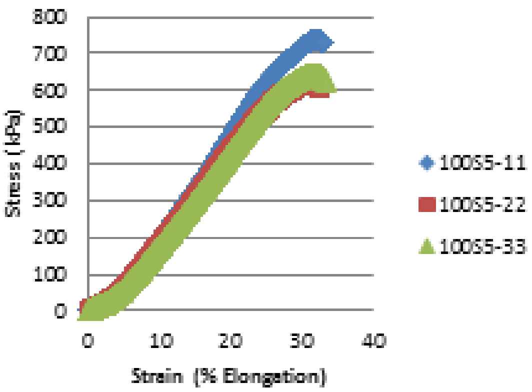


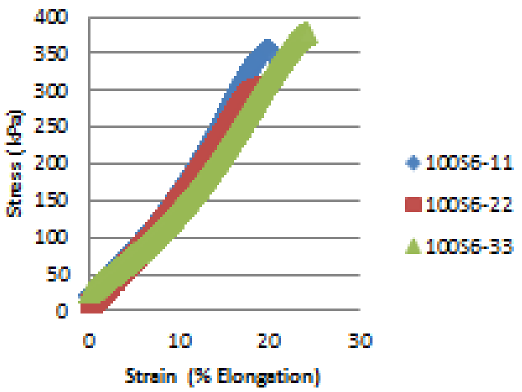


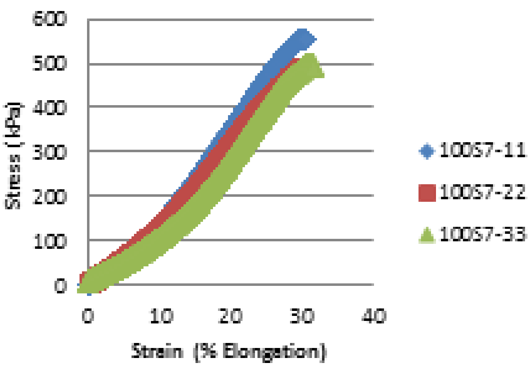


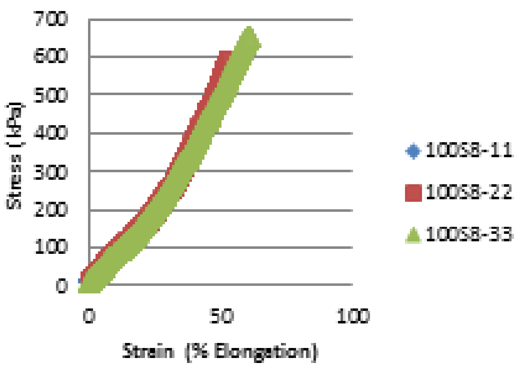

EPDM[1] @ 100°C

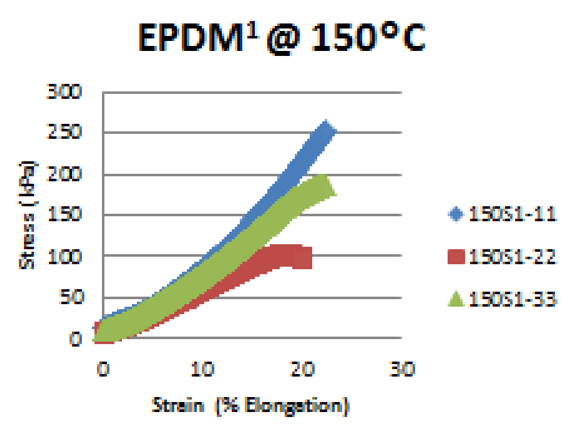

TPU[2] @ 100°C

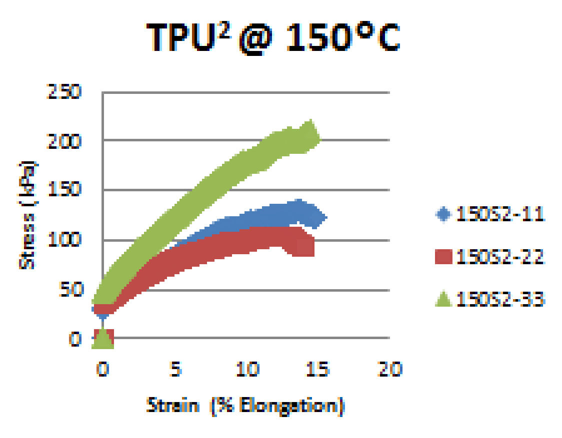

EPDM[3] @ 100°C

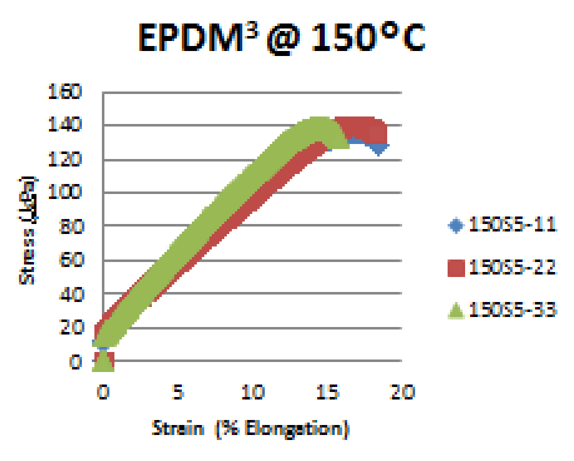

TPU[4] @ 100°C

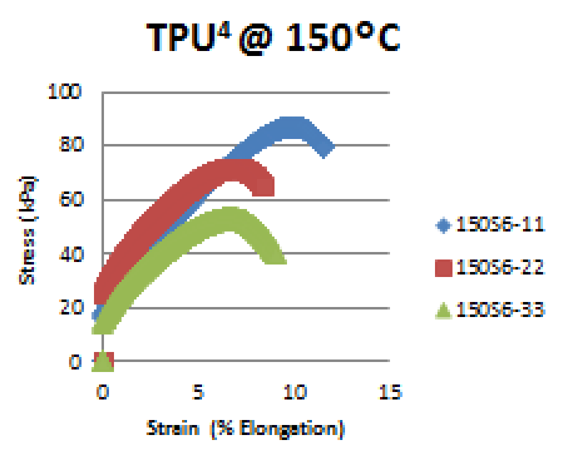

EPDM[5] @ 100°C

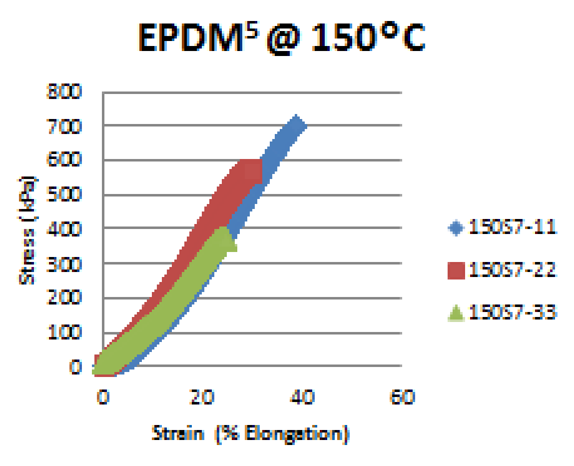

TPU[6] @ 100°C

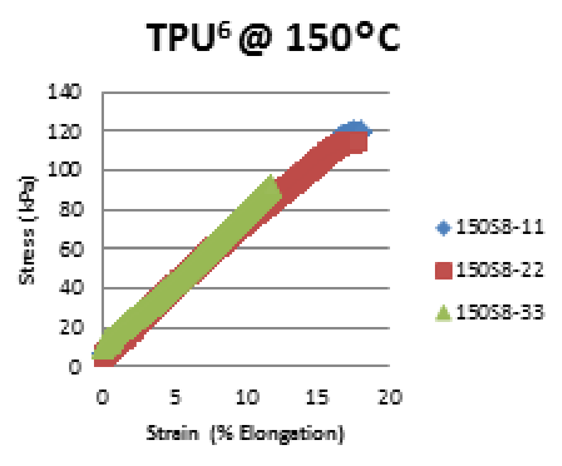

EPDM^1 @ 150°C
Stress (kPa)
300
250
200
150
100
50
0
0
10
20
30
Strain (% Elongation)
150S1-11
150S1-22
150S1-33


TPU^2 @ 150°C
Stress (kPa)
250
200
150
100
50
0
0
5
10
15
20
Strain (% Elongation)
150S2-11
150S2-22
150S2-33

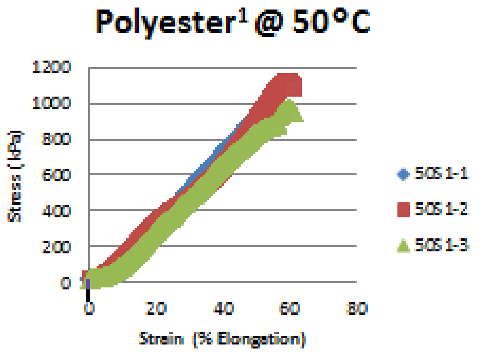

EPDM^3 @ 150°C
Stress (kPa)
160
140
120
100
80
60
40
20
0
0
5
10
15
20
Strain (% Elongation)
150S5-11
150S5-22
150S5-33

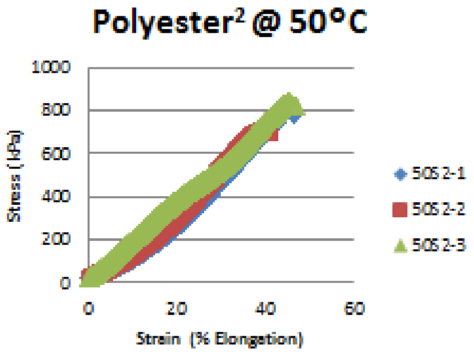

TPU^4 @ 150°C
Stress (kPa)
100
80
60
40
20
0
0
5
10
15
Strain (% Elongation)
150S6-11
150S6-22
150S6-33

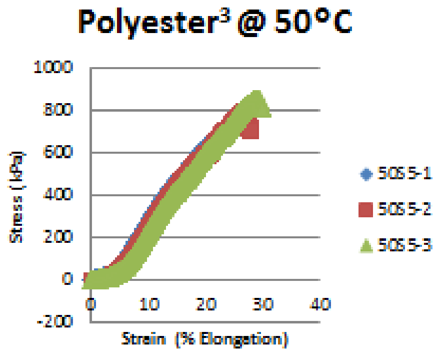

EPDM^5 @ 150°C
Stress (kPa)
800
700
600
500
400
300
200
100
0
0
20
40
60
Strain (% Elongation)
150S7-11
150S7-22
150S7-33

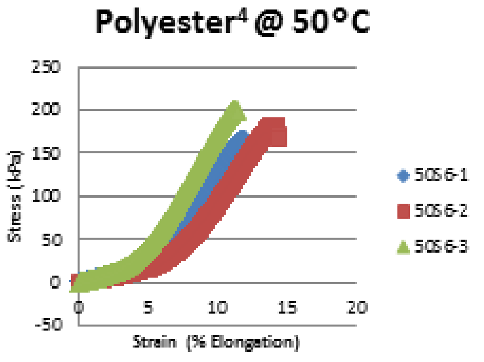

TPU^6 @ 150°C
Stress (kPa)
140
120
100
80
60
40
20
0
0
5
10
15
20
Strain (% Elongation)
150S8-11
150S8-22
150S8-33

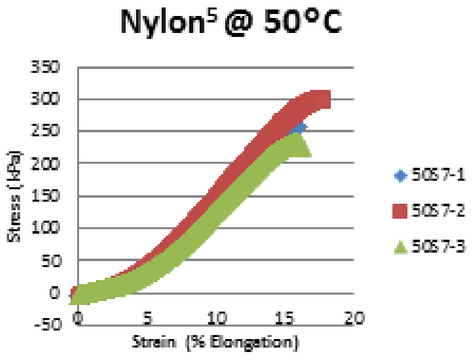
Appendix C: Outer Jacket Graphs

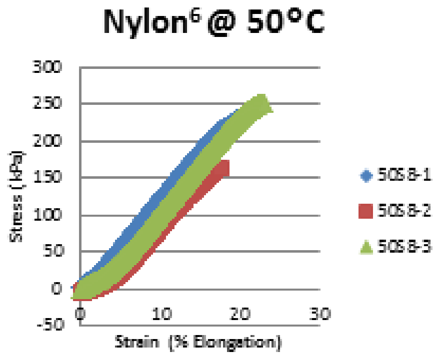


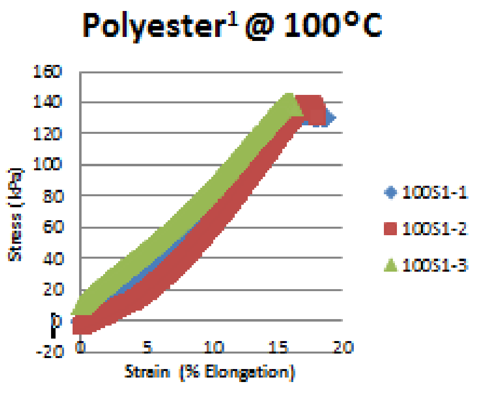


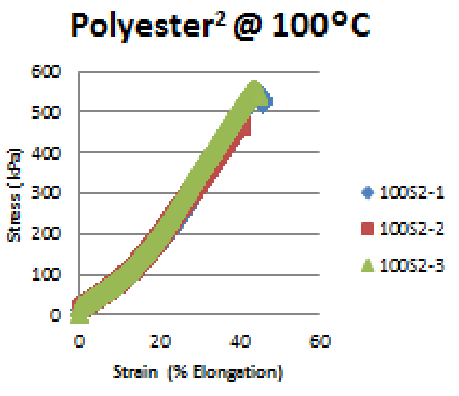


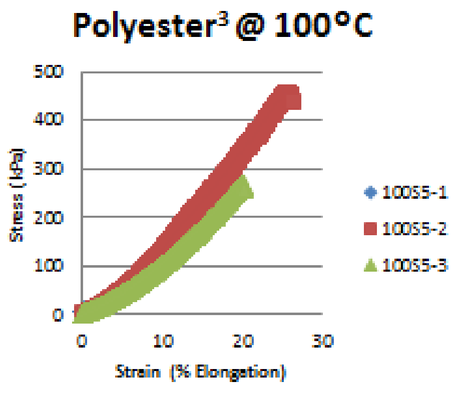


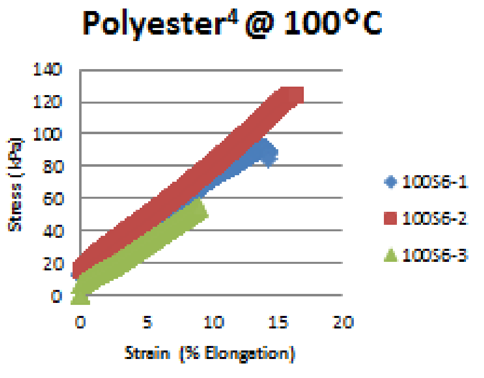


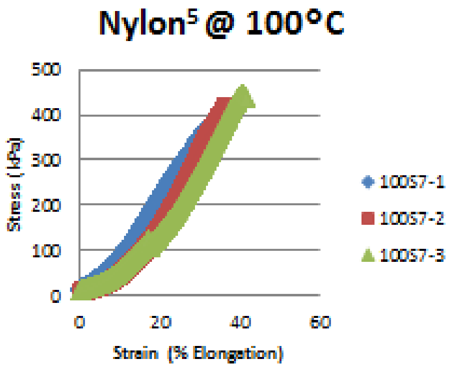


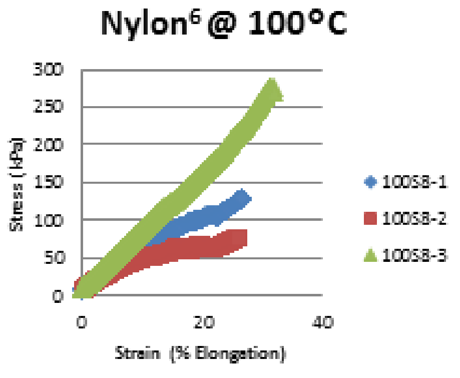


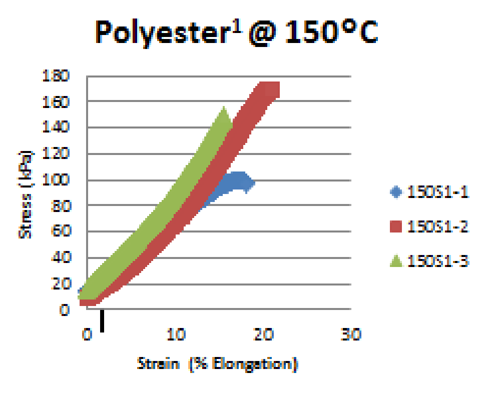


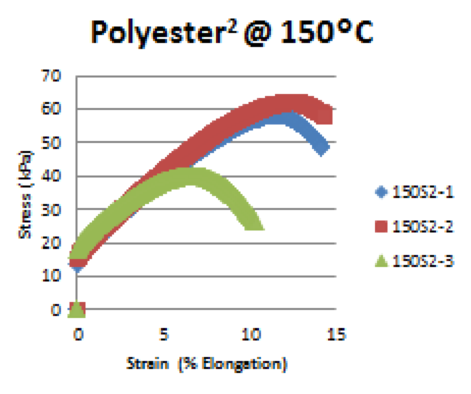


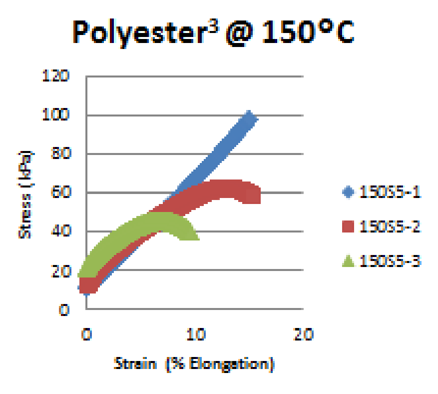


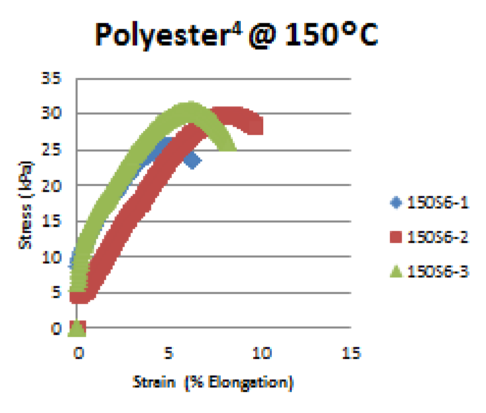


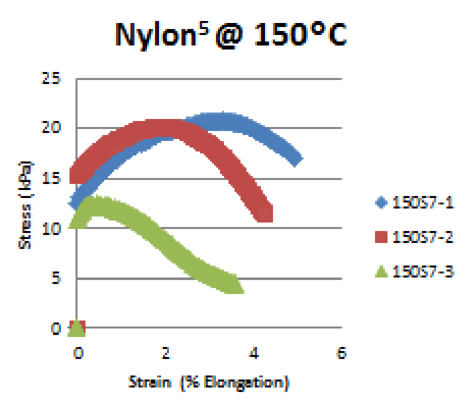


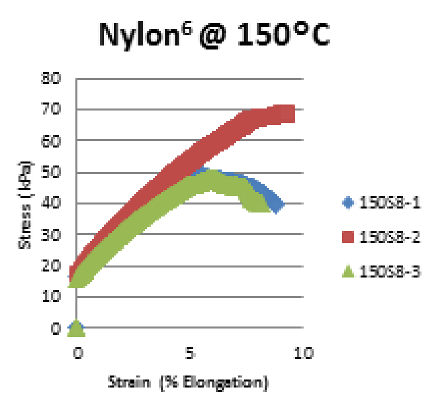

Polyester[1] @ 150°C
Stress (kPa)
180
160
140
120
100
80
60
40
20
0
0
10
20
30
Strain (% Elongation)
◆ 150S1-1
■ 150S1-2
▲ 150S1-3


Polyester[2] @ 150°C
Stress (kPa)
70
60
50
40
30
20
10
0
0
5
10
15
Strain (% Elongation)
◆ 150S2-1
■ 150S2-2
▲ 150S2-3


Polyester[3] @ 150°C
Stress (kPa)
120
100
80
60
40
20
0
0
10
20
Strain (% Elongation)
◆ 150S5-1
■ 150S5-2
▲ 150S5-3


Polyester[4] @ 150°C
Stress (kPa)
35
30
25
20
15
10
5
0
0
5
10
15
Strain (% Elongation)
◆ 150S6-1
■ 150S6-2
▲ 150S6-3


Nylon[5] @ 150°C
Stress (kPa)
25
20
15
10
5
0
0
2
4
6
Strain (% Elongation)
◆ 150S7-1
■ 150S7-2
▲ 150S7-3


Nylon[6] @ 150°C
Stress (kPa)
80
70
60
50
40
30
20
10
0
0
5
10
Strain (% Elongation)
◆ 150S8-1
■ 150S8-2
▲ 150S8-3

Appendix D: Tensile Testing Raw Data

				kPa		% Elongation		kPa		J/m^3	
Hose	Jacket	T	Specimen	Strength	Average/Std. Deviation/%	Fail Strain/Ductility	Average/Std. Deviation/%	Young's Modulus	Average/Std. Deviation/%	Toughness/Strain Energy(Area Under the Curve)	Average/Std. Deviation/%
1	Inner	50	50S1-11	668.6	889.7	36	41.5	1857.222222	2125.830969	116331.8	188539.2667
			50S1-22	969.8	193.8842696	44	4.769696007	2204.090909	239.2780236	219341.1	62757.85867
			50S1-33	1030.7	0.2179209504	44.5	0.1149324339	2316.179775	0.1125574079	229944.9	0.332863598
		100	100S1-11	583.2	597.9	41	40.16666667	1422.439024	1491.736818	106233.7	113736.8333
			100S1-22	613.3	15.06220435	42	2.362907813	1460.238095	89.31486785	127401.5	11852.94516
			100S1-33	597.2	0.0251918453	37.5	0.05882758041	1592.533333	0.05987307332	107575.3	0.1042137785
		150	150S1-11	391.2	226.9333333	37	25.83333333	1057.297297	819.8768769	26197.9	20519.76667
			150S1-22	103.7	148.0772208	18	9.928914006	576.1111111	240.6558414	14401.3	5910.614433
			150S1-33	185.9	0.6525141929	22.5	0.3843450583	826.2222222	0.2935268065	20960.1	0.2880449144
	Outer	50	50S1-1	918.5	1005.466667	49.5	56.33333333	1855.555556	1789.282291	215185.9	292492
			50S1-2	1127.5	108.8232665	59.5	5.923118548	1894.957983	150.2097559	343975.5	68167.40622
			50S1-3	970.4	0.1082316004	60	0.1051441162	1617.333333	0.08394972483	318314.6	0.2330573356
		100	100S1-1	131.3	137.1333333	18	17	729.4444444	809.5329521	15421.1	13271.16667
			100S1-2	140	5.052062285	17	1	823.5294118	74.08855761	11973.6	1875.156197
			100S1-3	140.1	0.0368405125	16	0.05882352941	875.625	0.0915201258	12418.8	0.1412955051
		150	150S1-1	99.5	137.8666667	17	17.66666667	585.2941176	784.7805789	11450.8	19637.5
			150S1-2	170.6	35.88319012	21	3.055050463	812.3809524	187.2183965	23167.2	7112.260118
			150S1-3	143.5	0.2602745899	15	0.1729273847	956.6666667	0.2385614547	24294.5	0.3621774726
2	Inner	50	50S2-11	858.5	743.3333333	23	20.5	3732.608696	3622.710835	110362.9	84450.86667
			50S2-22	634.8	111.9974256	17.5	2.783882181	3627.428571	112.3310551	61492.1	24568.88502
			50S2-33	736.7	0.1506691824	21	0.1357991308	3508.095238	0.03100745828	81497.6	0.290925197
		100	100S2-11	554.7	527.3	25.5	24	2175.294118	2199.119007	71605.4	63487.13333
			100S2-22	475.9	44.54615584	23.5	1.322875656	2025.106383	187.0664333	51694.1	10451.93281
			100S2-33	551.3	0.0844797190	23	0.05511981898	2396.956522	0.08506426102	67161.9	0.1646307253
		150	150S2-11	129	146.1666667	13.5	13.16666667	955.5555556	1097.208995	14207.4	15705.96667
			150S2-22	105.3	51.63645353	12	1.040833	877.5	315.3732295	11881.2	4754.59882
			150S2-33	204.2	0.3532710618	14	0.07905060757	1458.571429	0.2874322313	21029.3	0.3027256406
	Outer	50	50S2-1	805	783.8666667	44.5	43.33333333	1808.988764	1807.818599	166779.8	170841.1
			50S2-2	712.6	63.39915877	40	2.929732639	1781.5	25.75346259	142044.9	31026.84804
			50S2-3	834	0.0808800290	45.5	0.06760921474	1832.967033	0.01424560108	203698.6	0.1816123172
		100	100S2-1	544.4	523.8666667	44.5	42.83333333	1223.370787	1221.691777	112657.4	106382.0667
			100S2-2	471.5	45.70145877	40	2.466441431	1178.75	42.12737439	88802.7	15430.41008

			100S2-3	555.7	0.0872387225	44	0.05758229022	1262.954545	0.03448281733	117686.1	0.1450470983
		150	150S2-1	58	53.46666667	12	10.33333333	483.3333333	532.6393162	6106.6	5402.566667
			150S2-2	62.4	11.8681647	12.5	3.329164059	499.2	72.0973382	6649.4	1711.159993
			150S2-3	40	0.2219731552	6.5	0.322177167	615.3846154	0.1353586489	3451.7	0.3167309353
3	Inner	50	50S5-11	688	739.6666667	27.75	28.75	2479.279279	2551.52673	93039.1	114270.8
			50S5-22	572.9	197.7292172	23.5	5.814851675	2437.87234	162.3214543	75272.3	52911.93192
			50S5-33	958.1	0.2673220602	35	0.2022557104	2737.428571	0.06361738341	174501	0.463039831
		100	100S5-11	738.9	668.0333333	32.25	31.58333333	2291.162791	2113.420384	128409.5	117582.5
			100S5-22	620.4	62.57318382	30.5	0.9464847243	2034.098361	154.2253522	108505.4	10066.77266
			100S5-33	644.8	0.0936677568	32	0.02996785407	2015	0.0729742901	115832.6	0.0856145485
		150	150S5-11	137.8	139.0666667	16.5	16	835.1515152	873.2519925	16001.6	15571.66667
			150S5-22	140.3	1.250333289	17	1.322875656	825.2941176	74.6915127	16572.7	1271.726387
			150S5-33	139.1	0.0089908913	14.5	0.08267972847	959.3103448	0.08553259923	14140.7	0.0816692531
	Outer	50	50S5-1	825	822	28.5	28.16666667	2894.736842	2919.424089	126390	117782.5
			50S5-2	792.7	27.92113895	26.75	1.28290036	2963.364486	38.15037605	104232.9	11876.55398
			50S5-3	848.3	0.0339673223	29.25	0.04554675834	2900.17094	0.01306777463	122724.6	0.100834623
		100	100S5-1	210	320	15	20	1400	1558.333333	16873.8	32360.3
			100S5-2	475	138.1122732	25	5	1900	296.1559274	54362.3	19575.12997
			100S5-3	275	0.4316008537	20	0.25	1375	0.1900465844	25844.8	0.6049118818
		150	150S5-1	95	69.33333333	16	11.66666667	593.75	607.0436508	33451.4	15813.46667
			150S5-2	65	23.797759	12	4.509249753	541.6666667	72.93812447	9152.1	15426.5277
			150S5-3	48	0.3432369086	7	0.3865071217	685.7142857	0.1201530143	4836.9	0.9755310476
4	Inner	50	50S6-11	325	458.3333333	13	17.33333333	2500	2645.502646	47806.1	54832.26667
			50S6-22	500	118.1453907	21	4.041451884	2380.952381	360.0703066	61943.9	7069.28749
			50S6-33	550	0.2577717614	18	0.2331606856	3055.555556	0.1361065759	54746.8	0.1289256841
		100	100S6-11	350	341.6666667	20	20	1750	1715.046888	41318.9	46925.43333
			100S6-22	300	38.18813079	17	3	1764.705882	73.64422631	47839	5210.170641
			100S6-33	375	0.1117701389	23	0.15	1630.434783	0.04294006584	51618.4	0.1110308477
		150	150S6-11	87	71	10	7.666666667	870	932.8571429	7297.4	5326.3
			150S6-22	72	16.52271164	7	2.081665999	1028.571429	84.23727422	4851.1	1781.679974
			150S6-33	54	0.2327142485	6	0.2715216521	900	0.09030029395	3830.4	0.3345061251
	Outer	50	50S6-1	175	188.3333333	12	12	1458.333333	1579.351204	12080	11168.2
			50S6-2	190	12.58305739	13	1	1461.538462	206.8395871	11512.5	1124.212822
			50S6-3	200	0.0668126941	11	0.08333333333	1818.181818	0.1309649092	9912.1	0.1006619529
		100	100S6-1	90	90	13.5	12.5	666.6666667	703.7037037	9285.2	7962.7
			100S6-2	125	35	15	3.122498999	833.3333333	115.6481111	11874.4	4714.19414
			100S6-3	55	0.3888888889	9	0.2497999199	611.1111111	0.1643420526	2728.5	0.592034629
		150	150S6-1	26	29	5	6	520	487.6190476	1553.7	1870.133333
			150S6-2	30	2.645751311	6	1	500	40.03399916	2038.1	274.2126973

			150S6-3	31	0.0912328038	7	0.1666666667	442.8571429	0.08210097483	2018.6	0.1466273513
5	Inner	50	50S7-11	750	900	29	30.33333333	2586.206897	2959.985632	108275	145462.5667
			50S7-22	990	130.7669683	32	1.527525232	3093.75	328.0322744	172308.1	33245.71723
			50S7-33	960	0.1452966315	30	0.05035797467	3200	0.1108222522	155804.6	0.2285517023
		100	100S7-11	550	520	29.5	29.5	1864.40678	1762.848237	104718.4	88983.46667
			100S7-22	500	26.45751311	29	0.5	1724.137931	88.7764785	86460.9	14637.59035
			100S7-33	510	0.0508798329	30	0.01694915254	1700	0.05035968306	75771.1	0.1644978657
		150	150S7-11	700	550	39	29.66666667	1794.871795	1851.645402	94040.6	77759.8
			150S7-22	575	163.9359631	27	8.326663998	2129.62963	254.393997	87935.9	23114.7682
			150S7-33	375	0.2980653875	23	0.2806740673	1630.434783	0.1373880748	51302.9	0.297258586
	Outer	50	50S7-1	300	270	17	15.83333333	1764.705882	1704.722749	18674.1	20827.73333
			50S7-2	275	32.78719262	15	1.040833	1833.333333	166.8925533	25566.9	4109.916048
			50S7-3	235	0.1214340467	15.5	0.06573682104	1516.129032	0.09790011505	18242.2	0.1973290124
		100	100S7-1	370	413.3333333	30	34.33333333	1233.333333	1205.847953	57662.3	73863.6
			100S7-2	420	40.41451884	35	4.041451884	1200	25.07810718	75395.5	15492.25832
			100S7-3	450	0.0977770617	38	0.1177121908	1184.210526	0.0207970724	88533	0.2097414467
		150	150S7-1	22	18	2.5	1.666666667	880	1207.619048	9209	6679.666667
			150S7-2	20	5.291502622	1.75	0.8779711461	1142.857143	364.3426659	7580	3079.832842
			150S7-3	12	0.2939723679	0.75	0.5267826876	1600	0.3017033117	3250	0.4610758284
6	Inner	50	50S8-11	775	651.6666667	41	40.33333333	1890.243902	1612.537441	143281	136836
			50S8-22	630	114.0540807	42	2.081665999	1500	241.9363134	141362	9549.490615
			50S8-33	550	0.1750190497	38	0.05161155371	1447.368421	0.1500345401	125865	0.0697878527
		100	100S8-11	625	628.3333333	58	56.33333333	1077.586207	1118.018932	140729	183262.3
			100S8-22	600	30.13856887	51	4.725815626	1176.470588	51.84632719	210450.1	37307.79039
			100S8-33	660	0.0479658921	60	0.08389021822	1100	0.04637338932	198607.8	0.2035759149
		150	150S8-11	120	108.3333333	12	11.83333333	1000	916.6666667	22805.1	23175.26667
			150S8-22	115	16.07275127	11.5	0.2886751346	1000	144.3375673	21201.5	2182.521671
			150S8-33	90	0.1483638579	12	0.0243950818	750	0.1574591643	25519.2	0.0941746087
	Outer	50	50S8-1	230	213.3333333	20	19.16666667	1150	1104.263566	28433.1	23980.26667
			50S8-2	160	47.25815626	16	2.843120352	1000	90.52109625	14290.2	8401.0038
			50S8-3	250	0.2215226075	21.5	0.148336714	1162.790698	0.08197417632	29217.5	0.350329874
		100	100S8-1	150	165	26	27.66666667	576.9230769	572.099359	22335.4	25985.63333
			100S8-2	70	103.3198916	25	3.785938897	280	289.7176192	21866.4	6732.640601
			100S8-3	275	0.6261811612	32	0.136841165	859.375	0.5064113682	33755.1	0.2590908797
		150	150S8-1	50	55.66666667	5	6.333333333	1000	886.1111111	3562.4	4502.2
			150S8-2	70	12.50333289	8	1.527525232	875	108.7598442	6816.4	2015.901912
			150S8-3	47	0.2246107705	6	0.2411881945	783.3333333	0.1227383821	3127.8	0.4477592982