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Long Term Loading and Additional Material Properties of Vectran Fabric for Inflatable Structure Applications

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Long Term Loading and Additional Material Properties
of Vectran Fabric for Inflatable Structure Applications

Timothy L Weadon, Jr

Thesis submitted to the
College of Engineering and Mineral Resources at
West Virginia University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Department of Mechanical and Aerospace Engineering

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Abstract

Long Term Loading and Additional Material Properties of Vectran Fabric for Inflatable Structure Applications

Timothy L Weadon, Jr

The recent production of high performance fibers has given way to the development of inflatable structures capable of fulfilling architectural needs that once required the use of metal alloys. The design of these structures requires engineers to know many properties about the unique textile of which the structure is composed. This thesis presents both testing methodology and results for a number of key properties using woven fabric constructed of Vectran fibers.

The primary source for test standards was the American Society for Testing and Materials (ASTM). Some alterations were made to standards in an effort to uniquely characterize specific properties of Vectran woven fabric in situations and environments not specifically discussed by ASTM. ASTM standards are also evaluated for their ability to properly characterize Vectran woven fabric, and concerns are discussed for complications which were encountered while using ASTM methods for this specific work.

Material characterization was primarily focused on the creation of a model capable of accurately predicting creep failure times given an applied stress in the fabric. Complications with the long term loading of specimens for creep testing required the development of a new loading frame and material grips, both of which are described in detail. Quasi-static testing was performed, providing the ultimate strength and Young's modulus of the material. Quasi-static testing was also performed to evaluate the fabrics ability to withstand the affects of submersion and environmental crease folding. Finally, friction testing was performed on a number of surfaces, both wet and dry.

Long term loading produced a logarithmic model for predicting creep failure times with an estimated accuracy within 3.67% of the applied load. It was suggested that this error is the direct result of the known repeatability and accuracy errors in the loading frame. Despite this error, the manufactured loading frame and material grips displayed improved results over testing with MTS systems.

Quasi-static testing provided tensile values in both the warp and fill direction for multiple Vectran woven fabric constructions. The Young's modulus was found to have two distinct values for strain of low and high magnitudes in both the fill and warp directions. Additionally, neither submersion nor changes in pressure for crease folding appeared to affect the strength of Vectran. However, the simulated environment used for the crease fold method negatively affected the material. Though further testing is called for, it was suggested that Vectran may observe an increasing loss in strength with respect to time at elevated temperatures. Friction tests were completed, characterizing both bare Vectran woven fabrics, and urethane coated woven fabrics on a number of surfaces, both wet and dry.

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Chapter 1 - Introduction

1.1 – Importance of Work

Inflatable structures have been under development since the early 1960's when the United States human lunar exploration program began to advance [1]. Specialized companies have been continually researching and developing new technology in this field since that time period [2]. Today inflatable structures are used by a number of industries such as civil engineering, architecture, aerospace engineering and military and marine applications among others [2][3][4].

While the benefits of inflatable structures over traditional structures are ever increasing, obvious motives for their development are a means of replacement for large, heavy bodies traditionally made of metal alloys and rigid composites [1]. These compactable, lighter alternatives significantly lower the cost of transportation, deployment, and reduce time for onsite assembly and maintenance. They have proven themselves very durable and even reduce storage space when not in use. Some civil and architectural uses include membrane roofs and covers, tents, shelters, pavilions, furniture, buildings and radomes. Aerospace companies are using them to build airspace structures, evacuation slides, lighter-than-air vehicles, airships, aerostats and other applications. Military and marine applications include boat sails, boats, buoyancy systems and many more specialty items [2][3][4].

Common components of inflatable structures include but are not limited to fabrics, foams and elastomeric polymers [1]. This work will focus specifically on inflatable structures made of Vectran fabric. Current design projects using this material vary from expandable lunar habitats to bumper shields for protecting existing space facilities from debris that are too small to be tracked from earth (100mm and under) [5][6][7].

Inflatable structures are no longer just a thing of the future. Though they are sometimes concealed while not in use, or mistaken for typical architecture by the unknowing passerby, inflatable structures are now a part of everyday life for many people. The research for this thesis is focused on one such structure which, if completed and implemented, could assist in the protection mass transit systems which exceed 4 billion trips each year [8].

In 1987, passengers traveling on the London Underground Victoria Line exited at the King's Cross station. It is speculated that one traveler dropped a match onto the wooden

escalators after lighting a cigarette. A small fire quickly turned into a big problem as many travelers became trapped inside the tunnel. As the fire grew 150 firefighters entered the tunnel wearing breathing apparatuses in order to extinguish the fire and assist those trapped in the tunnel. In the end, 30 travelers and one firefighter died from the fire and smoke inhalation [9][10].

The London Underground Victoria Line now uses inflatable structures to prevent such an event from reoccurring. Inflatable walls produced by Lindstrand Technologies Ltd. have been installed in 100m intervals in order to section off the tunnel in case of another fire. A representative view of this structure as used for automotive tunnels is shown in Figure 1. These inflatable walls can be easily installed into the existing structure since they are small and light in their deflated form. Upon activation, they quickly fall from the ceiling and inflate, preventing smoke from traveling through the tunnel and cutting off the air source to the fire. A center door creates a passageway that can be easily unzipped by trapped travelers who find themselves on the wrong side of the structure. The inflation process can be activated remotely reducing the role of firemen at the actual site of the fire, possibly saving additional lives [11].

Figure 1 - Lindstrand Technologies Inflatable Structure System for Tunnel Fires [11]

West Virginia University (WVU) is developing an inflatable structure system concept under the Resilient Tunnel Project (RTP). The concept consists of creating an inflatable structure capable of protecting travelers not only from smoke inhalation and fire, but also from a wide range of potential disaster situations such as the spread of flood waters, debris, fires, smoke and other toxic fumes [12][13][14]. Preliminary designs show the proof of concept in Figure 2.

Figure 2 - West Virginia University Preliminary Inflatable Structure [12]

Depending on the type of protection required, the structure may be inflated to high pressures for extended periods of time. Consequently, it is important to fully understand the long term loading properties of the materials used in the construction of the structure. Failure to do so could result in premature failure of the inflatable structure producing additional threats rather than preventing danger [15]. However, much of the research on the creep behavior of high-performance fibers has been focused on primary creep. Primary creep can be described as the brief creep initially observed in the material before a constant creep rate is observed. While it is useful, it does not provide the necessary information required for understanding the lifetime of the fiber [16][17].

1.2 – Objective

The objective of this work is to determine the long term loading properties of Vectran woven fabric. In order to complete this task a number of preliminary objectives must first be accomplished.

To begin, the Ultimate Tensile Strength (UTS) of the fabric should be quantified in order to obtain a starting point for creep rupture testing. Next, a procedure must be developed in order to ensure uniform testing practices for creep rupture testing. It is necessary that this procedure takes into account the effects of material construction, and also that it is similar in technique to the standard used to characterize the UTS. In order to properly perform the new procedure, necessary testing systems required for accurately and consistently collecting results must be identified.

Finally, creep rupture times should be recorded for a series of loads below the UTS. Using this data, a function capable of predicting breaking times, given an applied load, should be created for Vectran woven fabric. This function should be simple, and should fit the experimental data with an acceptable accuracy.

Additional objectives include characterization of the Young's modulus of the material, as well as quasi-static wet testing and crease fold testing of Vectran woven fabric. Friction testing is also desired for a number of surfaces, both wet and dry.

1.3 – Organization

This thesis comprises 6 chapters. The first chapter presents an introduction and motivation for the topic, and provides the scope of the work at hand. Important terminology is presented at the end of this chapter in order to prepare the reader for the body of the thesis. Chapter 2 presents a literature review of previously performed testing in the area. Discussion is mainly concerning long term loading since it is the primary focus of the thesis.

The third chapter is composed of 5 sets of quasi-static testing sections. These are: strip method tensile testing, wet testing, crease fold testing, Young's modulus characterization and modified grab tensile testing. While similar in their procedures, each of these sections provides useful information and insight about different Vectran woven fabric material properties.

The fourth chapter focuses on the single topic of long term loading. It begins with an introduction to the development and implementation of the generic testing procedure. The first set of test results were obtained using an MTS system, however the results were not

satisfactory. As a result, available testing systems are evaluated, and a new in-house design is presented as a replacement for the MTS machine. Available testing grips are also evaluated, and a new in-house design is presented for gripping high performance woven fabrics.

The fifth chapter outlines friction testing as performed by ASTM standards. The results displayed and discussion is presented concerning key topics such as surface differences, wet and dry conditions and the affects of testing pressure differences.

Finally, chapter 6 gives a summary of the conclusions made in each chapter and continues with further discussion of the results. This chapter also summarizes the findings of the work and evaluates the use of the in-house loading frame and grips. Future work is suggested as is necessary for further conclusions, and limitations and error are discussed. Each test is shown with its corresponding section number in Table 1.

Table 1 - Summary of Vectran Fabric Testing Results		
	2x2 Vectran Fabric	4x4 Vectran Fabric
Ultimate Tensile Strength	3.1.2	3.1.4
Modulus of Elasticity	-	3.2.2
Wet Testing	3.3.2	-
Crease Fold Testing	-	3.4.3
Modified Grab Testing	3.5.2	-
In-house Loading Frame Varification	-	4.4.3
In-house Grip Varification	-	4.5.3
Long-Term Loading Using Frame	-	4.6.2
Long-Term Loading Using MTS	4.3.2	4.7.3
Multi-Surface Friction Testing	5.2.2	5.3.2

1.4 – Terminology

1.4.1 – Terms Regarding Testing Procedure

- **Creep** – the increase in total strain with time, experienced in a material under constant load [18].
- **Creep Failure** – the observation of accelerated strain within a material after it has been loaded for a long period of time [19].
- **Creep Rupture (Creep Fracture)** – the observation of material fracture due the long term effects of creep [19].

- **Fatigue load** – for the purposes of this work a fatigue load can be simplified as a localized load occurring at a set frequency and specific amplitude which is less than the ultimate tensile strength of the material [19].
- **Long-term Load** – in this report the term will be used only to denote specimens that have been under a constant load until creep rupture occurs.
- **Static Load** – a specific load that is applied to a material resulting in a particular equilibrium state which is maintained through time [20].
- **Stress Relaxation** – the decrease in stress with time, experienced in a material that has been subjected to an initial strain at a fixed dimension [18].
- **Quasi-static Load** – a load which is changing through time, resulting in a changing equilibrium state with time [20].
- **Ultimate Tensile Strength (UTS)** – the force required to break a material in the tensile direction.

1.4.2 –Terms Regarding Fabric Construction

- **Basket Weave** – a weave where the warp yarns pass over two or more fill yarns, and the fill yarns pass over the same number of warp yarns. This construction creates a loose weave with a flat appearance and a higher strength than a plain weave [21].
- **Fiber** – the most fundamental element used to in creating a textile; it is characterized by having a length at least 100 times its diameter [22].
- **Fill / Weft** – the strands (yarns/tows) which make up the width of the fabric [23].
- **Strand** – a group of fibers assembled together [22].
- **Tow** – a twist-free strand of fibers that can be woven into a textile or twisted into a yarn [22].
- **Turns per Inch (tpi) / Turns per Centimeter (tpc)** – the number of turns per inch (or cm) contained in a yarn.
- **Yarn** – a strand of fibers which have been twisted together, usually with a diameter in the order of micron meters (μm) [22][23][24].
- **Warp** – the strands (yarns/tows) which run the entire length of the fabric [22].
- **Woven Fabric** – a material produced by at least two sets of tow / yarn which are interlaced into a repeating pattern [22][24].

Chapter 2 – Literature Review

2.1 – Vectran High-Performance Fiber

Through 30 years of research and development, Vectran liquid crystal polymers (LCP) have been created with “properties unmatched by other high performance fibers [25]”. As with many other popular fibers, Vectran is made using a process known as melt spinning. In melt spinning, the bulk material is melted and quickly drawn through a spinneret which gives the fiber its geometry. The extremely small strand of melted bulk material is quickly hardened with cold air producing a fiber [26].

The fiber is then drawn to align its molecular structure, providing it with exceptional tensile strength. Drawing is performed by the use of two rollers, each running at different speeds. The fiber begins with a slow velocity after leaving the first roller, and finishes with a higher velocity after leaving the second roller. This process elongates the fiber, resulting in the molecular orientation [27]. Conventional polyesters are created with string like molecules which experience chain folding when melt spun. In order to create a stiff, rod-like structure LCP molecules are created. After being melt spun these crystals provide superior alignment over the conventional polyesters as shown in Figure 3. This alignment is what gives Vectran its remarkable tensile properties [25].

Figure 3 – Vectran Molecular Structure after Melt Spinning and Drawing [25]

2.2 – Fabric Used for Testing

In this work two types of Vectran woven fabric will be used. In order to conveniently distinguish between the two, they will each be fully described in this section and referred to by abbreviated names in the remaining chapters. The first woven fabric is constructed of Vectran HS fiber, 1500 denier, with a 2x2 basket weave pattern.

Table 2 displays the material properties for this fiber. It is characterized by a total of 30 yarns/in in the warp direction and 32 yarns/in in the fill direction and a measured thickness of 0.0315 inch. This fabric received a urethane polymer coating applied topically to only one side as shown in Figure 4.

Figure 4 – 2x2 Vectran Bare Fabric

The second woven fabric is also constructed of Vectran HS fiber, 1500 denier, this one with 1.5 tpi, and a 4x4 basket weave pattern. It is characterized by a total of 34 yarns/in in the warp direction and 42 yarns/in in the fill direction and a thickness of 0.033 inch. This fabric received a urethane polymer coating on both sides by impregnation as shown in Figure 5.

Figure 5 – 4x4 Vectran Fabric

In order to easily differentiate between the two woven fabrics they will be referred to by their weaving pattern. The first will be referred to as 2x2 Vectran woven fabric, and the second 4x4 Vectran woven fabric.

Table 2 – Vectran HS Fiber and Other Common Material Properties [28]

Material	Density (g/cm ³)	Tensile Strength (G Pa)	Specific Strength (km ⁻¹)	Tensile Modulus (G Pa)	Specific Modulus (km ⁻¹)
Vectran NT	1.4	1.1	79	52	3700
Vectran HT	1.4	3.2	229	75	5300
Vectran UM	1.4	3	215	103	7400
Titanium	4.5	1.3	29	110	2500
Stainless Steel	7.9	2	26	210	2700
Aluminum	2.8	0.6	22	70	2600
E-Glass	2.6	3.4	130	72	2800
Graphite (AS4)	1.8	4.3	240	230	13000

*Specific strength = Strength/Density (also divided by force of gravity for SI units). Also known as breaking length, the length of fiber that could be held in a vertical direction without breaking.
 ** Specific modulus = Modulus/Density (also divided by force of gravity for SI units). This measure increases with increasing stiffness and decreasing density.
 (KAI data)

Ferrari précontraint 1002S is also used in this work though the properties of this fabric are not desired. Ferrari fabric is much simpler to handle than Vectran and was used to assist in gaining a better understanding of the standards being used. Ferrari fabric is pictured in Figure 6, and the manufacturer's specifications are given in Table 3.

Figure 6 – Ferrari Fabric

Table 3 – Ferrari Specifications [29]

Technical properties	Précontraint® 1002 S back PVDF
Yarn	1100 Dtex PES HT
Weight	1050 g/m ² / 31 oz/sqyd
Width	180 cm
Tensile strength (warp/weft)	420/400 daN/ 5 cm

2.3 – Testing Background

In 1990 the owner and manufacturer of Vectran published an article with physical characteristics of Vectran fibers, braids and wire ropes cited from private reports and oral presentations. Creep tests, stress relaxation tests and fatigue testing were the main topics of discussion in this article [30]. It seems to be the first public article with information concerning the material properties of Vectran, and is later cited by NASA reports [18], composite handbooks [31], and composite journals [32].

Creep tests were performed by an independent corporation (Whitehill Manufacturing Corporation) on Vectran fibers with loads of 25% and 33% of the ultimate tensile strength (UTS). After 569 days no creep was observed in the specimens. The fiber was prepared with one turn per centimeter (tpc) and loaded to 50% UTS. After 115 days, claims were made that no creep was observed; however, these claims would later be disputed by researchers at NASA [18]. Creep tests were also performed by another independent corporation (Martin Marietta) on Vectran braids at loads of 37% UTS. Initially the specimens experienced elongation due to adjustments in the construction of the braid. After 180 days, no additional creep was reported [30].

A stress relaxation test was performed by Whitehill Manufacturing Corporation on a ½” wire-rope construction specimen of Vectran. Initial tensioning of the specimen created a load of approximately 22% UTS. After 1,000 hrs (6 weeks) the load was maintained, meaning that no

stress relaxation was observed in the specimen. Similar constructions of Kevlar (Aramid) and Spectra (UHMWPE) were also tested with the results shown in Figure 7 [30].

Figure 7 - Wire-Rope Construction Vectran Stress Relaxation Test with Re-tensioning [18]

In summary, the manufactures of Vectran have cited experimental data from two independent testing sites, both claiming to have observed no creep or stress relaxation at loads up to 50% UTS for Vectran fibers, twisted fibers, braids and wire rope construction. They have also shown that fatigue testing on Vectran braided specimens produces exceptional results when compared with other leading high performance fibers [30].

In 2004, NASA Goddard Space Flight Center published an article as a response to the manufacturer's 1990 publication. The article focused primarily on creep and stress relaxation, neglecting fatigue testing entirely. A primary assumption of the report was that "the effects of material construction (yarn twist, weave, braid, and wire rope packing) are eliminated during initial tensioning and the material will subsequently perform similarly to a single fiber". This assumption was initially made and verified by testing Kevlar braided cords earlier that year. However, differences between Vectran and Kevlar will bring the assumption back into discussion later in this report [18].

Creep tests were performed on 12 strand braided cords of Vectran at 50% UTS. A displacement vs. time plot of four tested specimens is displayed in Figure 8. Notice that the position is not constant with respect to time, indicating the observation of creep in the materials.

The results directly contradict Hoechst Celanese Corporation's claim that "Vectran had no measureable creep when loaded up to 50% of the breaking load [30]". Rather, it was recorded that the creep is on the order of five times less than Kevlar. While testing was performed at different temperatures, it was not determined if the Boltzmann superposition principle could be used to further simplify the results [18].

Figure 8 - Vectran Braided Cord Creep Test at 50% UTS [18]

Figure 9 - Stress Relaxation with Re-tensioning [18]

Figure 10 - Normalized Stress Relaxation [18]

A stress relaxation test was performed using the same 12 strand braided cords of Vectran. The tests were performed in a similar manner as those by Whitehill Manufacturing Corporation in order to produce results that could be directly compared with those published by the manufacturer. The cords were initially tensioned to 40% and 60% UTS, being re-tensioned twice over a period of 10 weeks. The raw data is displayed in Figure 9 where the re-tensioning of the cord can be observed. The data is averaged and normalized by setting the time equal to zero each time the specimen is re-tensioned as shown in Figure 10 [18].

The report concluded that “Vectran is NOT a zero creep material. This assumption was uncontested and repeated in available literature, based on a stress relaxation test. The material experienced logarithmic creep and stress relaxation [18].” The assumption that construction effects are eliminated after initial tensioning was also re-discussed. It was decided that this assumption “may not be applicable for Vectran”. The paper called for additional testing to be performed before any definite conclusions could be made [18].

In 2007, the University of Massachusetts Amherst published a paper discussing failure criteria of high-performance fibers. Using an Instron system, they performed creep testing on individual yarns of Kevlar, Vectran HS, Technora and Nomex. Specimens were loaded until creep rupture occurred producing the long term loading plot shown in Figure 11 [16].

Figure 11 - Long Term Loading on 1500 Denier Yarn Specimens [16]

The y-axis represents applied load / ultimate strength (or %UTS), while the x-axis represents $\ln(t_c)$, where t_c is the creep rupture time in seconds. This has been found to be the first instance of long term loading on Vectran using numerous loads to produce a % UTS vs. time plot for creep rupture testing. Very few specimens were tested to produce this plot, thus providing only preliminary results. However, it provides a valuable comparison between several high-strength fibers under long term loading [16].

In 2008, Scarborough et al. published a paper picking up exactly where NASA left off by investigating the role of temperature on creep testing. They found that Vectran fabric tested at 80°C did indeed follow Arrhenius behavior, allowing them to use Boltzmann's superposition principle as suggested by NASA [18]. In order to accelerate creep testing they used a technique known as the Stepped Isothermal Method (SIM). This method allowed them to perform simulated creep tests for theoretical times exceeding ten million years [15]. The basic theory behind the method is as follows:

The fundamental premise of SIM testing is that viscoelastic processes are accelerated at elevated temperatures in a predictable manner. The Arrhenius equation provides the basis for the relation between the rate of reaction and temperature. On the other hand, the Williams–Landel–Ferry (WLF) equation and Boltzmann superposition principle provide justification for scaling and shifting strain data obtained at each isothermal exposure in order to define a master creep curve corresponding to the reference (room) temperature [33].

Creep tests were performed on Vectran woven fabric at 40%, 50%, 60%, 70% and 80% of the UTS. Using SIM testing, Scarborough et al. created plots for each of the 5 loads recording strain vs. time data through creep failure, and all of the way to creep rupture. This appears to be the first instance of long-term loading on Vectran woven fabric [15].

In order to create the strain vs. time plot for 50% UTS, five consecutive tests were performed. The first was performed at room temperature (26.7°C) for the actual time of approximately 2 days. The second test was performed at 36.9°C, and with the use of superposition was placed appropriately after the test on the plot. Similarly the third, fourth and fifth tests were performed at 45.6° C, 54.4° C and 65.9° C, respectively, until creep failure and creep rupture were observed in the fifth specimen. The resulting plot is shown in Figure 12 [15].

Figure 12 - Vectran Fabric Creep Testing at 50% UTS [15]

The 40%, 60%, 70% and 80% UTS plots were created in a similar manner and the creep failure and creep rupture times were recorded. Using these times a preliminary long-term loading plot was created for Vectran fabric as shown in Figure 13. It is important to note that each data point consists of only 1 creep rupture experiment, and is not the average of a set of experiments [15].

Figure 13 - Vectran Fabric Long Term Loading Using SIM Testing [15]

In this work, it is desired to obtain long term loading properties of Vectran fabric. Since NASA concluded that material construction effects cannot be eliminated with preconditioning, all testing should be performed using construction identical to that desired for the given application [18]. While Scarborough et al. claim that SIM testing can be used for Vectran, these claims have not been verified by traditional testing or a second source according their article [15]. For this work traditional long term loading will be used to provide the desired information.

Chapter 3 - Quasi-Static Testing

3.1 - Strip Method

3.1.1 - Testing Standards / Procedure

In order to predict the maximum bearable pressures within inflatable structures, the tensile strength of the material is required. Quasi-static tensile testing was performed on 2x2 and 4x4 Vectran fabrics in accordance with ASTM D5035-06 with only slight modifications. These modifications do not conflict with the standard but rather make use of the standards flexibility as will be further discussed. If comparisons are to be made between these testing results and those from another laboratory, special care should be taken to note any differences in the testing methods and the data should be carefully reviewed to seek out a statistical bias. If a statistical bias is found, its cause should be sought out and discussed [34].

All quasi-static testing was performed using an MTS 810 material testing system with a constant rate of extension. The standard requires that tests be performed at a rate of 12 in/min, so testing was initially performed using that value [34]. However, it was observed that this rate was too high for Vectran woven fabric as specimens observed a breaking time of approximately 1 second at loads exceeding 2000 lbf. Rates of this magnitude caused variability in testing, resulting in difficulties properly characterizing the stress vs. strain curve. As a result, it was concluded that a slower rate of extension was required for properly evaluating the tensile properties of Vectran.

In order to determine a new rate of extension, the standard was carefully reviewed. Though the standard did not provide alternative rates for testing, it was found that a breaking time of 20 seconds is suggested for comparison between testing laboratories [34]. By observing the extension distance at a break a new rate was calculated. Using the new extension rate additional tests were performed. This process was repeated, recording the extension at break of the new tests and calculating yet another rate of extension. Finally an extension rate of 0.85 in/min was determined and used for the remainder of testing.

Test specimens are required to have a gauge length of 3", a grip length of 2" on either side and a width of 1" as shown in Figure 14. The standard outlined two types of specimen preparation in order to obtain the desired width:

Cut Strip Method – samples are carefully cut to the exact width of 1”.

Raveled Strip Method – in order to prevent the damage of fibers during the cutting process specimens will be originally cut with a width larger than 1”, and strands will be removed by hand until the desired width was achieved.

This is the only point where the two types of fabric differed in preparation. The 2x2 Vectran fabric used the cut strip test, where the 4x4 Vectran fabric used the raveled strip test [34].

Figure 14 - Strip Test Specimen Dimensions

Cutting the material proved to be a difficult task. Razors, snips and high quality scissors designed for cutting sheet metal proved to only mash and distort the fabric with little to no progress in cutting entire yarns. Large scissors with serrated edges were found to produce good results when the two scissor blades were highly tightened and blade edges were new and sharp. Since the blades were highly tightened they had a tendency to dull rather quickly, and since serrated edges cannot be easily sharpened, new scissors are often required.

Hydraulic wedge grips (MTS 647.10A) were used to hold the specimens on the loading frame as shown in Figure 15. These steel grips have an abrasive diamond pattern designed to reduce specimen slip. A number of different pressures were tried, resulting only in specimen slipping or breaking at the location of the grip. The standard requires that all breaks must occur at a distance no less than 0.25” from the jaw. Any specimen which breaks nearer to the jaw than that distance must be discarded unless it is concluded that necking in the specimen is causing all tests to result in breaking at the grips [34].

Figure 15 – MTS Testing Setup

The standard gives a number of solutions for trouble shooting issues such as these. The first suggestion involves the use of a pin to reduce slipping, though this method cannot be used with hydraulic grips [34]. New grips were manufactured in-house using 0.25" mild steel with 4 tensioning points (2 per side) over the 2" grip length as shown in Figure 16. The setup appeared similar to that of the standard as shown in Figure 17. Each of the 4 points was tensioned to 75 ft-lbs using a torque wrench and the specimens were tested. The brittle Vectran specimens immediately broke at the location of the pin when tested with a number of pin diameters ranging from 0.25" - 1".

Figure 16 – Initial In-house Grip Design

Figure 17 - Reduced Slip Testing With the Assistance of a Pin [34]

Another suggestion for preventing stress concentrations at the grips is the addition of padding between the specimen and the grips [34]. Returning to the wedge grips, a number of pads were tested to provide protection from the abrasive steel grips. Also, the grip pressure was varied in search of a pressure that would prevent slip without the addition of significant stress concentrations. Different padding and pressures were used for the two types of Vectran woven fabric due to differences in tensile strength and coating properties.

For the 2x2 Vectran fabric, a piece of Ferrari fabric was used with a grip pressure of 300 psi. For the 4x4 Vectran fabric a combination of thin rubber and an abrasive sand paper were used to simultaneously cushion and grip the specimen. A pressure of 1,600 psi was used for these tests. While these combinations of padding and grip pressure worked at the testing rate of 0.9 in/min, they have not been proven to work at any other rate. Testing with a higher rate has proven to cause slip in the grips, and testing at a lower rate has proven to greatly increase the chance of an observed stress concentration at the location of the grips. As a result, testing at different rates will likely require alternate techniques from those provided in this work.

Careful positioning of the specimens is very important to ensure proper breaking. If specimens are inserted at an angle between the two grips, a tearing effect will occur resulting in a reduced UTS. The patterned grips helped to ensure that specimens were properly aligned during installation. First the specimen was placed in the upper grips, and the lower grips were raised to their proper height. At this point neither of the grips were fully tightened. Next, the specimen was carefully placed such that it was correctly aligned with the pattern on the lower grips. Figure 18 shows a demonstration of a specimen being properly aligned. Finally the upper grips were tightened, the lower grips were again adjusted for height, and the lower grips were tightened.

Figure 18 - Specimen Alignment

Specimens were tested in both the fill and warp directions in order to fully characterize the woven fabric. Each test set consisted of 5 specimens, and each specimen was carefully examined after breaking in order to ensure that it followed the standard's requirements. Specimens that broke within 0.25" of the grips, tore at an angle, or demonstrated any other obvious signs of incorrect breakage were marked VOID and their results were discarded [34].

3.1.2 –Results - 2x2 Vectran Fabric

Originally, one test set was performed for 2x2 Vectran fabric in the fill and warp directions. The force vs. displacement curves for the test set in the fill direction is displayed in Figure 19.

Figure 19 - 2x2 Vectran Fill Direction Cut Strip Test Set 1

The peak force of each test run was recorded and the average, standard deviation (Stdev), and coefficient of variation (C.V.) were calculated for each test set as shown in Table 4. The coefficient of variation is calculated as follows:

$$C.V. = \frac{Stdev}{Average}$$

Notice the high coefficient of variation for the fill tests. For this data set there were specimens in both the fill and warp directions with breaks within 0.25" of the grip. Using this data, rather than voiding it as directed by the standard, can cause error in the results.

Table 4 - Original 2x2 Vectran Cut Strip Data Set 1

Specimen #	Fill (lbf)	Warp (lbf)
1	2076	1720
2	2065	1802
3	1365	1843
4	2125	1695
5	2177	1676
Average	1961	1747
Stdev	336	72
C.V.	17.1%	4.1%

Notice that the third fill specimen is labeled Void in the picture (Figure 20 (A)). It is clear that this specimen experienced stress concentrations at the point of contact with the grips. Similarly, notice that the fourth and fifth specimens tested in the warp direction were broken directly at the location of the grip (Figure 20 (B)).

Figure 20 - 2x2 Vectran Cut Strip Tests: A) Fill Direction, B) Warp Direction

The results for the first and third specimens in the fill direction are plotted again in Figure 21. Notice that the curve from the improper failure in specimen 3 has a much lower peak than the proper failure in run 1, and the improper failure observes a larger displacement before failing entirely.

Figure 21 – Cut Strip Method Voiced Specimen Plot

By voiding specimens from the data as instructed by ASTM we notice a great improvement in the coefficient of variation. Table 5 contains the corrected cut strip data.

Table 5 - Corrected 2x2 Vectran Cut Strip Data Set 1

Specimen #	Fill (lbf)	Warp (lbf)
1	2076	1720
2	2065	1802
3	VOID	1843
4	2125	VOID
5	2177	VOID
Average	2111	1788
Stdev	51	62
C.V.	2.4%	3.5%

Typically, new specimens would be tested and used to replace voided specimens, and the resulting test set would be considered final. As shown by the high number of voided specimens, the first test set possibly contained an abundance of user error. In order to produce more accurate results, an entire new test set was produced for the fill direction as shown in Table 6 below. Since warp direction values were not needed, and materials were limited, no additional warp direction testing was performed.

Table 6 – 2x2 Vectran Cut Strip Data Set 2

Specimen #	Fill (lbf)
1	2227
2	2287
3	2286
4	2285
5	2306
Average	2278
Stdev	30
C.V.	1.3%

3.1.3 – Discussion - 2x2 Vectran Fabric

Though all specimens were prepared and tested in a uniform manner, 30% of the original test runs resulted in voided data. Plotting the results for the first and third specimens in the fill direction provided helpful insight regarding the mode of failure for the third specimen, which was voided. Rather than an abrupt failure, this specimen stepped down from its peak. While stress concentrations likely contributed to the improper failure of the specimens, they may not be the only cause.

If all of the yarns were equally loaded during extension of the specimen, then they should all have similar strain values. In this case, a significant change in strain should not be observed between breaks unless some of the fibers were damaged before loading, causing them to break prematurely, or the specimen was installed at an angle.

Figure 21 suggests that the third specimen was not simply weaker than the first, but that it actually experienced a different type of failure. It seems unlikely that the material was damaged prior to testing resulting in such uniform step sizes. In addition, the total displacement for breaking all fibers in the third run was approximately 0.5 in, where the total displacement for breaking fibers in the first run was approximately 0.3 in. If Vectran fibers break at a constant

strain, then it would be unlikely for the fibers in the first and third runs to have such large differences in their displacement at the time of failure.

In conclusion, it seems that the void specimen in the fill direction broke as a result of improper installation in the grips rather than a result of stress concentrations caused by a lack of padding. The specimen was likely installed at a small angle causing sets of yarn to be loaded before those adjacent to them. Since only a couple of yarns were attempting to bear the entire force of the displacement, they more quickly reached their maximum strain causing them to fail. Immediately, the next set of yarns bore the load causing a cascading effect until the entire specimen failed.

The voided specimens in the warp direction have only slightly lower strength values as the specimens observing proper failure. Because of the high number of voided specimens, it is likely that the grips were simply too tight, damaging the fibers. It is difficult to determine the exact cause of the improper breaks without performing further testing.

Additional testing was performed in the fill direction, producing no void specimens. Shown in Table 6, these results provide an improved tensile strength for 2x2 Vectran woven fabric.

One variable that will be easily avoided with future 4x4 Vectran fabric testing is the damage of fibers due to the cut strip method. When specimens are cut the fibers composing the yarns will inevitably be damaged. These damages can cause premature failure in specimens that appear to break correctly in the gage length, increasing the variability of the results. As explained in the procedure, 4x4 Vectran testing will use the raveled strip method.

3.1.4 –Results - 4x4 Vectran Fabric

Using the raveled strip method, two tests sets were acquired for the 4x4 Vectran fabric in both the fill and warp directions. The results yielded data with no voided specimens. A plot of the first test set in the fill direction is shown in Figure 22.

A summary of the breaking forces for each specimen is displayed in Table 7. Notice that on average the fill direction is nearly 250 lbf stronger than the warp direction for the same 1” specimen being tested in the same method.

Figure 22 - 4x4 Vectran Fill Direction Raveled Strip Test Set 1

Table 7 - 4x4 Vectran Raveled Strip Test Data

Specimen	Fill	Warp
#	(lbf)	(lbf)
Test Set 1	1	2531
	2	2536
	3	2677
	4	2539
	5	2557
Test Set 2	6	2745
	7	2521
	8	2536
	9	2356
	10	2672
Average	2567	2319
Stdev	108	130
C.V.	4.2%	5.6%

3.1.5 – Discussion - 4x4 Vectran Fabric

The 4x4 Vectran woven fabric displayed a higher strength over the 2x2 Vectran woven fabric (see Table 8). Since both fabrics were made of Vectran HT fibers, their construction (yarn

tpi, weaving pattern) likely played a large role in their strength properties. By dividing the breaking strength of the fabric by the number of yarns per inch, the approximate experimental strength of the yarns can be calculated. Comparing the experimental strength of the yarns for each of the different woven fabrics will allow differences in strength due to fabric construction to be estimated. Table 8 displays the results of these calculations.

Table 8 - Approximate Observed Yarn Strength in Specimens				
	4x4 Vectran		2x2 Vectran	
	Fill	Warp	Fill	Warp
Strength (pli)	2567	2319	2278	1788
Yarn / Inch (#/in)	42	34	32	30
Strength / Yarn (lbf/yarn)	61	68	71	60
Average Strength/Yarn (lbf/yarn)			65	
% Diff. from Ave. (%)	-6.2%	4.8%	9.0%	-8.7%

Due to the limited number of specimens tested for the 2x2 Vectran woven fabric, it is difficult to make definitive conclusions concerning the results. A preliminary examination shows that the percent difference between individual yarn strengths and the average yarn strength is similar to the coefficient of variation between tested specimens making up each test set. This makes it impossible to make any definitive conclusions without further testing.

According to NASA, construction effects cause the fibers which compose the yarns to vary in strength [18]. This means that the tpi of the yarns for each fabric, in addition to the basket weave pattern and coating type, would cause a difference in the observed strength of the yarns composing the fabric specimens. If this is the case, we would expect to see a trend in the strength of the yarns as we change single variables in the construction. Observing Table 8, notice that the number of yarns per inch decreases from left to right, meaning that yarns are less compact in the construction moving from left to right on the table. Comparing the strength of the individual yarns, there is no apparent trend to be linked with this variable.

Without knowing the fine details of the processing methods for the two basket weave patterns, and the differences in the 2x2 and 4x4 patterns themselves, it is difficult to say that the number of yarns per inch is the only variable in the table. We can conclude that increasing the number of yarns per inch does indeed increase the strength of the woven fabric, but not proportionally. However, further testing will be required before additional conclusions can be definitively made.

3.2 –Modulus of Elasticity - 4x4 Vectran Fabric

3.2.1 – Procedure

The Young's modulus of the specimens is indirectly found in the load vs. displacement curve obtained from the quasi-static testing results. Dividing the applied load by the width of the specimen provides the membrane stress in units of pounds per linear inch (pli). Since the specimens are 1" wide, the magnitude of the stress in pli is equal to the magnitude of the load in lbf. Next, the displacements are converted to engineering strains by dividing the displacement with the gage length. Example calculations are shown in the equations below for the values observed 9 seconds into the test.

$$\sigma = \frac{force}{width} = \frac{1,441 \text{ lbf}}{1 \text{ in}} = 1,441 \text{ pli}$$

$$\varepsilon = \frac{displacement}{gage \text{ length}} = \frac{0.15 \text{ in}}{3 \text{ in}} = 5\%$$

Once the data has been converted to the proper units, the instantaneous Young's modulus can be calculated at any point by dividing the stress by the strain.

$$E = \frac{\sigma}{\varepsilon} = \frac{1,441 \text{ pli}}{5\%} = 28,820 \text{ pli}$$

Plotting the stress vs. strain curve can assist with the estimation of the modulus. If the stress is placed in the y-axis and the strain in the x-axis, then the slope of the curve corresponds to the Young's modulus. Applying a linear fit trend line provides an equation:

$$y = mx + b$$

where m is the slope of the fitting line corresponding to the Young's modulus.

3.2.2 – Results

A plot was made for every test run in both the fill and warp directions. A distinct change in slope was observed in the plots near 2.5% strain, so two different linear curves were fitted to the plot. The modulus observed at low and high strain values are referred to as the low modulus and high modulus, respectively. Each specimen was fit with a separate curve and characterized by its own unique slope. Results for the first fill and warp direction specimens are shown in Figure 23 and Figure 24, respectively.

Both the low and high modulus values were calculated for each of the first 5 quasi-static tests performed. Their averages, as well as the standard deviation and coefficient of variation between them, are summarized in Table 9. The coefficient of determination (R^2) for each linear fit equation is displayed beside its corresponding slope value.

Figure 23 - 4x4 Vectran Fill Direction Modulus for Specimen 1

Figure 24 - 4x4 Vectran Warp Direction Modulus for Specimen 1

Table 9 - 4x4 Vectran Fabric Modulus Data

Sample #	Fill				Warp			
	Low Modulus ¹		High Modulus ²		Low Modulus ³		High Modulus ⁴	
	(pli)	R ²	(pli)	R ²	(pli)	R ²	(pli)	R ²
1	17,948	0.995	41,484	0.999	18,518	0.992	45,132	0.999
2	19,199	0.995	42,820	0.999	18,150	0.993	38,789	0.999
3	18,899	0.994	41,298	0.999	18,853	0.994	36,899	0.999
4	19,496	0.994	40,041	0.999	18,305	0.993	39,041	0.999
5	18,444	0.995	41,293	0.999	19,665	0.994	39,164	0.999
Average	18,797		41,387		18,698		39,805	
Stdev	614		986		601		3,116	
C.V.	3.26%		2.38%		3.22%		7.83%	

1 - Fill Direction Low Modulus Taken Between 0% - 1.50% Strain

2 - High Modulus Taken Between 3.36% - 6.17% Strain

3 - Warp Direction Low Modulus Taken Between 0% - 1.91% Strain

4 - High Modulus Taken Between 3.28% - 7.47% Strain

Notice that strain values for calculating the Young's modulus were chosen where the slope of the curve is most constant. This was done in an effort to produce a more accurate approximation to the linear relationship between stress and strain for the unique upper and lower slopes.

3.2.3 – Analytical Model

An analytical model was designed to predict the Young's modulus for 4x4 Vectran woven fabric. The manufacturer's specifications provide the Young's modulus, denier, and density of the Vectran HS fiber[28].

$$E = 75 \text{ Gpa}$$

$$\text{Denier} = 1,500 \frac{g}{9,000 \text{ m}}$$

$$\rho = 1.41 \frac{g}{cm^3}$$

Performing basic calculations with the given information provides the cross-sectional area of the fiber. To simplify the process, a fiber with a length of 9000 m will be used for calculations.

$$\text{mass}_{\text{fiber}} = \text{denier} \times \text{length} = \frac{1,500 \text{ g}}{9,000 \text{ m}} \times 9,000 \text{ m} = 1,500 \text{ g}$$

$$\text{volume}_{\text{fiber}} = \frac{\text{mass}}{\rho} = \frac{1,500 \text{ g}}{1.41 \frac{g}{cm^3}} = 1,064 \text{ cm}^3$$

$$area_{fiber} = \frac{volume}{length} = \frac{1,064 \text{ cm}^3}{1,500 \text{ cm}} = 0.00118 \text{ cm}^2$$

The cross-sectional area of the fibers composing 1" of fabric is thus:

$$A_{fill} = (Number \text{ of fibers}) \times area_{fiber} = 42 \times 0.00118 = 0.05 \text{ cm}^2$$

$$A_{warp} = 34 \times 0.00118 = 0.04 \text{ cm}^2$$

The cross-sectional area of 1" of 4x4 Vectran fabric, both fill and warp, is:

$$A_{fabric} = (1 \times 2.541) \times (0.033 \times 2.541) = 0.2131 \text{ cm}^2$$

Finally, the Young's modulus can be calculated:

$$E_{fill-analytical} = \frac{E_{Vectran HT} \times A_{fill}}{A_{fabric}} = \frac{75 \text{ Gpa} \times 0.05 \text{ cm}^2}{0.2131 \text{ cm}^2} = 17.47 \text{ Gpa}$$

$$E_{warp-analytical} = \frac{75 \text{ Gpa} \times 0.04 \text{ cm}^2}{0.2131 \text{ cm}^2} = 14.15 \text{ Gpa}$$

The average experimental Young's modulus values can be converted from pli to Gpa as follows:

$$E_{fill (high)-experimental} = \frac{41,387 \text{ pli}}{0.033 \text{ in}} = 1,254 \text{ ksi} = 8.65 \text{ Gpa}$$

$$E_{warp (high)-experimental} = \frac{39,805 \text{ pli}}{0.033 \text{ in}} = 1,206 \text{ ksi} = 8.32 \text{ Gpa}$$

Table 10 summarizes both the analytical and experimental results.

Table 10 - 4x4 Vectran Young's Modulus Summary			
Fill Direction Modulus		Warp Direction Modulus	
Experimental ¹	Analytical ²	Experimental ¹	Analytical ²
8.65 GPa	17.47 GPa	8.32 GPa	14.15 GPa

¹ - Average high modulus values taken from a total of 5 specimens
² - Calculated using manufacturer's specifications

3.2.4 – Discussion

As was noted in the experimental results, two distinct Young's modulus values were obtained during testing. It is suspected that the appearance of the lower modulus is a direct result of the material construction affects (twisting of yarns, weaving of fabric), though further testing is required to support this theory.

The analytical model resulted in Young's modulus values approximately twice the magnitude of the experimental results. Again, it is suspected that the material construction affects account for a large part of this difference. However, further testing is required to determine if there are other affects which influence this observed difference.

3.3 –Wet Testing - 2x2 Vectran Fabric

3.3.1 – Procedure

Wet testing was performed on 2x2 Vectran fabric using the cut strip method in order to examine the affect of tap water on the strength of the material. Specimens were soaked in water for the allotted amount of time in a closed container at room temperature. While the standard requires specimens to be soaked in distilled water [34], tap water was used for testing since it is expected to be used in the final products.

After specimens were removed from water, they were immediately tested in order to maintain moisture that was absorbed, if any. In order to properly grip specimens without slip, it was required that the grip areas be dried just before testing. This was done by gently patting the specimens with a cloth.

3.3.2 – Results

The second test set from quasi-static testing in the fill direction was used as a reference point. After 1 and 3 weeks, 5 specimens were removed from the water and tested. Table 11 summarizes the results.

Table 11 – 2x2 Vectran Fill Wet Testing

Specimen #	Dry (lbf)	1 Week Soaked (lbf)	3 Weeks Soaked (lbf)
1	2227	2309	2398
2	2287	2235	2313
3	2286	2220	2296
4	2285	2262	2294
5	2306	2172	2272
Average	2278	2240	2315
Stdev	30	51	49
C.V.	1.3%	2.3%	2.1%

3.3.3 – Discussion

The average value for the wet tests remained nearly constant, with differences being within the range of the standard deviation. After three weeks, testing was stopped since no apparent effect was being observed. The average strength of the dry 2x2 Vectran woven fabric slightly increased as compared with original quasi-static cut strip testing. This is likely a result of the observed decrease in user error as the testing procedure was more accurately followed with practice.

3.4 - Crease Fold Testing

3.4.1 – Background

The purpose of crease fold testing is to characterize any loss in strength observed in Vectran woven fabric as a result of tightly packing the inflatable structure and storing it for extended periods of time. Testing is also meant to observe any losses in strength resulting from pinching observed during or after the inflation process.

An ASTM standard for characterizing the breaking force after crease folding is available specifically for architectural applications. However, this standard is meant only to replicate folding observed in the shipping process. In summary, the method requires that a strip of fabric is placed on a flat surface, and a 10 lb cylinder is rolled over the strip a total of ten times. The strip is then tested, and its breaking strength recorded [35].

Since this method is meant to represent short term folding observed during shipping, it may not accurately represent the extended folding that will be observed in storing an inflatable structure for extended period of time. It will also fail to represent the high forces applied to crease folds during or after the inflation process. As a result, a new procedure should be designed with a conditioning method that will more accurately represent the intended application of the inflatable structure concept.

3.4.2 – Procedure

For this set of test data all testing was performed on 4x4 Vectran woven fabric. In an effort to maintain uniformity between tensile testing methods, specimens for crease fold testing were prepared in accordance with the raveled strip method. Once specimens were fully prepared for testing, they were preconditioned according to the application which they were meant to replicate.

To begin, specimens were folded in the center and mounted to a clean, flat surface. The folded specimens were placed so that approximately one square inch was located within the loading area as shown in Figure 25 (A). In order to prevent specimens from moving they were held in place using a thin, non corrosive tape. Multiple layers were placed together in order to minimize the number of weights needed, and maximize testing space in the environmental chamber as shown in Figure 25 (B). Finally, the desired pressure was applied to the specimens using a weight as shown in Figure 25 (C). To represent the storage folding a pressure of 1 psi was used, and in order to represent folding in the inflation process a pressure of 15 psi was used.

Figure 25 - Crease Fold Testing

It is suspected that high the temperature, and humidity being observed during the storage and testing of the structure could expedite the affects of crease folding. In order to take this into account, the folded samples were placed in an environmental chamber at 100°F, and 95% humidity. The pressures were maintained in this environment for 1 and 2 months at 15 psi, and 1, 2, and 4 months for 1 psi.

Once specimens were removed from the environmental chamber, they were allowed a short time to return to room temperature before being tested. This was to prevent any loss in strength as a result of elevated material temperatures during the testing process, which was proven in the literature review to decrease the strength [15]. The testing process was performed using the raveled strip method. A decrease in the breaking strength of the raveled strip specimens was the expected outcome. Characterizing this loss in strength in relation to the applied pressure magnitude and duration could then quantify the affects of crease folding on the material.

3.4.3 – Results

The broken specimens for the first crease fold test set (1 month at 15 psi) are shown in Figure 26. Table 12 summarizes the breaking strength of each broken specimen.

Figure 26 – Crease Fold Specimens

Table 12 - Crease Fold Data						
Crease Pressure (psi)	-	15		1		
Crease Time (months)	0	1	2	1	2	4
# Specimens	10	12	4	8	4	4
Average Breaking Strength (lbf)	2319	2205	2074	2189	2030	1980
Stdev (lbf)	130	88	58	84	58	138
C.V.	5.6%	4.0%	2.8%	3.8%	2.9%	7.0%
Loss in Strength (lbf)	-	114	245	131	290	339

Notice that the loss in strength is higher than the standard deviation, indicating that a loss in strength was actually observed through time. Also, notice that the difference in the loss in strength compared between 1 psi and 15 psi, for the same time, is smaller than the standard deviation. This indicates that the loss in strength is independent of the crease pressure. The breaking strength vs. crease fold time is plotted in Figure 27.

Figure 27 – Crease Fold Results

3.4.4 – Discussion

Upon observation of the data, it is immediately noticed that the results were affected by something other than the crease fold pressure. The 15 psi specimens observed a similar loss in strength as the 1 psi specimens. However, Figure 26 shows that the crease fold itself heavily influenced the data, as every specimen was broken at the crease location. Thus, the affects of the environmental chamber (temperature and humidity) in combination with the crease fold must have caused the observed loss in strength.

Since the water used for wet testing was received from the same source as the water used to produce the humidity in the environmental chamber, it can be assumed that the affects of humidity should be similar for both test sets. It was concluded that the water in the wet testing results did not affect the strength of the specimens, thus it is also assumed that the humidity did not affect the strength of the specimens in the crease fold testing. In addition, the wet testing was performed on the 2x2 Vectran woven fabric which is only coated on one side. Since the 4x4 Vectran woven fabric is double coated, it is unlikely that the water could affect the fibers.

The only known remaining difference between the control specimens and those conditioned in the environmental chamber is the difference in temperature. According to the manufacturer, the specimens observe a noticeable loss in strength when tested at elevated

temperatures [30]. However, the crease fold tests were allowed to cool to room temperature before testing was initiated.

The manufacturer also exposed the fibers to various temperatures for 24 hrs, and after allowing them to cool, tested their strength [30]. The data points from this testing were used to create the plot in Figure 28. An exponential trend line was fit to the points, and the resulting equation was used to predict a loss in strength of 0.6% at a temperature of 100 °F. However, since the manufacturer only conditioned specimens for 24 hrs, and did not apply a crease fold to specimens, it is difficult to directly compare the results.

Figure 28 - Temperature vs. Loss in Strength [30]

Though this work suggests that an additional loss in strength will be observed through time for specimens experiencing a crease fold at temperature as low as 100°F, it cannot be definitively concluded. As a result, it is suggested that further testing be performed to characterize the strength of Vectran after the observation of 100°F, for crease fold times varying from 1 to 120 days. This will allow a more definitive conclusion to be made concerning the crease fold results.

3.5 - Modified Grab Method – 2x2 Vectran Fabric

3.5.1 - Testing Standards / Procedure

In an attempt to better understand the addition in strength provided by neighboring yarns in Vectran woven fabric, additional quasi-static testing was performed according to ASTM D5034-09. For this test only 2x2 Vectran fabric was used. This standard outlined two similar types of testing, the grab test and the modified grab test. Since the modified grab test is focused more specifically on high-strength woven fabrics, it was exclusively chosen for testing. While modified grab testing is meant to compliment strip testing, there is no simple correlation between the modified grab and strip testing results. Such a correlation would depend on variables such as fabric construction and material properties of the fiber and coating [34].

Modified grab testing was performed in an identical manner to strip testing in all aspects except the geometry of the specimen. As a result, only the geometry of the specimen will be discussed in this section. Specimens had a gage length of 3" and a grip length of 2" on either side. The width was 4" and a 1.5" slit was cut parallel to the length of the specimen at the midpoint of the gage area. This left 1" of uncut fibers in the center of the specimen as shown in Figure 29 below. This requires that the same number of yarns be broken with the modified grab test as with the strip test. Theoretically, an increase in breaking strength should be observed with the modified grab test (compared with the strip test) which will represent the assisted strength of neighboring fibers in the Vectran woven fabric [34].

Figure 29 – Modified Grab Test Specimen Dimensions

3.5.2 - Results

Since materials were limited, and modified grab testing uses four times the material as strip testing, a single specimen was tested first to observe differences and to consider the significance of the testing method. The force vs. displacement plot is displayed in Figure 30.

Figure 30 - 2x2 Vectran Fill Direction Modified Grab Test

From Figure 30 notice that the curve has multiple peaks rather than the single peak observed in the cut strip method on 2x2 Vectran fabric. The peak also appears to be much lower than expected despite the test method's claim to produce higher strength values. After observing this plot, it was decided that modified grab testing should be further investigated before additional Vectran material was used for testing. A picture of the tested specimen is shown in Figure 31.

Figure 31 - 2x2 Vectran Fabric Modified Grab Test

3.5.3 – Discussion

Similar to the plot observed in the voided 2x2 Vectran fill direction cut strip test, the modified grab test seems to have experienced a different type of failure than expected. Plotting stress strain curves for the fill direction modified grab test and cut strip test together in Figure 32, additional observations can be made.

Again the breaking pattern appears to be stepped, as was previously concluded to indicate a tearing effect rather than instantaneous breaking. However, for this test the displacement values are similar between the two specimens, indicating similar strain values required for the breaking of all fibers. The greatest concern in this plot is the observation of breaking in the fibers sooner than expected.

Figure 32 - 2x2 Vectran Fill Direction Modified Grab vs. Cut Strip Tests

The purpose of the modified grab test was to observe the expected increase in strength observed in fabric provided by the assistance of neighboring fibers. Theoretically, the neighboring fibers were expected to bear a small portion of the applied load, and to assist the fibers undergoing a tensile load in maintaining their rigidity. This assistance was expected to increase the Young's modulus, and in turn reduce the strain observed for a given load. Test results provided a different conclusion.

Results show that the modified grab specimen experienced similar strain values despite the assistance from neighboring fibers. It is likely that the vast majority of strain occurred at the location of the slit on the modified grab specimen since this was the location where the loaded yarns received the last assistance from neighboring fibers. This means that there was a strain/stress concentration at the location of the slit. This concentration prohibited the distribution of strains along the vertical axis of the yarns.

It is important to understand that the introduction of construction on a material simultaneously requires the introduction of variances in the materials observed loading pattern. If a single fiber is independently loaded, a constant strain value will be observed through its cross section at any given point in its gage length. Placing two fibers next to each other, it is nearly impossible to align them perfectly and load them identically. Thus, loading two fibers with one force will result in the observation of two distinct strain values at any given cross section in the gage length. Similarly, twisting sets of 300 fibers together to make a piece of yarn, and weaving that yarn together with a total of 42 yarns/in, the application of a load on this cross section will result in a number of different strain values across any cross section in the gage length.

If the gage length for a given specimen were to be increased, it would be expected that the overall misalignment in the fibers and differences in their observed loading would decrease as both were averaged out, producing similar strain values across a given cross section. This is observed in cut strip testing, where differences in strain values are reduced because the observed strain in the material is distributed along the length of the fiber/yarn for the 3" gage length.

However, when the strain is concentrated to a specific point on the specimen, larger differences in alignment and applied load will be observed through a given cross section of the material, producing differences in the observed strain at that given section. This is precisely the effect that modified grab testing is observing at the location of the slit. Since some fibers reach their maximum strain value more rapidly than others, we observe failure in these fibers much sooner.

If testing were being performed using a constant rate of load, failure of a group of fibers would cause the abrupt loading of neighboring fibers, resulting in nearly instantaneous failure of the specimen with respect to time. However, quasi-static testing is performed using a constant rate of extension. This means that when a group of fibers fails, the neighboring fibers do not

observe any abrupt changes in their loading state. Rather, the neighboring fibers continue to observe a constant rate of extension, resulting in a constant increase in strain through time after initial loading has occurred. This is not to say that all fibers will observe the same magnitude in strain through time, because as was previously explained, not all fibers will receive their initial loading at the same point in time as a result of differences in misalignment and load application. This simply means that once a group of fibers begins to observe strain, their increase in strain will be constant with respect to time, until maximum strain is achieved and the fibers fail.

This is precisely what we observe in Figure 32 above. Small groups of fibers observe an increase in strain until failure occurs, providing strength values lower than those expected for the material as a whole. Once the displacement of the material as a whole produces critical strain values in all of the fibers, the specimen fails. The small increase in overall strain observed in modified grab testing is likely the result of twisting in the specimen. It is suspected that when fibers on only one side of the specimen fail, a moment is observed causing the specimen to rotate in the grips. This rotation decreases the strain values on the other side of the specimen allowing the fibers to last a few moments longer. Once the specimens on the other side of the grip fail, only the fibers in the center of the grip are remaining. Figure 43, found in the next section, shows this breaking sequence.

In order to check the assumptions made this section, additional testing should be performed to further investigate the relationship between the cut strip and modified grab methods. It is important to evaluate the modified grab method in order to conclude if it can be used for characterizing Vectran woven fabric. Since the modified grab method was created specifically for woven fabrics, rather than all textiles (non-woven, felted), it could be valuable for providing additional characterization of the fabric.

3.6 – Cut Strip vs. Modified Grab Testing Using Ferrari Fabric

3.6.1 – Background / Procedure

Further investigation of the relationship between the cut strip method and the modified grab method was performed using a new specimen design. Shown in Figure 33, this new design will use characteristics from both the cut strip and modified grab methods, and will be referred to as the cut grab method. Notice the arrows labeled “Secondary Gage Length”; additional slits of varying length will be introduced to the specimens at this location. By slowly

transitioning from one method to the next, results will allow for further discussion and evaluation of their relationship. Ferrari fabric will be used for testing in order to conserve the Vectran material.

Because of the low tensile strength demonstrated by Ferrari fabric, an electromechanical Instron machine will be used to perform tests. Threaded, pre-padded, grips were tightened to 25 ft-lb with the assistance of a torque wrench.

Figure 33 – Cut Grab Test Specimen Dimensions

3.6.2 – Results

For each test set only two specimens were tested, as the results are meant for observation purposes only. When tested, each specimen was identified by the secondary gage length. Traditional modified testing load vs. displacement plots are presented in Figure 34. Notice that a number of load steps are observed in both specimens, indicating the failure of different groups of fibers as displacement occurs.

Figure 34 - Ferrari Modified Grab Tests

A load vs. displacement plot for cut grab specimens with a secondary gage length of 0.5" is displayed in Figure 35. Notice that each of these specimens has two load steps, indicating that it experienced two breaks.

Figure 35 - Ferrari 0.5" Cut Grab Tests

Load vs. displacement plots for cut grab testing with secondary gage lengths of 1.0", 1.5" and 2.0" are displayed in Figure 36, Figure 37 and Figure 38, respectively. Notice that these appear to observe only one break.

Figure 36 - Ferrari 1.0" Cut Grab Tests

Figure 37 - Ferrari 1.5" Cut Grab Tests

Figure 38 - Ferrari 2.0" Cut Grab Tests

Three specimens were tested for cut strip testing as displayed in Figure 39. Notice that the coefficient of variation for these tests is smaller than any other test set in this section despite the larger number of specimens.

Figure 39 - Ferrari Cut Strip Tests

Creating an average load vs. displacement curve for each test set, the results were plotted together as shown in Figure 40. This allows a quick visual comparison between each test set since exact values are of no concern.

Figure 40 - Ferrari Modified Grab vs. Cut Strip Testing

For Ferrari fabric there seems to be a direct correlation between the size of the secondary gage length and the strength / breaking displacement of the specimen. For modified grab testing, the secondary gage length is considered to be 0.0" and for the cut strip testing, it is considered to be 3.0".

A close-up image of a specimen from the modified grab test is shown in Figure 41, and of a specimen from the 0.5" cut grab test in Figure 42. Notice that the specimens do not appear to have a uniform breaking pattern.

Figure 41 – Modified Grab Specimen

Figure 42 – 0.5" Cut Grab Specimen

3.6.3 - Discussion

Upon further review of the results it was found that the frequency used to collect data was lower than desired. While the recorded data is a close representation to the actual observed force and displacement values, recorded peaks could be anywhere from 0% to 5% lower than those actually observed in the specimens.

Despite this error, it is observed that larger secondary gage lengths result in higher breaking strengths for Ferrari woven fabric, as was suggested in the modified grab discussion (Section 3.5.3). Comparison between a specimen from the 0.5" test set and its load vs. displacement plot reveals further confirmation of the assumptions made in this section. The suggested failure sequence for this specimen is shown in Figure 43 below. Notice that there are three distinct breaks observed in the specimen, and three distinct load steps in its corresponding plot. The specimen from the 1.0" cut grab test exhibits similar results as shown in Figure 44.

Figure 43 – Suggested Failure Sequence for Modified Grab Specimen

Figure 44 – Suggested Failure Sequence for 0.5" Specimen

Table 13 provides a summary of the averaged results from this section. Here we can see a direct correlation between the secondary gage length and the average stress and strain observed at the peak of the force vs. displacement curve. This proves the initial assumption that increasing the gage length will in turn increase both the observed maximum stress and strain in the specimen. However, further testing is still required to determine if the source of this trend is the result of misalignment and differences in loading in the fibers, as was previously suggested.

The lower values observed at 2.0" secondary gage length are likely due to a combination of the low frequency used for recording data, and the low number of specimens tested for each point.

Table 13 - Ferrari Cut Grab Data

	Modified Grab	Cut Grab				Cut Strip
Secondary Gage Length (in)	0.0	0.5	1.0	1.5	2.0	3.0
Stress (pli)	314	325	388	430	414	523
Strain	15%	16%	19%	21%	21%	27%

From this information it was decided that modified grab testing would not be used to characterize Vectran woven fabric since it does not accurately represent the bulk material.

Chapter 4 - Long Term Loading

4.1 – Introduction

When a material is loaded beyond its UTS it observes instantaneous failure. Additionally, when a constant load below the UTS is applied through time, strain is observed in the material. Under these circumstances, strain is referred to as creep. Figure 45 shows a typical creep curve.

Zones:

- 1 - Primary Creep
- 2 - Steady State Creep
- 3 - Tertiary Creep

Critical Points:

- A - Initial Load
- B - Creep Failure
- C - Creep Rupture

Figure 45 – Typical Creep Curve

Given an applied load through time, creep will eventually result in creep rupture. From the curve in Figure 45, this point is identified at time t . In order to predict creep rupture times, a number of specimens will be loaded, each with different loads, until creep rupture occurs. By plotting the load vs. creep rupture time, the creep rupture time can be characterized. The resulting curve is referred to as the long term loading curve for the material.

4.2 – Testing Standard

4.2.1 – Background

A variety of testing methods are available for finding material properties, so it is important to determine which method best fits the desired application of the material in question.

It has been found that the effects of material construction such as yarn twists and fabric weaves are not eliminated during initial tensioning for Vectran fabric [18]. As a result, all material used for testing should accurately represent the construction of the material used for the desired application, in this case a woven fabric comprised of twisted yarns.

While it is unclear exactly how wide a specimen should be in order to accurately represent the bulk fabric, recommendations can be found in ASTM standards. For inflatable structures and architectural uses, standards recommend that a specimen with a width of 1 inch be used for tensile testing [15][35][36].

Since ASTM does not currently have standards for creep rupture testing, the closest standards are used as guidelines for testing. Those standards are ASTM D5034 and ASTM D5035, the strip and modified grab methods.

4.2.2 – In-house Procedure

It is important to maintain a similar testing method between long term loading and quasi-static loading so that results can be compared and discussed. Since modified grab testing resulted in additional questions and complications rather than useful data, strip testing will be used as a basis for long term loading. As with quasi-static testing, 2x2 Vectran fabric will use the cut strip method, and 4x4 Vectran fabric will use the raveled strip method. Specimens will have a gage length of 3" - as was used for strip testing. Since both the MTS wedge grips and the new bollard grips will be used, the grip length for each specimen will not be included in this procedure.

Each test set will consist of 5 test runs as is required for ASTM textile testing. A constant rate of extension is not required for long term loading since the time between initial load application and the observation of the full load is insignificant. However, for loads in which the breaking time is anticipated to be low, the application time could affect the time to break. This requires that specimens reach their full applied load within a finite time.

Quasi-static testing can be considered to be long term loading at 100% UTS with a breaking time of 0 seconds, creating the first point for testing. Quasi-static specimens reach their full applied load at a time of 20 seconds and immediately break thereafter. By considering this to be the first point on the long term loading plot, the time to full load application has already been set to 20 seconds. Therefore, any load expected to produce a breaking time of less than an hour should be applied in 20 seconds.

Again, a constant rate of extension cannot be required to meet the 20 second standard for full load application. Since the specimens will not be breaking immediately after the full load is applied, it is important that the load remains constant after the full application. If a specimen is loaded to high forces too quickly, the control system will have a tendency to overshoot the desired load and requiring a small settling time before reaching an acceptable error. In addition to the error, the process of overshooting can significantly weaken the specimen by noticeably reducing the time to break. In this work, loads were applied sequentially, first applying 90% of the desired load in the first 15 seconds, then applying up to 98% of the load over the next 3 seconds, and finally applying the remaining load over the last 2 seconds.

For loads experiencing a breaking time of over an hour the exact application time was not as critical. Loads were applied in a timely manner and the maximum desired load was not exceeded. The actual procedure for testing is further specified in procedure section for each set of tests described below.

4.3 –Long Term Loading - 2x2 Vectran Fabric Fill Direction

4.3.1 – Procedure

For 2x2 Vectran fabric, long term loading, all specimens were tested in the fill direction using the MTS system. Specimens for 2x2 Vectran long term load testing were identical to those used for quasi-static testing. For each load step tested, the grip pressure was reevaluated to reduce stress concentrations while preventing slip. As before, Ferrari fabric was used as padding for all test specimens. Specimen which did not slip within the first 30 min of testing typically remained stationary for the remainder of the test. This was due to an observed bonding, which increased with time between the test specimens and the grip padding material. If test specimens observed any amount of slip the test was stopped and the specimen discarded. Slipping was found to cause damage to the specimen fibers, lowering the time to break.

During quasi-static testing it was found that gripping specimens too tightly caused stress concentrations, resulting in improper breakage. This improper failure was many times not observed until the specimen had been loaded for up to half of its predicted life span. The preferred method for determining the proper grip pressure was to start at a low pressure, and slowly raise it until slipping no longer occurred.

The first specimen was tested at 2,000 lbf, and its creep rupture time was recorded. Testing was continued as the load was sequentially decreased between each creep rupture test by 50 lbf, with the exception of the applied load of 1625 lbf. Table 14 shows the relationship between the applied load and the corresponding %UTS.

Table 14 - 2x2 Vectran Fabric Long Term Loading Load Increments

Load (lbf)	% UTS
2271	100%
2000	88%
1950	86%
1900	84%
1850	81%
1800	79%
1750	77%
1700	75%
1650	73%
1625	72%
1600	70%

4.3.2 – Results

Specimens were tested one at a time on the MTS frame and their breaking times recorded. Working towards the end goal of two tests sets for each load, testing was stopped early due to the high coefficient of variation observed. Notice the additional point located at 1625 lbf, or 77% UTS, in Table 14. This point was added after the first set of tests was completed in order to increase the resolution on the lower end of the long term loading plot. The average breaking times, as well as their standard deviation and coefficient of variation, are shown in Table 15. The original data can be found in Appendix A.

Table 15 - 2x2 Vectran Fabric Fill Direction Long Term Loading Break Times

Load (lbf)	% UTS	# Specimens	Average (min)	Stdev (min)	C.V.
2271	100%	5	0.01	-	-
2000	88%	4	0.70	0.16	23%
1950	86%	4	1.31	0.65	50%
1900	84%	4	2.87	2.18	76%
1850	81%	5	4.23	2.96	70%
1800	79%	5	3.07	1.86	61%
1750	77%	8	48.68	44.74	92%
1700	75%	6	80.71	47.37	59%
1650	73%	6	111.40	89.88	81%
1625	72%	5	847.60	461.43	54%
1600	70%	7	1021.12	1029.89	101%

The average breaking time for 100% UTS is recorded as being 0.01 minutes rather than 0 minutes so that a logarithmic trend line of the data can be made. The load for 100% UTS is the result of quasi-static testing. These results can be found in Section 3.1.2. The breaking times are plotted against the %UTS with the raw data in Figure 46.

Figure 46 - 2x2 Vectran Fabric Long Term Loading

4.3.3 – Discussion

An extremely large coefficient of variation was observed in the test sets as seen in Table 15. While some possible causes for this variation were identified in the quasi-static discussion, these effects were minimized as specimens were more carefully prepared and installed in the

testing machine. Once all preparation and installation issues were considered, the machine was checked for consistency.

Since creep strain information was of no concern, the machine was programmed to only record the initial loading time and break time, discarding any feedback from the sensors between those times. Recording the time, displacement and load for hours at a time would produce an abundance of useless data as only the breaking time is needed. To gain an understanding of the actual forces being observed in the specimen through time, the machine was setup to record the time and load at 0.25 Hz for a long term load test run. In order to conserve material, Ferrari fabric was tested at 350 lbf until failure in the specimen occurred. This data was then plotted as shown in Figure 47.

Figure 47 - Ferrari Fabric Long Term Loading on MTS

Notice the large spikes throughout the data showing load peaks of up to 404 lbf and dips as low as 312 lbf. Smaller oscillations fill the plot at nearly 2 cycles a min with amplitudes higher than 2 lbf, creating a total of over 3,500 cycles over the total loading span - 8% of those being larger than 5 lbf. Vectran woven fabric is known to fail much quicker when subjected to a

cyclic load rather than a static load [16]. A mix between cyclic loading, and large spikes in the load, could be some of the causes of the large observed coefficient of variation in the test specimens. These results caused long term loading to be immediately discontinued on the MTS, and all data to be considered only preliminary.

Upon closer inspection of the specimens, it was later found that fibers were affected by the pressure of the wedge grip. Though separation of the specimens appeared near the center of the gage length, the actual breaking of the fibers occurred at the location of the grips in every test run performed. Specimens were closely observed, and fully separated into two pieces by breaking the coating which remained after the breaking of the fibers. Such a specimen is shown in Figure 48. Notice that the division of the two halves is clearly not at the location of the grips, yet the fibers themselves broke directly at the location of the upper and lower grips as indicated by the black lines.

Figure 48 – 2x2 Vectran Long Term Loading Specimen

From the preliminary results it appeared that the use of servo-hydraulic or electro-mechanical testing machines is not suitable for long term loading since these machines require control systems to actively seek out a desired load rather than directly applying loads. A new testing machine was created in order to reduce the variability and to minimize spikes and cyclic loading on the specimens.

In addition, new testing grips were created to reduce stress concentrations on the specimens. While ASTM D5035 allows for breaking at the grip for specimens observing necking, necking breaking does not seem to be the cause of the breaking for these specimens.

New grips were proven by not only breaking specimens in the gage length, but also by breaking fibers within the gage length.

4.4 – Long Term Loading Frame

4.4.1 – Background

Long term loading characteristics for Vectran fabric are desired for breaking times in the range of 8-10 weeks for meeting the requirements of the concept developed by WVU, and ASTM standards for the tensile testing of textiles require 5 correctly broken specimens for each data point [34][37]. Thus, in order to properly characterize Vectran fabric for times ranging from quasi-static instantaneous breaks to 8-10 week creep rupture breaks with an appropriate resolution, many sets of tests should be performed. Testing a single specimen at a time will require years to complete the results, consequently it is desired that multiple tests be performed simultaneously to save time.

Today a number of industrial solutions are offered for tensile testing fabrics. The use of servo-hydraulic or electro-mechanical testing systems is the preferred method of testing. Using a machine with a constant rate of extension, constant rate of traverse or constant rate of loading is the method recommended by ASTM standards [34][35][36][37][38]. However, these machines are costly and require extended time for shipping and initial setup. A new machine with a reasonable cost and initial setup time is desired so that testing can be initiated in a timely manner. Table 16 below shows the time and cost values for a number of long term loading frames including the one developed in this work. The approximate cost per specimen is found by dividing the total cost of the loading frame, by the number of specimens it is capable of testing simultaneously. The time to use is composed of shipping time and initial setup time estimated by the manufacturer.

Table 16 – Load Frame Comparison		
	Cost / Specimen	Time to Use
Instron ¹	\$20,000	14 Weeks
MTS ²	\$100,000	90 Days
SDL Atlas ³	--- Not Available ---	
In-house	\$1,000	10 Days

1 - Verbal Estimate from Instron Engineer for Dead Weight System

2 - Email Estimate from MTS Representative for Hydraulic System

3 - Email Discussion with Multiple SDL Atlas Representatives

In order to prove the accuracy of a testing machine, the force was verified using ASTM standards. There are three methods of verifying the output force of a machine: First is the “use of standard weights”, second is the “use of equal-arm balances and standards weights”, and third is the “use of elastic calibration devices [39]”. The first method is only intended for vertical systems and should not be used for a horizontal loading system. The second method is designed specifically for hardness testing machines and is not recommended for other types of machines. The third is the preferred method for the testing involved in this work. The tools required to perform this test are further discussed in ASTM E74 [40].

4.4.2 – In-house Loading Frame

The loading frame was designed to fulfill the following requirements:

- Apply loads up to 2,000 lbf on a single specimen.
- Maintain uniform loads through time and displacement.
- Test a minimum of 5 specimens at a time.
- Maintain rigidity preventing load noise between test specimens.
- Horizontal testing to allow for specimen submersion in future testing.

In breaking the design down part-by-part, these requirements are fulfilled. A gear box was used to create a mechanical advantage reducing the actual applied force required. In order to further reduce this force, a winch setup was used, adding the extra component of a moment arm. Both the gear box and the moment arm were specially chosen for this specific application.

Spur gears failed to consistently transmit the high loads because of a binding effect that was observed as a result of the small contact area between the gears. Linearly increasing the input force, a gear box containing spur gears will produce an output force which could be roughly characterized by a sine wave with a linearly increasing slope. Reducing the size of the teeth on the gears was found to decrease the effects of binding, but did not eliminate them. Helical and herringbone gears were both considered for a time, but neither were used because of the high prices and manufacturing times involved.

The best solution for this application was found to be the use of a worm gear. It did not produce the wave effect with the output load, though some binding was still observed at high loads. A premade hand winch was purchased, where the gears were already prepared to drive

a wire rope drum. This allowed a quick and easy four bolt installation of the gear box, and the ability to transmit the applied force through flexible wire rope to any desired location.

In order to apply a uniform load through time, Newton's second law was used. By simply attaching a constant mass to the gear box, gravity was used to assist in producing a constant input force, independent of time. However, the force was also required to remain constant with respect to displacement.

Strain and relaxation in the material caused a linear displacement in the wire rope, in turn causing angular displacements in the gear box. Due to the gear ratio, a small angular displacement in the output shaft caused large angular displacements in the input shaft. Since the assistance of a moment arm was being used on the input shaft, this moment arm received these large angular displacements, causing full rotations in the arm when the wire rope observed only small linear displacements. As the moment arm rotated, its angle with respect to gravity also changed, causing the moment, M , to gradually approach zero as shown in the equation below and in Figure 49 (A).

$$F = ma$$

Where: m = mass, a = acceleration of gravity = g , F = resulting force

$$M = r \times F = r \times mg = rmg \sin \alpha$$

Where: M = moment, r = arm length, mg = weight, α = angle between the arm and gravity

By replacing the moment arm with a pulley, a right angle between the moment arm and the applied force through the act of displacement was guaranteed as depicted in Figure 49 (B). In order to maintain the location of the applied force on the pulley, the pulley was wrapped with a wire rope, and the weight attached to the wire rope.

Figure 49 – A) Moment Arm, B) Pulley

Since we knew that the vertical displacement of the weight will be much greater than the horizontal displacement of the specimen, the winches were placed at a height such that the weight did not make contact with the floor too quickly. Using the circumference of the winch as the height ensured that once the weight makes contact with the floor, the wire rope could be wound around the pulley once more, returning it to its original position. The width of the loading frame was primarily determined by the total length of the specimen including the grips and other mounting hardware. A preliminary sketch is shown in Figure 50.

Figure 50 – Preliminary Frame Design

The beam holding the winches observed forces primarily in the y direction, and two small moments were observed about the z-axis, one between the input force and the center, the second between the output force and the center. The input force was considered negligible because of its size. In order to ensure that the moment from the output force was negligible, the force was placed very close to the center of the beam. This design allowed for the use of an H-

beam for mounting the winches. In addition to reducing the weight of the frame, this design allowed for easy access to the top and bottom of the surface on which the winches were mounted. The use of a square beam here would have made it extremely difficult to mount the winches.

The previous simplifications in the design allowed the supports holding this H-beam to assume the observation of only compression forces. In an effort to simplify the fabrication of the final product, these compression beams were made of the same H-beam. As seen in the final design, small horizontal legs were also constructed of this beam.

The beams running perpendicular to the specimens observed large forces in both the x and y directions. These beams were used to redirect the output force by 90°. They observed a positive force along the y-axis from the winch, and a positive force along the x-axis from the specimen. The beams also observed a moment about the z-axis, since the load applied in the y-axis was not centered on the beam. Square beams were chosen here to increase the inertia about both the x and y axes.

The beams running parallel to the specimens observed compression forces and a moment about the z-axis. While H-beams could have been used here, square beams were used to add rigidity in all directions.

While evaluating the beams, it was noted that the design criteria was not dependant on yielding, but rather deflection. For this frame it was important that displacements were kept to a minimum, since a movement as small as 0.125" could result in a significant increase in load for 4x4 Vectran woven fabric.

$$\sigma = \varepsilon E = \frac{0.125 \text{ in}}{3 \text{ in}} \times 39,805 \text{ pli} \times 1 \text{ in} = 1,659 \text{ lbf}$$

Preliminary designs were made using Wildfire Pro/Engineer in order to check points of concern and to reveal any unforeseen complications with the configuration. Points of concern included the winch bolting pattern on the H-beam, the pulley clearance against the H-beam, the wire rope path through the H-beam / around the pulley / through the square beam, the acceptable pulley diameter range, and the pulley mounting location. The original design mirrored the setup about a center square beam allowing for two sets of tests to be simultaneously performed, while minimizing load noise between the test sets. Figure 51 shows this original design.

Figure 51 – Original Loading Frame Design

While the items in this design do not appear out of the ordinary, not all of them can be purchased as stock items. The pulley used as a moment arm on the winch requires a diameter of 16" in order to provide the necessary output forces with a weight that can be lifted by hand. Since pulleys larger than 10" are not available commercially, one was locally manufactured using a 16" bike rim slightly modified to serve the purpose of the design.

The pulley used to change the direction of the output load at the base of the frame required a robust design. Standard sleeve bearing pulleys could not be purchased in a flat mount block configuration for loads higher than 3,000 lbf. Though this appears to greatly exceed the required design standards, we will be using the pulley at a 90° angle. This means the observed load in the pulley is:

$$F_{pulley}^2 = F_{wire}^2 \times 2(1 + \cos \theta)^2$$

$$F_{pulley} = 2000 \times \sqrt{2} = 2828 \text{ lbf}$$

leaving a factor of safety of only 1.06.

The solid, stainless steel pulley is not the limiting factor in this design. The mild steel shaft and block housing were the limiting factors for the rated strength of the flat mounted block pulley. By replacing the shaft with a grade 8 bolt, and replacing the block housing with 0.375" steel angle iron, the pulley was quickly upgraded.

The wire rope used for transferring the load from the winch to the specimens was carefully chosen. Using a wire rope with too large of a diameter can reduce the output force from the winch in addition to being difficult to work with. Stiff materials such as stainless steel are deformed by the small radius of the winch drum and pulley, causing the resulting load to vary. Materials too soft can experience creep strain creating additional problematic variables during long term loading. For this setup, a galvanized steel wire rope with a 0.25" diameter and a max load rating of 7,000 lbf was used, as was recommended by the manufacturer of the winch.

In order to accurately measure the load being transmitted to the specimens, a hydraulic scale was mounted between the winch and the pulley which is used to redirect the applied load. Since the scale was not mounted directly in line with the specimen, it was important to know the exact mechanical loss being observed in the pulley between them. Rather than attempt to predict this loss, it was simply measured and taken into account.

Since the applied load was observed using an analog method rather than a digital method, it was important that a system for observing the time to failure was created. In order to reduce cost, setup time and data acquisition, a surveillance camera was used to observe the specimens. This allowed a single sensor to measure all 5 specimens simultaneously, in addition to revealing environmental effects on the specimens or loading frame. Construction of the final loading frame is shown in Figure 52 and Figure 53.

Figure 52 – Final Loading Frame

Figure 53 - Loaded Specimens

4.4.3 - Loading Frame Verification

Using ASTM E4 as a basis, the loading frame was tested for repeatability. According to the standard, test machines exhibiting accuracy or repeatability errors larger than 1% “do not comply with Practices E4 [39].” Verifications loads were calculated as directed in the standard, and winch 4 was loaded 5 times for each load. Table 17 contains the results, and the equation for calculating repeatability is shown below.

$$Repeatability = \frac{F_{max} - F_{min}}{F_{desired}}$$

Table 17 – Force Verification of Loading Frame

Test #	200 (lbf)	400 (lbf)	800 (lbf)	1400 (lbf)	2000 (lbf)
1	200	403	800	1402	2002
2	202	390	800	1402	1997
3	201	399	790	1405	2006
4	200	402	780	1417	2008
5	202	393	790	1409	2003
Max	202	403	800	1417	2008
Min	200	390	780	1402	1997
Repeatability Error	1.00%	3.25%	2.50%	1.07%	0.55%
Average Repeatability Error	1.67%				
Maximum Repeatability Error	3.25%				

From this table we find that the average repeatability error is 1.67% and the maximum is 3.25%. The hydraulic loading scale has an accuracy of 2% according to the manufacturer. The manufacturer’s documentation is attached in Appendix B. This means that neither the accuracy nor the repeatability meet the requirements of ASTM E4. However, the standard acknowledges that users may allow larger error systems. Since the main focus in building this frame was to decrease testing time and eliminate cyclic loading and stress concentrations, this error was considered to be acceptable.

4.5 – Long Term Loading Material Grips

4.5.1 – Background

Since the focus of the testing is to eliminate the need for multiple Servo-hydraulic or electro-mechanical testing systems, machine powered grips cannot be considered. Externally powered hydraulic, pneumatic and advantage wedge grips and clamping grips are also available in industry and have proven themselves to work in quasi-static applications. However, in-house testing has shown that stress concentrations prohibit their use in long term load tests. According to ASTM standards, the specimens must be discarded due to the location of their break (in contact with the grips) [34]. A variety of grips are readily available for testing a single yarn [41][42][43][44]. Nonetheless, from the literature review we understand that all tensile testing is to be performed with a cross section of 1 inch in order to properly characterize the woven fabric. Finally, special self-tightening grips are available for testing fabric specimens. However, MTS does not make grips with a load capacity high enough for testing the tensile strength of a one inch specimen of Vectran woven fabric (2300 lbf for this instance) [42].

Specialized businesses such as MTT, LLOYD, Tinius Olsen and Instron offer grips which meet the loading capacity required. MTT offers an offset split drum style capstand grip set which is designed and constructed according to ASTM standards [45][46]. This grip features a mechanical wedge which is tightened by compression forces created as tension is applied to the specimen as shown in Figure 54. Instron offers a similar grip with the ability to rotate the drum nearly one rotation after the specimen is installed. This additional feature does not increase the contact area between the specimen and the grip, though it does make specimen installation much easier [41]. Figure 55 shows the Instron grip in use.

Figure 54 – MTT Grip Featuring Self Tightening Ability [45]

Figure 55 – Instron Grip Featuring Self tightening and Single Rotation Abilities [41]

A similar design referred to as a split bollard locking ratchet tensile grip is offered by LLOYD [43]. This grip provides the same self tightening technique but adds the ability to wrap the sample multiple times using the ratcheting feature, as shown in Figure 56. Initial testing has shown that without enough wraps around the drum, Vectran material still breaks at the entrance of the split drum due to stress concentrations. This is a result of high strength, brittle properties and insufficient frictional forces. Though the ratcheting grip can fix this problem by allowing the sample to be wound, they have been discontinued and can no longer be purchased. Due to the complexity and strength requirements of the inner working mechanisms of the ratcheting grips, they cannot be easily manufactured by a local machine shop.

Figure 56 – LLOYD Grip Featuring Self Tightening and Ratcheting Abilities [43]

SDL Atlas, LLOYD and Tinius Olsen offer one more grip which meets the required loading capacity called a double bollard grip [43][44][47]. This is the same type of grip that was used by Scarborough et al. (2008) for Vectran creep testing [15]. While these grips have been proven to work they have some setbacks for this application. These grips are expensive and require an extensive waiting period for their arrival. They could be fabricated, but they require more than twice as much material and machine time than the in-house designed grips. A time to use and cost comparison is shown in Table 18, where the time to use is composed of the manufacturing and shipping time estimated by the manufacturer.

Table 18 – Time to Use and Cost of Grip

	Cost / Specimen	Time to Use
Lloyd ¹	\$2,258	1-2 Weeks
MTS ²	--- Not Available ---	
SDL Atlas ³	\$1,327	10-12 Weeks
In-house	\$100	1 Week

1 - Email Estimate from Lloyd Representative

2 - Email Conversation with MTS Representative

3 - Email Estimate from SDL Atlas Representative

4.5.2 – In-house Grips

Figure 57 – In-house Material Grip Design

The grip shown in Figure 57 was constructed from aluminum tubing in order to reduce weight and fabrication time. Harder materials such as steel were found to be heavy and difficult to fabricate with the dimensions required. An outer diameter of 1.5" provides sufficient surface area to reduce stress concentrations and produce adequate frictional forces. A thickness of ¼" provides the required strength for testing at loads in excess of UTS (2300 lbf). This thickness is also required to create a smooth, uniform surface that prevents stress concentrations. Smaller wall thicknesses have been shown to both cut and tear the fabric far before reaching the desired load. Width requirements are calculated providing 1.5" for the fabric specimen, and 1.25" for mounting hardware on either side. This gives a total width of 4" for the grip. Figure 58 shows the details of the material grips.

Figure 58 – In-house Material Grip Drawings

The machining process consisted of three main categories. First, the tubing was cut to length using a band saw. The edges were trimmed and smoothed with the assistance of an angle grinder and a flapper wheel. Next, using a drill press two holes were carefully drilled perpendicular to the same tangent surface, such that they were centered through the tube.

These holes had a diameter of 0.375" centered at a distance 0.5" from either edge of the tube. Both holes passed through the entirety of the tube.

Finally slots were made in the tube for inserting the fabric specimen. Using an end mill bit with a diameter of 0.125", these slots were milled into the tube perpendicular to the mounting holes. Next, the tube was rotated 45° clockwise, and the end mill bit was lowered to the edge of the slot, moving across the length of the slot such that the sharp edge was removed. Figure 59 (A) shows the resulting 45° edges that were created. The process was only performed on one of the two slot edges. Rotating the tube an additional 125° clockwise, now sitting 180° from the first slot, the entire process was repeated.

Finally, the tube was firmly mounted in a vice, pressing along the axis to avoid deformation or abrasion of its surface, and a coarse sand paper was used to smooth the two 45° edges remaining from the milling process. The sliced view of the final tube is shown in Figure 59 (B).

Figure 59 – Sliced View of Bollard Grip: A) After Milling, B) After Sanding

After completing the fabrication process, mounting hardware was installed. Two bolts were inserted, each 2.75" long with a 0.375" diameter. The bolts were chosen for their tight fit within the tube, preventing twisting of the tube caused application of the load. With the assistance of a washer, a single chain link was tightened between each bolt head and the tube.

Again, this component was tight enough to prevent play. Each chain link was then attached to a quick release, allowing the tube to be swiftly mounted. Together these components made up the bollard grip used for testing.

Two grips are required to hold each specimen, one at either end. The grip at the base of the specimen was mounting to an eye bolt. This grip will required a shackle because of the large diameter of the eyebolt on which it was mounted. The grip at the top of the specimen was mounted to a wire rope. Since wire ropes have a tendency to rotate under the application of high loads, it was important to prevent this rotation from reaching the test specimens. Thus, the grip was mounted to an eye and eye swivel, allowing the wire rope to rotate freely without affecting the specimen. The grip setup in its entirety is displayed in Figure 60.

Figure 60 – In-house Bollard Grip Setup

As with the MTS wedge grips, the bollard grips required padding. It was found that the best padding was actually Vectran woven fabric itself. In order to minimize the amount of fabric used for each test run, a number of wrapping techniques were tested. The most efficient specimen preparation technique is described in the procedure section of this chapter. A specimen fully prepared for loading is shown in Figure 61.

Figure 61 – Specimen Prepared for Loading

4.5.3 – Grips Verification

After completing the grips, it was important to prove their effectiveness to properly break specimens. First the grips were installed on the MTS machine and used to perform quasi-static testing using 4x4 Vectran. Using the same system that the original quasi-static testing was performed on, all variables remained constant except the grips themselves. A full test set was performed with the results shown in Table 19.

Table 19 – 4x4 Vectran Warp Direction Quasi-Static Grip Test

Specimen #	Load (lbf)
1	2397
2	2338
3	2320
4	2395
5	2317
Average	2353
Stdev	40
C.V.	1.69%

Notice that the average strength (2353 lbf) in Table 19 is in the same range as the warp direction tested with the wedge grips (2319 lbf), and the coefficient of variation (1.69%) is smaller than that observed with the wedge grips (5.6%) as shown in Table 7. This proves that the grips are capable of being used at high loads without the observation of slipping or stress concentrations.

Next, the grips are used for long term loading to check the location of failure in the specimens, and to ensure that fibers are not breaking at the location of the grips. These tests were performed on both the long term loading frame and MTS. For 35% of the tests performed, the material did not observe any broken fibers near their contact with the grip (Figure 62 (A)). The remaining 65% of the specimens which did observe broken fibers at the location of their contact with the grip (Figure 62 (B)) were found to exhibit similar breaking forces as those which did not break at this location. With this being the case, all broken specimens were considered valid for characterizing the material. While not all specimens broke between the grips, specimens that did observe breaking between the grips also observed fiber breakage between the grips. This was a significant improvement compared to the wedge grips.

Figure 62 – 4x4 Vectran Fabric Long Term Loading with In-house Grips:

A) Failure in Gage Length, B) Failure at Grip

4.6 – Long Term Loading - 4x4 Vectran Fabric Warp Direction

4.6.1 – Procedure

All test specimens were tested in the warp direction for 4x4 Vectran fabric long term loading. Woven fabric was cut into pieces with a warp direction width of 10 basket weaves, or 40 yarns, and a fill direction length of 35". An entire basket weave (4 yarns) was removed from the length on one side of the specimen, and half of a basket weave (2 yarns) from the opposite side. This left a total of 1" (34 yarns) remaining in the warp direction. The specimen was then marked 16" from either end, revealing the 3" gage length in the center. Special care was taken not to damage fibers when marking the gage length by gently applying a felt tip marker. Sometimes a pen was used, but it is not advisable.

Once a full test set was prepared, all 5 specimens were installed on the bollard grips. The first step towards installing the specimens on the grips was correctly orienting the grips and installing the padding (a 1" x 15" piece of Vectran woven fabric). The correct orientation is shown in Figure 63. The padding was then extended from the back of the grip a distance of 4.75", and the specimen 5", the padding on the bottom and the specimen on top.

Figure 63 –Specimen Installation on Bollard Grips

Both the padding and specimen were tightly wrapped around the grip such that the gage length began just before the mounting hardware. This was done to allow for additional

tightening in the wrapped material upon application of the load, which will increase the total gage length. Figure 64 shows the specimen just after tightening. Electrical tape was used in order to prevent the specimen from unraveling from the grip before it was installed on the loading frame.

Figure 64 – Long Term Loading Specimen on Loading Frame

Once the specimens were fully prepared, it was important to prepare each loading setup individually. This was due to observed variations in the mechanical efficiency of the winches and pulleys as well as the accuracy of the scales being used. Before using the winches, a full rotation was applied through the gear box in order to fully lubricate the gears.

In some hydraulic scales it was found that the needle indicating the observed force would stick at high loads after the force was decreased, displaying forces up to 100 lbf too high. In order to prevent this error, the desired force was always approached from below and was not exceeded. If the desired force was accidentally exceeded, the load was fully removed, and the desired load was once again applied.

In order to calibrate the scale being used during testing, a second scale was mounted in place of the fabric specimen. Slowly, a load was applied by hand, turning the moment arm until the desired load was observed on the scale in place of the fabric specimen. Next, the scale being used during testing was observed, and its load recorded. In this way, each pulley was individually normalized for its unique mechanical inefficiency. By using the same scale in place of the fabric specimen for each calibration, the inaccuracy of the scales was also reduced to a

single scale. If different scales had been used, some could have accuracy errors on the upper range (2% too high), and others on the lower range (2% too low), resulting in a total error of 4%, rather than 2%.

In order to eliminate differences in the mechanical efficiency of the winches the weight required to produce the desired output load was uniquely determined. A first estimate of the weight was quickly calculated, using the overall mechanical advantage of the winch and moment arm. Trial and error was used from this point, until the exact desired weight was found to produce the desired output load on the scale. The resolution of the change in weight for this system was 0.5 lbf.

After all scales and weights were prepared, the specimens were installed and loaded. Careful consideration was used to check each specimen for alignment and twist before/while applying the desired load. As the load was applied, specimens observed a twisting motion resulting from the wire rope construction. This was corrected immediately.

While many loads were smoothly and accurately applied initially, high loads (over 1,800 lbf in the specimen) observed some binding / sticking in the gears after they had been static for a short time. In order to maintain the desired load, it was important to assist the winches in overcoming this obstacle by periodically breaking them free. For lower loads, winches may not observe this binding effect unless the gears remain static for times greater than a few hours. It was important to record which winch was being used for each test so that winches of ill repute could be replaced and their data discarded.

4.6.2 – Results

The times to creep rupture for 85% UTS, 80% UTS and 75% UTS specimens are summarized in Table 20, Table 21 and Table 22 respectively. Rather than simply testing two test sets, data was collected until two test sets worth of valid, useful data was collected. For each voided specimen a new specimen was tested in order to replace it. Specimens were only voided if it was proven that an incorrect load was applied, or if excessive binding in the winch prohibited the correct load from reaching the specimen for long periods of time.

Table 20 - 4x4 Vectran Warp Direction Long Term Loading at 85% UTS

Sample #	Time to Creep Rupture		
	min	hrs	days
1	14	0.23	0.01
2	13	0.22	0.01
3	30	0.50	0.02
4	33	0.55	0.02
5	12	0.20	0.01
6	67	1.12	0.05
7	30	0.50	0.02
8	20	0.33	0.01
9	55	0.92	0.04
10	79	1.32	0.05
Average	35	0.59	0.02
Stdev	24	0.40	0.02
C.V.		67.4%	

Table 21 - 4x4 Vectran Warp Direction Long Term Loading at 80% UTS

Sample #	Time to Creep Rupture		
	min	hrs	days
1	421	7.02	0.29
2	50	0.83	0.03
3	71	1.18	0.05
4	59	0.98	0.04
5	662	11.03	0.46
6	309	5.15	0.21
7	1080	18.00	0.75
8	229	3.82	0.16
9	1032	17.20	0.72
10	960	16.00	0.67
Average	487	8.12	0.34
Stdev	415	6.92	0.29
C.V.		85.2%	

Table 22 - 4x4 Vectran Warp Direction Long Term Loading at 75% UTS

Sample #	Time to Creep Rupture		
	min	hrs	days
1	18975	316	13.18
2	10735	179	7.45
3	19503	325	13.54
4	4734	79	3.29
5	4967	83	3.45
6	4869	81	3.38
7	3172	53	2.20
8	1618	27	1.12
9	2773	46	1.93
10	5823	97	4.04
Average	7717	129	5.36
Stdev	6542	109	4.54
C.V.		84.8%	

The time from each table was used to create %UTS vs. time plots where the raw data is shown in Figure 65. Again, quasi-static results were placed at the point 0.01 min, 100% UTS. Testing at 90% UTS was performed using an MTS system with the in-house material grips, because breaking times were in the same range as the time required to apply the 90% UTS load using the loading frame, causing excessive user error. Since breaking times for 90% UTS testing were low (less than 1 minutes on average), the unintentional loading observing from MTS systems was considered negligible, and the break times were used with the loading frame results to develop a new long term loading model. This topic is further discussed in Section 4.7, where 4x4 Vectran long term loading using MTS systems is presented.

Figure 65 - 4x4 Vectran Warp Direction Long Term Loading

4.6.3 – Discussion

While the new testing method did not significantly decrease the variability between the specimens for each test set, great advancements were made in testing creep rupture times. These advancements can be better explained with the assistance of a plot. Though the two Vectran fabrics had different tensile strengths, they were composed of the same fibers and should display similar (not identical) long term loading results when plotted using a % UTS rather than a specific load. The two sets of data are displayed together in Figure 66, where the average for each loading point is also plotted.

Figure 66 - 2x2 Vectran vs. 4x4 Vectran Fabric Long Term Loading

Notice that the 2x2 Vectran fabric testing results do not appear to fit the trend line as accurately as the 4x4 Vectran results. Though the actual character of the curves is unknown, it is unlikely that the 2x2 Vectran fabric is being accurately represented by this trend line. Take special note of the points located at 81% UTS and 79% UTS, where the experimental data actually predicts a shorter creep rupture time for the specimens observing a decreased load (79%).

Figure 66 also shows that the 2x2 Vectran results influence the trend line to deviate much further from 100% UTS than the 4x4 Vectran results. From Figure 65 and Figure 46, respectively, the failure rate of the 2x2 Vectran (0.0543) is found to be higher than that observed for 4x4 Vectran (0.0405), as is observed by slope of the two trend lines in Figure 66.

For 4x4 Vectran testing, using the new bollard grip and loading frame, systematic and seemingly accurate results are represented with the $\log_{10}$ equation:

$$y = -0.0405 * \log(x) + 0.9036$$

with a coefficient of determination of, $R^2 = 0.9494$. It is important to notice that the fitting equation has units of %UTS for y , and units of minutes for x .

Inversion of the fitting equation provides an exponential equation, providing the breaking time as a function of the applied %UTS.

$$\frac{y - 0.9036}{-0.0405} = -24.6914 * y + 22.3111 = \log_{10}(x)$$

$$x = 10^{-24.6914*y+22.3111}$$

Using this inverted equation in combination with the known inaccuracy of the testing frame, range of variability can be evaluated.

The fitting equation is created using the average of the creep rupture times. If it is assumed that the actual creep rupture time is located perfectly in the center of the error, thus being equal to the average, then it could also be assumed that the error is averaged out resulting in a fitting curve that perfectly represents the results. Working under this assumption, the known error in the loading frame can be used in combination with the fitting equation to predict the expected high and low creep rupture times produced by the frame.

The accuracy error of the frame is predicted to be 2% limited by the accuracy of the testing scales. The repeatability error is on average 1.67% limited by the loading system. Though sometimes these errors may be smaller, or may cancel each other out, the maximum expected error in the system can be predicted by adding the two. For 85% UTS these errors can be characterized by observing a total predicted error of 3.67% between high and low peaks.

$$F_{high} = 85\% + \frac{3.67\%}{2} 85\% = 86.56\%$$

$$F_{low} = 85\% - \frac{3.67\%}{2} 85\% = 83.44\%$$

Simple substitution into the inverse fitting equation gives:

$$x_{low} = 10^{-24.6914*0.8656+22.3111} = 9 \text{ min}$$

$$x_{high} = 10^{-24.6914*0.8344+22.3111} = 51 \text{ min}$$

$$Range = x_{high} - x_{low} = 51 \text{ min} - 9 \text{ min} = 42 \text{ min}$$

These calculations can be summarized by the plot shown in Figure 67.

Figure 67 – Predicted Error Range

By performing these calculations on the rest of the specimens Table 23 was created. Table 24 shows the corresponding maximum and minimum breaking times, and the range between them, for the experimental data.

Table 23 - Predicted Time Error Resulting From Loading Frame Errors

% UTS	High % UTS	Low % UTS	Low Time (min)	High Time (min)	Range (min)
85%	87%	83%	9	51	42
80%	81%	79%	157	833	676
75%	76%	74%	2836	13565	10728

Table 24 – Observed Experimental Time Range

% UTS	Low Time (min)	High Time (min)	Range (min)
85%	12	79	67
80%	50	1080	1030
75%	1618	19503	17885

Comparison between Table 23 and Table 24 shows that the known error of 3.67% is predicted to account of approximately 60% of the observed variation in the data. For 85% UTS, this is calculated as follows:

$$\frac{3.67\% \text{ Error}}{\text{Observed Error}} = \frac{42 \text{ min}}{67 \text{ min}} = 63\%$$

This leaves the remaining 40% of the variation to be accounted for in user error, variation within the material, and possibly other unknown factors.

In conclusion, the new testing methods appear to have greatly improved the long term loading results. The new bollard grips significantly reduced stress concentrations and increased specimen alignment. This allowed for more consistent testing and saved a significant amount of time by reducing the number of voided specimens. The new loading frame allowed entire test sets to be tested simultaneously. It also eliminated cyclic loading on the specimens and reduced the number of observed load spikes.

While the coefficient of variation was not significantly improved, the source of a significant portion of the variation has been identified, creating possibilities for great improvements in the future. Also, the accuracy of the plotted data as well as the trend line and its coefficient of determination were substantially increased.

4.7 – MTS Long Term Loading – 4x4 Vectran Fabric Warp Direction

4.7.1 – Introduction

Long term loading at 90% was desired to assist with the creep failure model being produced from the in-house testing frame. For testing of this magnitude, MTS systems were used rather than the loading frame because of the short duration of the tests. Testing at breaking times less than 1 hr was avoided on the testing frame because of the extended application time of the load required for the frame (up to 3 minutes). Although MTS systems had shown the unintentional application of cyclic loading, this affect was assumed to be negligible for test of short durations (under a few minutes).

A new long term loading plot was also desired for MTS systems using 4x4 Vectran with the in-house material grips. Such testing would allow for a direct comparison between the in-house loading frame, and MTS systems.

4.7.2 - Procedure

Specimens for long term loading using MTS systems were prepared identically with those used for the in-house loading frame. The in-house grips were then mounted to the MTS system and used for testing, rather than using the MTS wedge grips. Previous testing has shown that using a single loading ramp to apply the full load results in overshooting the load, causing specimen damage. Consequently, the load was applied in steps, until the full load was acquired. Figure 68 shows the testing procedure used for 90% UTS (2070 lbf) testing, where 1800 lbf is applied in the first 15 seconds, 2000 lbf is reached at 18 seconds, and the full load is reached at 20 seconds.

Figure 68 - MTS Long Term Loading Testing Procedure

4.7.3 - Results

For 90% UTS testing two test sets were acquired, each consisting of 5 specimens. The force vs. time curve for the first test set is shown in Figure 69. For 85%, 80%, and 75% UTS only one test set was acquired since values were only used for comparison, not for modeling.

Figure 69 – 4x4 Vectran Warp Direction Testing on MTS, 90% UTS First Test Set

The breaking time for each specimen is shown in Table 25. Notice that the coefficient of variation for these results is similar to that observed in both the 2x2 Vectran long term loading previously performed using MTS systems, and that observed on the loading frame with 4x4 Vectran. Figure 70 shows a plot of the results and the fitting equation.

Table 25 - 4x4 Vectran Warp Direction Long Term Loading Using MTS Systems

Specimen #		Time to Creep Rupture			
		90% (min)	85% (min)	80% (min)	75% (min)
Test Set 1	1	1.96	8.28	9.72	18.18
	2	0.64	6.22	10.20	181.98
	3	0.35	1.24	116.65	81.78
	4	0.01	1.53	20.25	49.75
	5	0.55	5.03	47.92	11.48
Test Set 2	6	0.89			
	7	1.20			
	8	0.41			
	9	0.53			
	10	2.05			
Average		0.86	4.46	40.95	68.64
Stdev		0.68	3.04	45.08	69.26
C.V.		80%	68%	110%	101%

Figure 70 - 4x4 Vectran Warp Direction Long Term Loading on MTS

3.7.4 – Discussion

Figure 71 was produced by magnifying Figure 69, in order to show the unintentional loading applied by MTS Systems. Notice that cyclic loading of varying amplitudes is observed between test specimens, even during loading. For 4x4 Vectran long term loading, this is the only known difference between testing with MTS systems and the in-house frame.

Figure 71 – 4x4 Vectran Warp Direction on MTS, 90% UTS First Test Set Magnified

Figure 72 shows a comparison of the 4x4 Vectran warp direction long term loading results obtained using MTS systems with those obtained using the loading frame. Both testing systems (MTS and in-house) used the in-house material grips. The effectiveness of the loading frame is further proven by observation of this plot.

**Figure 72 – 4x4 Vectran Long Term Loading in Warp Direction:
MTS Systems vs. In-house Loading Frame**

Observation of Figure 72 shows that MTS systems experienced breaking times much lower than the loading frame. Since the only known difference between the two testing methods is the observed introduction of cyclic loading and loading spikes from MTS systems, the results suggest that these effects are the cause of the lower breaking times. This means that the loading frame greatly improved the characterization of Vectran subjected to long term loading, by reducing the variability of the applied load through the duration of the test. A summary of all long term loading fitting equations from this work is located in Table 26.

Table 26 - Long Term Loading Summary

Material	Direction	Loading System	Grips	Fitting Equation y (%UTS), x (min)	UTS (lbf)
2x2 Vectran	Fill	MTS	Wedge	$y = -0.0543 \cdot \log(x) + 0.8518$	2271
4x4 Vectran	Warp	MTS	In-house	$y = -0.0583 \cdot \log(x) + 0.8774$	2300
4x4 Vectran	Warp	In-house	In-house	$y = -0.0405 \cdot \log(x) + 0.9036$	2300

Chapter 5 - Friction Testing

5.1 - Testing Standards

In order to predict the ability of the inflatable structure to maintain its position in the tunnel without slipping the coefficient of friction is required. A number of standards are available from ASTM for performing friction tests, each attempting to simulate a slightly different contact mode. ASTM G115 provides a list of the available methods provided by ASTM standards as well as supplementary information for friction testing being performed by any method or standard. Using this standard, it was determined that the method for testing a plastic film against a stiff surface would best fit the given application (ASTM D1894) [48].

While some minor modifications were made to ASTM D1894, the procedure discussed in this section follows the general outline and procedure described in the standard. Figure 73 provides the basic layout of the machine used for performing all friction testing.

Figure 73 - Friction Testing Machine

The sled is the surface on which the fabric specimen is located. Above the sled is the load which creates the normal force between the two surfaces. Below the sled is the surface referred to as the plane. The purpose of the test is to determine the friction coefficient between the specimen mounted on the sled, and the predetermined plane.

The sled remains stationary through the entire testing process. The plane is pushed horizontally beneath the sled by the hydraulic cylinder with a constant rate of velocity. Between the hydraulic cylinder and the plane is a load cell, which provides force information to the computer. The linear variable differential transducer (LVDT) sensor is attached to the plate and provides displacement feedback to the computer.

The coefficient of friction is not always independent of the normal force and plane speed [48], so the normal force and speed are provided with each data set.

5.2 - Friction Testing - 2x2 Vectran Fabric

5.2.1 – Procedure

The 2x2 Vectran fabric was mounted to the bottom of a 2"x2" sled with assistance from double-sided foam sticky tape as displayed in Figure 74. Both sides of the single coated Vectran were used for testing producing results for both Vectran yarns and urethane polymer coating. The sled is then oriented such that the motion is parallel to the fill direction of the fibers. The normal force was prepared using two 20 lb weights in addition to the 4.45 lb shaft, providing a pressure of 11 psi. The velocity was preset to 1.16 in/sec and maintained for all testing in this chapter.

Figure 74 – 2"x2" Friction Testing Sled

Different planes were used in order to create a table of friction coefficients for various surfaces. For this report, testing results will be displayed for smooth concrete surfaces coated with anti-skid, asphalt, epoxy and latex as shown in Figure 75, as well as bare surfaces consisting of rough concrete and smooth concrete as shown in Figure 76. All surfaces were tested in both wet and dry conditions. Before each use, surfaces were cleaned using nonabrasive tools and a noncorrosive, low residue fluid. Many specimens were cleaned simply using a sponge and water. Sometimes the use of soap, brushes and other tools was required.

Figure 75 – Coated Surfaces – From Left to Right: Anti-Skid, Asphalt, Epoxy, Latex

Figure 76 – Bare Surfaces – From Left to Right: Rough, Smooth Concrete

Wet testing was also performed using both coated and uncoated sides of the Vectran woven fabric on all surfaces. Every wet test was performed with the sled and plane fully submersed, using fabric and surfaces which were presoaked for a minimum of 24 hrs. Figure 77 shows an image of the wet testing in progress.

Figure 77 – Friction Testing Setup for Wet Conditions

Every test was performed according to the following sequence:

- Mount a clean, dry plane on the machine.
- Mount a new fabric specimen to the sled.
- Place the sled at the pre-established initial point of contact and apply the normal force.
- Perform the first test run.
- Remove the normal force and return the sled to its initial point of contact.
- Reapply the normal force and repeat until a total of 10 runs have been performed.
- Remove the fabric specimen for labeling and storage.

5.2.2 - Results

A sample plot of the force vs. displacement curve corresponding to bare fabric sliding on smooth concrete is shown in Figure 78. This is a typical plot for friction data with a breakaway force near 0.09 inch and slight stick-slip behavior thereafter. The small peak during initial loading is produced by a small bounce in the system caused by initial contact of the hydraulic cylinder with the plane.

Figure 78 - 2x2 Bare Vectran Fabric Against Smooth Concrete

The only combination in this test set which did not exhibit a breakaway force was wet Vectran coated fabric vs. epoxy coated smooth concrete. The first run of this test is displayed in Figure 79. For this case only, this work assumed the static coefficient of friction to correspond with the maximum force in the data. For the data displayed in Figure 79, this occurred at a distance of approximately 0.27 in.

Figure 79 - Epoxy Coated Smooth Concrete Not Exhibiting a Breakaway Force

The breakaway force directly corresponds to the static coefficient of friction, μ , as shown in the equation below.

$$F_{Static} = \mu_{static} N , \quad \mu_{static} = \frac{F_{Static}}{N}$$

Where: F_{Static} = Breakaway Force, N = Normal Force

The kinetic coefficient of friction was of no concern for this work, but could be easily calculated using a number of different methods. The most common calculation is performed using the average force observed directly after the breakaway force as shown below [48].

$$F_{Kinetic} = \mu_{Kinetic} N , \quad \mu_{Kinetic} = \frac{F_{Kinetic}}{N}$$

Where: $F_{Kinetic}$ = Average Force After F_{Static}

For each test (consisting of 10 runs) the breakaway force was found and recorded. These ten values were averaged and divided by the normal force of 44.45 lbf, producing the static coefficient of friction. The first dry run of bare fabric vs. smooth concrete (shown in Figure 78) was calculated as follows:

$$\mu_{static} = \frac{F_{Static}}{N} = \frac{19.53 \text{ lbf}}{44.45 \text{ lbf}} = 0.44$$

The static friction coefficients for wet and dry tests performed on bare Vectran woven fabric are summarized in Table 27, and for coated Vectran woven fiber in Table 28. The tables also include the standard deviation observed between the 10 runs for each test. The original test data can be found in Appendix C.1 and Appendix C.2.

Table 27 - Bare 2x2 Vectran Fabric Static Friction Coefficients

Sample		Ave	Stdev	C.V.
Anti Skid	Dry	0.58	0.03	5.4%
	Wet	0.62	0.03	5.2%
Asphalt	Dry	1.38	0.06	4.4%
	Wet	1.14	0.03	2.5%
Epoxy	Dry	0.28	0.02	8.1%
	Wet	0.34	0.02	5.3%
Latex	Dry	0.47	0.03	7.1%
	Wet	1.01	0.03	2.9%
Rough Concrete	Dry	0.55	0.03	6.3%
	Wet	0.54	0.02	3.1%
Smooth Concrete	Dry	0.44	0.02	3.9%
	Wet	0.38	0.01	3.1%

Table 28 - Coated 2x2 Vactran Fabric Static Friction Coefficients

Sample		Ave	Stdev	C.V.
Anti Skid	Dry	0.56	0.04	7.9%
	Wet	0.43	0.03	6.5%
Asphalt	Dry	1.48	0.09	6.2%
	Wet	0.97	0.04	4.1%
Epoxy	Dry	0.97	0.04	4.5%
	Wet	0.92	0.06	6.3%
Latex	Dry	1.15	0.08	7.3%
	Wet	0.63	0.03	4.7%
Rough Concrete	Dry	0.89	0.04	4.8%
	Wet	0.69	0.02	2.8%
Smooth Concrete	Dry	0.81	0.04	4.4%
	Wet	0.75	0.04	5.8%

Figure 80 - Bare 2x2 Vectran Fabric Static Friction Coefficients

Figure 81 - Coated 2x2 Vectran Fabric Coefficients of Static Friction

For the bare fabric (Figure 80) it can be clearly observed that asphalt and smooth concrete have larger coefficients for the dry condition than for the wet condition. Anti-skid, epoxy and latex produced larger friction coefficients for wet conditions. Rough concrete has similar values for both conditions with a greater standard deviation than the difference between the two. For the coated fabric (Figure 81) all coefficients are noticeably higher for the dry condition. A summary of all tested conditions and fabric surfaces is displayed in Figure 82.

Figure 82 - Multi-Surface Static Friction Coefficients Comparison

5.2.3 – Discussion

For the bare fabric specimens, the asphalt and smooth concrete surfaces observed lower frictional forces for wet conditions compared with dry conditions, as was expected. Unlike any other test, the rough concrete was not noticeably affected by the addition of water. This was the result of the extremely coarse texture on the surface. The coarse texture reduced the surface area and created force concentrations at the few points of contact. These forces were

able to penetrate the fabric, causing frictional forces to be overshadowed by the catching and abrading of the fabric specimens with the surface. Returning to the archive of fabric specimens, this can be seen by observing the wear on the specimens as displayed in Figure 83. The rough concrete was the only surface to produce noticeable wear on the bare fabric specimens.

Figure 83 – 2x2 Vectran Observing Wear from Rough Concrete

The bare fabric tested in wet conditions displayed interesting properties for the anti-skid, epoxy and latex planes. Rather than lubricating the planes, the water caused the frictional forces to increase. For the anti-skid surface, this is explained by observation during testing. The anti-skid surface was softened after being soaked in water and became gummy in texture. The porous fabric allowed the anti-skid material to bond the sled and plane together increasing the frictional forces.

The epoxy and latex can be more easily explained using an analogy. Imagine a porous material such as a sponge in contact with a non-porous material such as plastic. When the sponge is dry, it easily glides across the surface of the plastic. After wetting the sponge the water has a viscous effect causing it to stick to the plastic. Similarly, both epoxy and latex created a smooth, non-porous surface on the plane which caused the water to produce a viscous effect on the porous fabric.

Overall, the coated fabric observed higher friction coefficients for wet conditions, over dry conditions, as anticipated. Despite the force concentrations, rough concrete was not overwhelmed by abrasion forces, as was observed with the bare fabric. Though the anti-skid material once again softened after submersion, the coated fabric did not have a tendency to bond with it because of its slick, non-porous surface.

Similar to the anti-skid surface, the epoxy and latex did not exhibit the same viscous behavior as was observed with the bare fabric. Using the previous analogy, now place a non-porous glass bowl on dry and wet plastic surfaces. You will notice that the bowl slides more easily on the wet surface since the water does not have a tendency to bond as tightly to the non-porous surface. In the same way, the water worked more as a lubricating agent between the two non-porous surfaces as anticipated.

There is no direct correlation between the bare fabric and the coated fabric friction coefficients. The two surfaces are composed of different materials and have different surface characteristics. On average, the coated fabric experienced frictional forces 28% higher than the bare fabric. For rough and smooth concrete alone, the coated fabric experienced 48% higher frictional forces.

5.3 - Multi-Surface Friction Testing - 4x4 Vectran Fabric

5.3.1 – Background / Procedure

Additional testing was desired for 4x4 Vectran using a pressure of 30 psi. Since 4x4 Vectran is coated on both sides, only one side of the material was tested. For this testing, both rough and smooth concrete were used, but no coating was applied to either surface. Again, all testing was performed in the fill direction in order to reduce variables during testing.

In order to meet the new pressure requirements, a new sled was created. The use of a 4 in² (2"x 2") sled would require users to lift 120 lb between every test run. While use of a 1 in² sled would have been ideal for construction and testing, it was suspected that such a small surface area could be noticeably influenced by the sled edges. That is, additional friction might be observed by the catching of the fabric specimen edges with the surface.

A new sled was constructed with dimensions of 1.4"x1.4", providing a surface area of about 2 in². The application of 55 lb in addition to the 4.45 lb shaft provided a normal force of

59.45 lbf, resulting in a normal pressure of 30.33 psi. Because of the significant increase in the normal force, even coated fibers experience wearing during abrasion. As a result, only 5 runs were performed for each test in order to reduce the effect of wearing on the friction coefficients. The remainder of the process was identical to the previously performed friction testing.

5.3.2 – Results

All testing produced typical friction curves as displayed in Figure 84. The average coefficients of static friction are given in Table 29 as well as the standard deviation observed between the 5 runs for each test. A summary of the data is provided in Figure 85. The original data can be found in Appendix C.3.

Figure 84 - 4x4 Coated Vectran Fabric, First Friction Test

Table 29 - Coated 4x4 Vactran Coefficients of Static Friction

Sample		Ave	Stdev	C.V.
Rough Concrete	Dry	0.63	0.03	4.4%
	Wet	0.54	0.01	2.3%
Smooth Concrete	Dry	0.71	0.04	5.5%
	Wet	0.62	0.07	11.5%

Figure 85 - Coated 4x4 Vectran Fabric Static Friction Coefficients

5.3.3 – Discussion

Results show that the dry surfaces experience higher friction forces than the wet surfaces. One unexpected outcome is the higher frictional forces observed in the smooth concrete over the rough concrete.

Figure 86 - 2x2 Coated Vectran vs. 4x4 Coated Vectran Static Friction Coefficients

Although the two types of Vectran are coated with the same material, the processing technique and application thickness appear to have a great effect on the frictional properties of the final product. By plotting the two coated surfaces together (Figure 86), it is shown that the 2x2 Vectran observed higher friction forces in all four cases.

Chapter 6 – Conclusions and Future Work

6.1 –Quasi-static Testing Conclusions

This work has shown that the raveled strip method is the best method of testing for the characterization of Vectran woven fabric tensile properties. The method produced results with a low coefficient of variation (4.9% on average) and no complications (section 3.1.4). Testing with the cut strip method introduced an additional variable into the data without necessity. In this method, specimen preparation often resulted in damaged fibers, slightly reducing the strength of the specimen.

The raveled strip method was also used to experimentally characterize the Young's modulus of Vectran woven fabric. Results consistently displayed two distinct values for the Young's modulus, one for low strain, and another for high strain in the material.

Wet tests were performed for water immersion times up to three weeks at room temperature (70 °F), and results confirmed claims by the manufacturer that the fiber is not influenced by moisture (section 3.3). Crease fold testing was also performed at 100 °F, and 100% humidity with the assistance of an environmental chamber. Specimens were tested using a crease fold pressure of 15 psi for times up to 2 months, and 1 psi for times up to 4 months. It was concluded that differences in crease folding pressure had no effect on the strength of the material. However, a noticeable loss in strength was observed as a result of effects caused by the observed crease fold independent of pressure, and the increased temperature and humidity. While temperature was strongly suspected as the cause, further testing is required before any definitive conclusions can be made.

Modified grab tests did not accurately characterize the strength of the material and will not be used for any additional testing on Vectran fabric. It was concluded that stress concentrations were the source of the error observed.

6.2 – Long Term Loading Conclusions

Testing was performed on 2x2 Vectran using MTS systems and MTS wedge grips for loads down to 70% UTS. Questionable results prompted testing to be discontinued prematurely. Investigating potential causes of variability revealed two significant sources. First, it was determined that the servo-hydraulic loading frame was unintentionally producing loading

spikes, and cyclic loading during testing. Second, the MTS wedge grips were found to produce stress concentrations on the specimens, causing fibers to break at the location of their contact with the hydraulic wedge grips. This occurred even when the specimen appeared to separate in the center of the gage length. Though the grips did not have this affect on specimens broken using quasi-static methods, every long term loading test performed observed this type of failure.

A new loading frame and material grips were designed and manufactured in-house to improve test results. The loading frame eliminated both loading spikes, and cyclic loading, though it introduced a known maximum error of 3.67%. For 35% of the tests performed, the material did not observe any broken fibers near their contact with the grip. The remaining 65% of the specimens which did observe broken fibers at the location of their contact with the grip were found to exhibit similar breaking forces as those which did not break at this location. With this being the case, all broken specimens were considered valid for characterizing the material. Testing was performed on 4x4 Vectran using the new loading frame and material grips for loads as down to 75% UTS.

In an effort to further evaluate the in-house loading frame, additional testing was performed on 4x4 Vectran using MTS systems and in-house material grips for load down to 75%. In the end, it was concluded that the in-house loading frame and material grips greatly improved the characterization of Vectran under long term loading.

A similar variation was observed between testing performed on MTS systems, and testing on the in-house loading frame. However, known sources of error account for much of the variation observed using the in-house loading frame, allowing room for future improvements capable of reducing this variation. It is still desired that the variability within the material be quantified, since at this time sources of error are overshadowing the actual material variability.

6.3 – Friction Testing Conclusions

Friction testing was performed between 2x2 Vectran and 6 different surfaces for both wet and dry conditions. Testing both the bare and coated sides of the 2x2 Vectran, friction coefficients were evaluated under a total of 24 conditions in order to provide a reference chart of values.

Further testing was desired for 4x4 Vectran fabric using only smooth and rough concrete surfaces. For this testing the pressure was increased to 30 psi, and testing was again performed for both wet and dry conditions. Since 4x4 Vectran was coated on both sides, this resulted in only 4 friction coefficients.

6.4 – Future Work

Additional testing is required to determine if the gage length of 3" is adequate for characterizing Vectran woven fabric. Quasi-static testing should be performed on a unique type of Vectran woven fabric (2x2 and 4x4 Vectran may be different) using the raveled strip method for gage lengths beginning at 1" and increasing by 1" incrementally. Testing should be performed until three consecutive gage lengths result in three average strength values whose difference is less than the standard deviation for the test set for each individual gage length. Of the three resulting gage lengths, the middle length should be used for characterizing the unique Vectran woven fabric in question.

It is desired to determine the source of the low strain Young's modulus observed in Vectran fabric. It was suggested that this is the result of construction (yarn twists, fabric weave) effects in the material.

In order to more accurately characterize the repeatability error of the in-house loading frame, additional testing is required. Currently, only 1 of the 5 winches has been testing for repeatability error. Furthermore, only 5 readings were taken for each load step during repeatability testing. Testing all 5 of the winches, with 10 readings for each loading step, would produce a repeatability error which better represents the loading frame.

It would also be useful for testing if the known sources of error in the in-house loading frame could be reduced. The mechanical inefficiencies found in the winches and pulleys are the causes of the observed repeatability error. Upgrading the gears and providing a better method of lubrication could improve the mechanical efficiency of the winch setup. The current winch uses low quality gears, and a self lubricating design which is ineffective when gears remain static. Also, the pulleys could be completely eliminated if the frame was simply changed to a vertical loading setup, rather than the current horizontal configuration. This is due to the load's dependence on gravity, which acts vertically. Accuracy errors are caused by manufacturing limitations with the current scales. Simply upgrading to digital load cells could practically eliminate accuracy error within the system.

Currently, the variability of the material under long term loading is overwhelmed by testing error. If known errors in the loading frame can be sufficiently reduced, it would be beneficial to determine the variation within Vectran woven fabric. It is believed that performing the previously mentioned modifications to the loading frame could allow for the material variability to be truly quantified.

Creating a long term loading model with lower experimental loading values is also desired in order to more accurately predict creep rupture times. Further testing should be

performed for times down to 50% UTS. This would not only allow for better predictions at low times, but it could also improve the higher end of the model by producing more points for the fitting line.

A further analysis of the unintentional loading observed in MTS systems could allow for improvements with MTS testing, as well as a better understanding of the significance of the long term models produced using the MTS. Such an analysis should evaluate the observed frequency and amplitude of cyclic loading, as well as any changes in time, or between tested specimens of the frequency and amplitude. The analysis should also attempt to predict the causes of loading spikes, and record their regularity.

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Appendix A – 2x2 Vectran Long Term Loading Data

2x2 Vectran Long Term Loading Using MTS Systems – Raw Data										
Force (lbf)	2000	1950	1900	1850	1800	1750	1700	1650	1625	1600
% UTS	88%	86%	84%	81%	79%	77%	75%	73%	72%	70%
Breaking Time (min)	0.52	0.69	4.28	6.42	4.42	6.67	38.07	53.08	1280.00	632.38
	0.75	2.22	1.15	1.13	4.62	8.17	140.98	91.50	1278.00	3132.47
	0.90	1.26	0.88	0.87	4.16	65.20	117.87	51.65	724.00	854.00
	0.63	1.07	5.18	6.28	1.53	104.67	81.58	284.97	169.00	48.00
				6.47	0.61	32.95	15.22	127.27	787.00	748.00
						43.53	90.52	59.95		293.00
						7.33				1440.00
						120.88				
Average	0.70	1.31	2.87	4.23	3.07	48.68	80.71	111.40	847.60	1021.12
Stdev	0.16	0.65	2.18	2.96	1.86	44.74	47.37	89.88	461.43	1029.89
C.V.	23%	50%	76%	70%	61%	92%	59%	81%	54%	101%

Appendix B – Loading Frame Scale Documentation

CAUTION!

Avoid sudden shock loading on the scale and sling. Raise and lower all weights smoothly. Rapid acceleration or deceleration of an object adds the object's inertia to its mass, greatly increasing its momentary weight. This can damage the gage.

**SHERLINE
PRODUCTS**
INCORPORATED 1974

SHERLINE Suspended Hydraulic Scale

INSTRUCTIONS FOR USE

Please read all instructions carefully and follow the safety precautions provided. Lifting, weighing and moving heavy objects demands constant attention and the application of good common sense. This scale is intended to be used as an affordable way to determine the weight of heavy items. Gage accuracy is rated at 2-3% of the range of the gage. This means a 2000 lb gage is accurate to within 2% to 3% of 2000 pounds or 40-60 pounds, and a 5000 lb gage is accurate to within 100-150 pounds. For this reason, it would be unreasonable to expect a 5000 lb gage to provide an accurate reading when attempting to weigh a 200-pound item. The percentage of error becomes less significant as the weight increases. Select a gage that is properly suited for the item you are weighing.

RECOMMENDED GAUGE RANGES

CAUTION! Do not use a gage that measures a range over 5000 pounds or ever attempt to suspend weights over that amount from this scale.

For maximum accuracy, use a gage that will put your expected final measurement in about the middle of the gage's range. For example, for weights of about 1000 lb, use a gage that reads to 2000 lb. The gage included with your scale is accurate to within 2% at mid-range and 3% at extreme low or high readings. To provide a gage slightly more accurate would increase the cost of the scale significantly. The supplied gage was chosen as the most cost effective solution to providing a result that is sufficiently accurate for loading purposes.

Gages of different ranges and levels of accuracy are available from Sherline Products. Contact us for more information should you have a specific requirement that is not fulfilled by the gage you now own.

CHANGING GAUGES

To change gages, simply unscrew the installed gage and replace it with another gage which also reads in

PSI. It should have a 1/4" pipe thread fitting. Tip the body of the scale so the hole is up so that no hydraulic fluid is lost when the gage is removed. When replacing the gage, position the cylinder so that the beginning of the round part (just below the area relieved for the

hook and pin) is just above the top of the body. Push or pull it to that position if necessary.

When you install the new gage, lay the body of the scale on a flat surface with the gage hole in the 12 o'clock position (straight up). The fluid level in the threaded gage hole should be right to the top of the hole. If it is not, add a little low viscosity oil, such as 20-weight motor oil. Keeping the hole level, lightly tap the scale body and make sure no air bubbles appear in the hole. Use teflon tape on the gage threads to prevent leakage and reinstall the gauge. Do not overtighten!

LIFTING A WEIGHT WITH THE SHERLINE SUSPENDED SCALE

The Sherline scale was intended to lift a weight only high enough so that it is totally suspended while a reading is taken. It should be removed before swinging the lifted item into its final position. Do not leave a load suspended from the scale longer

than necessary to take a reading.

Always follow these safety rules:

- Before lifting, determine that the weight of the load is within the rated capacity of the scale and lifting chain or sling.
- Inspect chains and slings for damage before using.
- Keep all portions of your body from between the sling and the load and from between the load and the ground.

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2/20/01

Appendix C – Friction Testing Data

All Results collected with a 2"x2" sled, a normal force of 44.45 lbf, and a speed of 1.65 in/sec.

C.1 – 2x2 Vectran Bare Fabric Friction Data

Anti Skid Run #	Friction Coefficient		Latex Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	0.607	0.692	1	0.997	0.571
2	0.512	0.628	2	1.091	0.606
3	0.581	0.587	3	1.149	0.587
4	0.544	0.603	4	1.176	0.631
5	0.626	0.576	5	1.194	0.631
6	0.585	0.634	6	1.040	0.655
7	0.582	0.636	7	1.211	0.648
8	0.591	0.630	8	1.237	0.648
9	0.577	0.604	9	1.189	0.652
10	0.588	0.620	10	1.243	0.640

Asphalt Run #	Friction Coefficient		Rough Concrete Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	1.283	1.119	1	0.557	1.018
2	1.431	1.148	2	0.447	1.011
3	1.386	1.210	3	0.452	1.032
4	1.292	1.119	4	0.435	1.008
5	1.395	1.145	5	0.460	1.005
6	1.400	1.138	6	0.487	0.999
7	1.342	1.135	7	0.465	0.947
8	1.479	1.132	8	0.471	1.029
9	1.396	1.126	9	0.473	0.964
10	1.411	1.108	10	0.465	1.040

Epxoy Run #	Friction Coefficient		Smooth Concrete Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	0.245	0.373	1	0.439	0.411
2	0.287	0.335	2	0.427	0.378
3	0.293	0.323	3	0.436	0.376
4	0.316	0.367	4	0.463	0.393
5	0.303	0.348	5	0.461	0.374
6	0.267	0.322	6	0.430	0.373
7	0.282	0.328	7	0.419	0.394
8	0.287	0.324	8	0.451	0.385
9	0.248	0.341	9	0.442	0.378
10	0.296	0.347	10	0.410	0.384

C.2 – 2x2 Vectran Coated Fabric Friction Data

Anti Skid Run #	Friction Coefficient		Latex Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	0.513	0.467	1	0.997	0.571
2	0.558	0.425	2	1.091	0.606
3	0.490	0.407	3	1.149	0.587
4	0.499	0.403	4	1.176	0.631
5	0.556	0.400	5	1.194	0.631
6	0.604	0.417	6	1.040	0.655
7	0.584	0.426	7	1.211	0.648
8	0.589	0.436	8	1.237	0.648
9	0.586	0.478	9	1.189	0.652
10	0.613	0.460	10	1.243	0.640

Asphalt Run #	Friction Coefficient		Rough Concrete Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	1.308	0.871	1	0.929	0.695
2	1.416	0.946	2	0.850	0.659
3	1.487	0.971	3	0.840	0.653
4	1.497	1.008	4	0.876	0.674
5	1.535	0.972	5	0.852	0.681
6	1.355	0.981	6	0.888	0.696
7	1.522	0.971	7	0.879	0.706
8	1.529	0.998	8	0.973	0.703
9	1.580	1.011	9	0.933	0.702
10	1.581	0.979	10	0.914	0.699

Epxoy Run #	Friction Coefficient		Smooth Concrete Run #	Friction Coefficient	
	Dry	Wet		Dry	Wet
1	0.913	0.860	1	0.766	0.663
2	0.946	0.835	2	0.842	0.698
3	0.968	0.920	3	0.758	0.732
4	0.906	0.913	4	0.826	0.728
5	0.990	0.991	5	0.846	0.742
6	0.952	1.005	6	0.833	0.784
7	0.982	0.845	7	0.831	0.751
8	1.006	0.925	8	0.795	0.811
9	1.019	0.920	9	0.815	0.771
10	1.040	0.961	10	0.755	0.772

C.3 – 4x4 Vectran Friction Data

All Results collected with a 1.4"x1.4" sled, a normal force of 59.45 lbf, and a speed of 1.65 in/sec.

Smooth Concrete	Friction Coefficient	
	Dry	Wet
Run #		
1	0.668	0.541
2	0.670	0.546
3	0.740	0.628
4	0.721	0.692
5	0.751	0.679

Rough Concrete	Friction Coefficient	
	Dry	Wet
Run #		
1	0.616	0.550
2	0.668	0.540
3	0.619	0.522
4	0.641	0.552
5	0.595	0.533