ABSTRACT

CHARETTE, CHRISTINE DISANTO. Evaluation of Army Battle Dress Uniform Fabric Containing an Electrically Conductive Network. (Under the direction of Dr. Abdel-Fattah Seyam.)

Technology is being developed to add a conductive network to the Army Battle Dress Uniform (BDU). To embed the network within the BDU fabric, electronically conductive yarns are located at every ripstop location. To optimize conductivity, fabric construction had to be modified from MIL DTL 44436 requirements. The primary objective of this research was to determine how the addition of the electrically conductive network would change the comfort and durability properties of the BDU. To accomplish this, eleven fabrics of varying fabric constructions with and with and without the network were woven at the College of Textiles, NC State University. These fabrics were then evaluated for any changes in performance in the properties of breaking force and elongation, tearing strength, stiffness, thermal resistance, air permeability and abrasion resistance. The results from each of these tests were statistically analyzing using SAS JMP® software to reveal any property changes as a result of the fabric changes of yarn type, float length and location that were necessary to allow the addition of the network.

Evaluation of Army Battle Dress Uniform Fabric Containing
an Electrically Conductive Network

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Textiles

Raleigh, North Carolina

2009

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BIOGRAPHY

The author was born in Fall River, Massachusetts on November 19, 1976. She is the oldest of two girls born to Robert and Susan DiSanto. The author graduated from Tiverton High School, located in Tiverton, Rhode Island in June 1994. She had a love of sewing and fabric from a young age, making clothing and costumes for friends and family. At age 19, she opened a tailor shop in Middletown Rhode Island. Later, she enrolled in the Textile Sciences program at the University of Massachusetts, Dartmouth. In June 2003, she graduated Cum Laude with a Bachelor of Science Degree in Textile and a minor in Business. In August 2003 she began a career at the U.S. Army Natick Soldier Research Development and Engineering Center located in Natick, Massachusetts. There she works as a Textile Technologist and specializes in Parachutes.

She is married to Raymond Charette and they plan to live happily ever after in Ashland, Ma with their little rescue dog Fergaline.

ACKNOWLEDGEMENTS

Foremost, I would like to thank my advisor, Dr. Abdel-Fattah Seyam, and my committee who provided me with the opportunity to work on this project and shared with me a lot of their expertise and research insight and were always available to me with steady encouragement. I have learned so much from you and from my time at NC State. Thank you.

I am deeply grateful to my chain of command at the U.S. Army Natick Soldier RDEC who made it possible to obtain this degree. I'd like to acknowledge my coworkers who had to pick up some extra work from my absence; I'll make it up to you! I know I am fortunate to have this opportunity and I cannot overstate how much I appreciate it. A sincere thank you is due to Carole Winterhalter and Infoscitex who allowed me to work on this incredibly interesting project. I'd like to thank William Barefoot, NC State, because he has the patience of a saint and because he got that loom going just in time!

My most heartfelt love goes to my little sister Nichole for all those phone conversations and emails that made me laugh! Lastly, and most importantly, I wish to thank and acknowledge my husband, Raymond for all the free IT support and dinners he delivered to the library so I could keep working late into the night. But I especially need to thank him for the unbelievable amount of encouragement, love and patience he has shown me, particularly over the last six months. I couldn't have done this without him!

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CHAPTER 1 INTRODUCTION

Electronic textiles -or more commonly called “e-textiles”- are fabrics that incorporate electronics and interconnections into the fabric construction to create a flow of electricity resulting in a circuit. Traditionally, electronic circuits are created on hard, stiff boards. In the case of e-textiles, the electronic components are embedded or integrated within the fabric and it is the fabric that acts as a flexible base for the circuitry. This flexibility allows the technology to be used in many new and exciting ways that traditional “hard” formats would not allow.

The electronic circuit is created in the fabric through the use of conductive yarns or wires that are used in place some of the regular, non-conducting yarns. In a woven fabric some of the warp or filling yarns may be replaced with conductive yarns in a particular pattern and interconnects can be created between them to form circuits of any desired pattern. Conductive yarns can also be placed directly into knit fabrics using traditional knitting techniques. Nonwoven fabrics can become conductive when wires or sensors are embedded between multiple layers. An alternative would be to have e-yarns embroidered onto the textile after it is woven. [1]

Electrically conductive textiles were first introduced in the 1920’s as an electric blanket. This was nothing more than two layers of blanket with a resistive heating coil between the two.[2] Of course, since then there have been many developments in e-textile technology with the most interest and advancement occurring in the last 10 years. Today, weaving technology has become so advanced that conductivity can be incorporated into the fabric so that the conductive network becomes discrete, durable, lightweight and flexible enough to be worn as a garment. And today's e-textile does a lot more than provide heat. There are garments that can be used in the health care industry to monitor vital signs of a patient, study locomotion of the elderly or those in rehabilitation. Fashion garments can be created from conductive fabric and can have the ability to play music, incorporate lights and be a flexible keyboard to control small electronic devices such as an mp3 player. Safety personnel such as fire fighters or emergency personnel can benefit from the incorporation of e-textiles into their garment because sensors can be attached to the conductive network to identify the presence of hazardous chemicals in the air.

There is an intense need for a more advanced and technologically communicative Army uniform. Incorporating e-textiles into clothing is a long range goal for the Army, specifically falling in line with Army soldier programs such as Objective Force Warrior, Land Warrior and Future Force Warrior. Electrically conductive fabric would provide a foundation for electronics, software and optics that would provide the soldier with enhanced situational awareness, mobility and communications.[3]

Putting a flexible, body conformal conductive network inside a garment was originally known as “smart shirt” technology and was developed by Georgia Institute of Technology as the Georgia Tech Wearable Mother Board or GTWM, as seen in Figure 1. This uses plastic optical fiber (POF) imbedded spirally into a hand-woven or circular body conformal knit T-shirt to create a flexible “BUS” (Binary Unit Structure) structure. This research was initiated in 1996 by the U.S. Department of the Navy as a way to communicate to medics that a soldier had been struck by a bullet. Through the use of sensors attached to the bus platform, the shirt can also monitor heart rate, blood pressure, body temperature, and other vital signs of the human body. The conductive network performs by utilizing a POF with an emitter at one end and a receiver at the other. A signal of light is sent from the emitter, through the POF and ends at the receiver. There are special sensors and devices that can be added to this network to provide the capability of monitoring the soldier’s vital signs, alerting the soldier to the presence of toxic gasses, as well as processing information. The network is connected to a controlling unit called a personal status monitor that is worn on the belt. The POF is spiraled through the shirt to create the network. When a bullet or other weapon strikes the soldier and penetrates the shirt, the network is broken and the signal does not reach the receiver alerting the status monitor that the soldier has been shot. Severity of wound is identified as the POF detects blood and vital signs are monitored. This information is communicated wirelessly to medics who are now better equipped to respond to the situation. [4, 5]

Figure 1 Third Generation GTWM, woven [4]

While this technology is more commonly used in the health and medical industries, and can be lifesaving, there are practical drawbacks and limitations. Using this technology is still an additional article of clothing that has to worn or carried by the soldier. Also, the conductive yarn used in this shirt is larger, stiffer and bulkier than the non conductive yarns resulting in fabric that is bulky and prevents the electronic components from being fully integrated into the fabric. Also, since the conductive components are woven spirally into the torso of the shirt, this technology cannot be cut and sewn into different shapes or garments. One issue in trying to incorporate optical fibers into woven or knitted fabric in a larger scale is that as the yarns take their naturally wavy path through all the fabric interlacings, the ability for the optical fiber to carry the light beam along its length is diminished. Putting the conductive yarn into a woven fabric instead of a knit fabric would reduce the length of e-yarn required for the network because the amount of crimping and waviness is reduced. The yarns in a woven fabric are crimped much less through each interlacing than in a knit fabric. This is one factor that makes woven fabrics more suited for conductive networks. However, unlike knit fabrics that can be knitted directly into a final garment shape, woven fabric usually needs to be cut into pattern pieces and re-sewn together into a final garment. It is this cut and sewing operation that generally prevents woven fabrics from being widely used as foundation for conductive garments. The need for a conductive network that can be woven into a fabric that can be used in a traditional cut and sewn garment has not been filled commercially.

In 2006, a Small Business Innovation Research (SBIR) solicitation Topic A06-176 entitled "Wearable Electronic Network Made form Discrete Parts" was released to industry with the objective to use industrial knowledge to take the full integration of traditional and electronic yarns as woven textile fabrics a step further to develop a material or method that would allow conductivity in a garment constructed from woven conductive fabric. The fabric would be made conductive through the use of a mix of traditional and conductive yarns woven in a traditional manner to result in fabric that was as similar as possible to the current uniform fabric. The resultant fabric would have the ability to be cut into discrete pattern pieces and formed into a garment such as the Army BDU jacket while still being able to perform as an electrical conductive network. [6]

The SBIR topic of putting a conductive network into a woven garment made from discrete parts instead of a knitted one piece garment was proposed for multiple reasons, first, as stated in the SBIR solicitation, “woven broadloom fabrics provide the greatest flexibility in functionality of garment design, durability and the application of camouflage print technology”. [6] Also, woven fabrics provide many opportunities to place connect and route conductive yarns throughout the width of the fabric to create a network. Using previously discussed narrow fabrics simply added onto the existing garments also is not an option here because of the increase in weight and bulk although it would prevent issues with reforming the conductive network across garment seams.

The work in this thesis is focused on evaluating the fabric prototypes resulting from this SBIR solicitation to understand and identify how the addition of the conductive network has impacted the durability and comfort of the BDU fabric.

CHAPTER 2 LITERATURE REVIEW

In researching the literature relevant to the present topic, a historical approach has been taken: that is, the focus has been on the evolution of the U.S. army uniform, from its beginnings to its current form. The presentation of findings has also been given a historical outline: beginning with Uniforms in the History of the U.S. Army, continuing on to consider Present-Day U.S. Army Uniforms, and concluding with The Future of the U.S. Army Uniform (at least as it is conceived of today). Given the nature of the topic, the principal sources for this review have been governmental reports, along with periodicals produced by the U.S. Army or the U.S. Army Natick Soldier Research, Development & Engineering Center. This organization is also represented in many ways thorough this review and in the references. The organization began as the Quartermaster Research and Development Center in 1953 and was later renamed Natick Laboratories, then U.S. Natick Soldier Center and several other variations. When necessary to create a more complete presentation, other books, journals, and online sources providing documentation on the historical development of the uniform were used.

Besides the trousers, shirt, and jacket issued to soldiers in their clothing kits, there are other items as well: boots, hats, undergarments, and outerwear; however, these are not covered in the present review. In considering the evolution of the U.S. Army uniform, the specific focus of this study has been on the technical changes that have been made over time to the fabric used in the uniform—particularly the changes and/or improvements to the fabric fiber type, weave construction, color, and chemical finish applied. Information regarding why or when fabric changes occurred is not readily available, especially prior to the 1960s. Available information in governmental and historical documents tends to discuss the uniform patterns and colors, leaving the exact type of fabric to the discretion of the individual soldier or their local leaders. Where there is information that was made available for public release concerning the reason for making a technical change to the fabric of the uniform, this information has been included in the present review.

The two main objectives of the military uniform are to provide protection from combat and environmental conditions, and to present the wearer as a soldier representing the United States Army. This dual purpose, however, already represents an evolution. Initially, the sole purpose of the uniform was to identify a soldier's allies and enemies during close combat. [7] As time progressed and the tradition of the Army grew, the uniform began to function not only as an identification, but as a source of protection for the soldier. Ultimately, it also became a source of pride. [8]

Unlike the U.S. Navy and Air Force, the uniform of the U.S. Army does not have a long tradition of distinctive style; rather, it has changed with every war fought so as to provide more functionality and comfort to the soldier. Over the last 100 years, the combat, or Battle Dress Uniform (BDU), has been largely tailored to the environmental condition of the particular war being fought and, until recently, was distinct from garrison (i.e., non-combat) wear. Through the years, the primary uniform changes have been in the areas of style, fit, and comfort for various climates, as well as to compensate for wartime material shortages. Interestingly, a 1980s survey of over 3,000 male and female Army soldiers identified the most important feature of a uniform in the eyes of its wearers as its military appearance. [9]

Major additions to the technical performance of the uniform—such as ballistic, chemical, and thermal protection—have been addressed by the development of special items of clothing, not by functional improvement to the regular BDU. These additional types of gear are provided separately to the soldiers and are beyond the purview of the present research.

2.1 Uniforms in the History of the U.S. Army

During the first conflicts throughout the period of the Colonial Wars (1620–1774), and until the Continental Army was formed, the soldier's uniform consisted of whatever he already owned, with the addition of color to identify himself as part of a particular regiment or army. This identification was worn as an arm-band over the soldier's own jacket, or it could be a jacket of a particular color.

At the start of the War of Independence in April of 1775, a soldier's uniform was a sort of hunting dress styled after the clothing of Native American hunters. This style of uniform came at the recommendation of General George Washington, and it was generally thought that this would be the most functional uniform, as well as the easiest and cheapest to obtain. [10] The hunting dress consisted of a fringed shirt and trousers. This uniform was practical, comfortable for combat, and effective in providing a degree of camouflage for the soldier, making it very useful in wooded areas. [8] Later, in 1775, the government mandated that the Army uniform would consist of a blue wool coat with red lining, long sleeves, and coattails, fitted to the body to give a neat and tidy appearance. These coats were to be worn with long, wool, knit stockings or buttoned gaiters over the boots, as trousers were not adopted yet. [7] These were influenced by French Army uniforms (chosen as much because of France's assistance as because of the distaste for Britain) and were intended to make a statement and set a tone and style for the soldier; comfort and camouflage were not yet taken into consideration. [10] The soldier's clothing of this era was made out of wool in the winter and cotton in the summer, with the trousers (or breeches) made from animal skins. Although red, blue, green, and white colors have been documented, usually the uniforms of this era were brown because, at the time, that was the easiest color for the men to have their families dye them at home. [10] Wool fabrics were often "homespun" kerseys or flannel—all coarse and felted fabrics. [11]

During the War of 1812, U.S. military regulations decreed that Army uniforms were to be blue in color. However, with the increasing number of soldiers requiring blue cloth, a shortage occurred; brown and grey fabrics were, therefore, substituted. The uniforms during this time made the soldier stand out and look sharp, thus providing a morale boost to the soldier. Camouflaging the soldier in his combat environment was not a requirement at this time because the nature of battle required very close combat, since muskets did not have a long reach. As technology progressed, leading to the use of rifles and canons that were more effective at long ranges, the use of colors that would camouflage the soldier became more necessary. [12]

Although the writing was on the wall for the start of the Civil War, the United States was unprepared for it. Severe shortages of uniforms, skilled seamstresses, and fabric anal presented significant problems that had to be overcome in the beginning of the Civil War; this resulted in a situation in which soldiers had to make-do with wearing anything they could find. The government could not produce an army very quickly, so the union states took it upon themselves to recruit, train, outfit, and equip their soldiers. This resulted in many different uniforms being worn by soldiers fighting side-by-side. Many states sent buyers to Europe to procure surplus uniforms wherever they could find them. This resulted in New York's volunteer Army being outfitted in a decidedly French uniform, with all of the formality and ornateness that entailed. [13]

The Army uniform that soldiers wore before the Civil War began was heavy and very tightly fitted because the soldiers themselves usually had tailored their uniforms according to the civilian styles of the day. Once the war began, these tailored uniforms proved unsuitable for combat. [14] Sewing machines were not generally used to make the uniforms because hand sewing was still considered to be more durable. [15] Many types of coarse and heavy wool fabric, such as kersey, were used, and any subdued color was allowed. As seen in Figure 2, kersey is a flat or ribbed type of twill weave. It can be light to heavy in weight and is usually felted to provide increased warmth and wind protection.

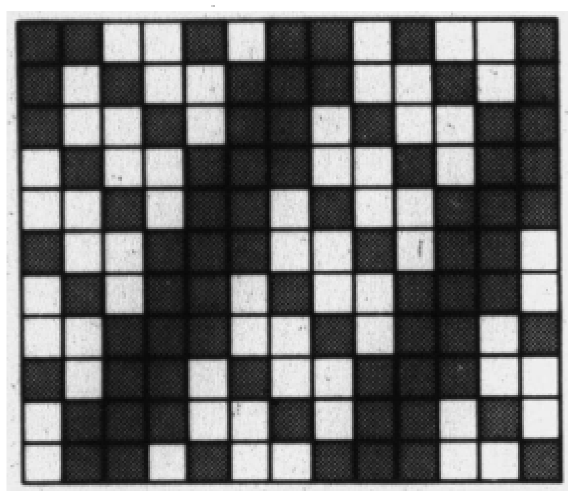

Figure 2 Weave diagram of kersey

[16]

Inconsistent uniform color was a problem because both Union and Confederate soldiers wore grey. This resulted in many deaths from friendly fire because of the inability of soldiers to distinguish between the uniforms of the two armies. [8] To resolve this problem, on September 23 of 1861, the Acting Secretary of War mandated that no more Union troops would be outfitted in grey; from then on, blue was to be worn. [15]

At one point, to clothe the growing Union Army properly during the winter months, 1.2 million yards of light and dark blue kersey were ordered from London. The cloth was not available domestically because local suppliers, such as Brooks Brothers, were producing substandard quality fabric at exorbitant prices. Alarmed to see such a large procurement of fabric from foreign companies, the “Boston Board of Trade,” a group of New England textile factory owners, promised the government that the textile industry of the northern states could produce an adequate amount of high-quality fabric to clothe the entire U.S. Army in a reasonable amount of time. [15] They succeeded and, by the second year of the Civil War, most Union troops were well clothed with domestically procured uniforms.

Later, the Quartermasters-General directed the U.S. Army to be clothed in a manner similar to that of the “Chasseurs a Pied.” the marksmen of the French Army. Unfortunately there was not nearly enough funding to achieve this, and soldiers still wore whatever they could. Usually a woolen or cotton sack coat was worn, similar in comfort and style to modern military jackets. [15] Uniform regulations of 1861 provided directions for the soldiers regarding the correct appearance of their uniforms for dress and fatigue use and for identifying rank, but did not provide much technical detail. The fatigue uniform was to be a sack coat and trousers made from a dark-blue flannel. [17]

There were many complaints and problems with the uniforms that were actually made available to the soldiers. Uniform trousers made from the coarse woolen kersey caused severe discomfort to soldiers when marching. Shirts were made from woolen flannel and, according to reports, attracted so many insects that soldiers had to hang the shirts over campfire smoke to fumigate them. [15]

When the Spanish American War began in 1898, again the U.S. Army was not prepared. Reserves of uniforms were insufficient to clothe an entire army, and there were no funds to purchase more. Had adequate funding been available, it would undoubtedly have led to significant transformations in uniform style, as this was an era when functionality and practicality were finally beginning to win over display and fashion. [18] At the start of the war, uniforms were made from blue wool serge and cotton khaki twill. Kersey was not used because, despite the advantages for comfort of the reduction of kersey weight, this led to significantly reduced durability.

There was also a new consideration. This was the first overseas campaign for the U.S. Army, and that fact necessitated certain clothing changes to provide more functionality and comfort to the soldier. [19] The formal, heavy, fitted blue wool coats of the past were not appropriate for combat in the climates of Cuba, the Philippines, and Puerto Rico. Next, the necessary changes in uniform fabric, color and patterns that had to be made in order to be appropriate for the overseas combat will be discussed.

At the start of the Spanish–American War, the same uniforms that were used during the tough North American winters were used in the summer in the subtropical environments. To make these uniforms more appropriate, the heavy wool kersey and flannel coats had their linings removed to make them cooler. Then the fabric weight was dropped from 22 ounces per square yard (oz/yd2) to 16 oz/yd2. The fiber of choice remained wool because, at the onset of the war, the American Army thought it is the best fiber to use in warmer environments; as a result, no special summer clothing was issued. Halfway through this short five-month war, cotton emerged as the superior fabric for subtropical environments, and cotton canvas uniforms were shipped to the soldiers. Over 1,000 prototype uniforms made from khaki-colored cotton drill were sent to soldiers for evaluation. [19] However, these uniforms sat in railroad cars in Florida and were not shipped out in time for use during the Spanish–American war. Many commanders in Cuba looked at local sources for fabric (and, indeed, for uniforms) to provide their soldiers with cotton fabric in a till or duck that was light-brown in color. [20]

The change in the color of the U.S. Army uniforms was required because the dark blue made the Army soldiers an easy target in tropical environments. Newer combat equipment, like smokeless gun powder and magazine long arms, made combat camouflage a necessity. After only two weeks of combat, a light tan khaki color was authorized to replace the dark blue and, by the end of the war, the U.S. army had been “transformed into a khaki clad modern force.” [19] The new khaki color was used for summer combat uniforms, while a darker olive-drab color was used for winter combat uniforms. [9] However, by 1902, khaki cotton was phased out and olive drab wool was the fabric of choice for the Army. [19]

During this time there were many problems with the quality of the mass-produced uniforms. Electric sewing machines and cutting instruments were used for the first time to deliver massive quantities of uniforms. The rushed nature of the procurement led to inferior construction and poor-quality fabric that actually faded after only a few weeks of use. [19] The new lighter-weight cotton khaki provided a cooler and more comfortable uniform, but was not very durable. During the fourth month of combat, the commander of a Philippine regiment was so perturbed that he advised his superiors back in the U.S. that no more American made uniforms or fabric be sent to him; instead, he would fill his uniform and fabric needs with locally produced goods. The reasons he provided for this were the poor workmanship and defective material of the U.S.-produced uniforms and fabric. [19]

In 1917, the uniforms that soldiers were wearing when they entered into the First World War were those adopted five years earlier, in 1912. At this time, there was one “service” uniform for both combat and dress occasions; by many accounts, it was poorly suited to both purposes. [7] This uniform was a khaki to olive drab-colored trouser, shirt, and coat combination. The winter version was made of 100% wool, and the summer version was made of 100% cotton. [21]

When the American Army entered the Second World War, it was again without a dedicated combat uniform. Many soldiers wore the same uniform type as in WWI, twenty years earlier, [21] as there was no money for uniform development between WWI & WWII.

Army soldiers were issued cotton or wool uniforms, depending on the climate where they were stationed. For soldiers fighting in the South Pacific, the traditional 8.2 oz khaki uniform was not breathable enough to be comfortable. On March 24 of 1938, the Army released a 6.0 oz cotton twill to replace it. In providing these uniforms to as many soldiers in as little time as possible, corners were cut and quality was sacrificed. By way of example, the double-needle machines used to make the trousers were not readily available, so single-needle machines were used instead; this lead to tears and reduced overall durability in the jungle environment. [21]

Later, in 1941, the combined uniform was developed. This was an attempt at improving comfort and functionality. The combined uniform replaced separate dress and combat uniforms. It was olive-drab in color and comprised of wool trousers, shirt, and tunic, as well as a cotton field jacket. The stand-out article from this development was the M1941 field coat. It was made of a tightly woven cotton poplin shell, lined with 10 oz wool flannel, and it was supposed to be more comfortable and resistant to water and wind than the uniforms it was replacing. [21, 22]

Another stand-out development in Army uniforms of this time was the use of herringbone twill (HBT). Research showed that appearance was improved by the use of a right-hand twill, specifically as it best hid the ends of the staple fibers and provided a smooth look. This weave combined a reduction in weight and improved durability with snag resistance, and it was preferred by the soldiers. Because this was a tight weave, it also provided additional protection against insect bites. [22]

In 1942, HBT was chosen as the fabric for the jungle combat uniform to be used by those soldiers fighting in North Africa and the South Pacific. [22] This uniform also incorporated a camouflage print for the first time, although in limited issue. The first version of the camouflage uniform was a one-piece jumpsuit with a high-contrast green-and-brown brush stroke camouflage on one side, reversible to solid tan on the inside. This served to provide camouflage in the sand when arriving on the beach, and then also later when the soldiers would be fighting in a jungle environment. [23, 25] Due to comfort issues with the one-piece uniform, a two-piece reversible camouflage suit was issued in later years. However, due to its similarity to the German uniforms, some soldiers were killed due to mistaken identity. After only two years of use, camouflage uniforms were phased out by 1944 and replaced with the

Dark Green 07 uniform, due to the belief that, in a jungle environment, solid colors proved more effective for hiding than the patterns. [22, 25]

In 1943, the U.S. Army again tried to improve its uniforms and began to develop a uniform that would provide better comfort and durability in any environment or climate. This resulted in the M1943 uniform, which used a layering system to provide adjustable warmth or cooling properties in any climate. [22, 25] This system was issued in 1944. [22] The main uniform components were the trousers and field jacket, made of a 9 oz/yd2 wind-proof, double-layered cotton sateen intended to be worn over wool serge trousers and shirt in the coldest environments; in warmer seasons, the layers could be worn alone. Sizing, however, presented a problem. Wearing all the layers to keep warm resulted in a uniform that was very tight-fitting. Wearing only the cotton sateen outer layer to keep cool resulted in a uniform that was too large. All in all, soldiers were very unhappy with this uniform. [22, 25]

The Army also tried to improve the comfort of soldiers fighting in hot and humid environments, and undertook a project to develop a tropical-weight uniform. Many fabric types—such as poplin, Byrd cloth, HBT, and twill fabric—were evaluated for their performance in terms of their ability to resist tears and snags while keeping the soldier free from insect bites and, at the same time, cool and dry in the hot, humid climate of a jungle environment. Through research conducted in Florida and Panama, the Army determined that poplin and Byrd cloths were much more comfortable and breathable, and provided more mosquito protection, than the HBT and Army Twill. In terms of durability, HBT was determined to perform best. Due to the unavailability of Byrd cloth, the research team nominated poplin as the fabric of choice for the Army uniform; soldiers seemed to be in support of this. However, due to a concern that even the poplin cloth would also have issues with durability and availability, in 1944, General MacArthur chose HBT as the new Army uniform fabric. [7, 21]

To add to the uniform's problems, due to a 40-million-dollar overstock of uniforms at the end of World War II, civilians and foreign military were able to purchase U.S. Army uniforms at very cheap prices. Because the uniforms were made to be comfortable outdoors and rugged enough for heavy labor tasks, farmers, hunters, auto mechanics, contractors, and even prisoners out on work patrol were wearing the U.S. Army uniform. There were many instances of thieves and other criminals caught and arrested while wearing a uniform, leading the newspapers to report inaccurately that it was "an ex GI" who was caught. The Army uniform no longer presented the iconic image of the American soldier. There was a need for a new uniform because of comfort and protection, but there was also a need to improve morale. [26] Finally, in 1949, a dedicated Army Uniform Board was developed to indentify long-range goals for the uniform. [9]

With the sudden onset of the Korean War in 1950, the U.S. Army found itself fighting in a rugged, mountainous environment where the climate that ranged from sub-zero temperatures in the winter to tropical heat in the summer. [27] North Korean troops invaded South Korea on June 25 of 1950, and in only 10 days, infantry from the U.S. Army were engaged in combat. The uniform worn by these initial troops was the same as, or very similar to, the unpopular M1943 uniforms worn in World War II. It consisted of a wool shirt and trousers. [27] The 610.3 g/m^2 (18 oz/yd^2) wool serge material used in these uniforms became scarce as the government tried to increase its uniform supply. [27]

By the second winter of combat, inadequate protection against the cold weather was the greatest cause of soldier deaths. [27] To provide additional warmth, buttons were added to the M1943 jacket in 1950 to allow the use of a separate liner. This was only an interim solution, as the M1951 uniform was to be introduced soon thereafter. The M1951 uniform was olive-drab in color and utilized new fibers, such as nylon. It consisted of several items, with the trousers, shirt, and jacket at the core. The trousers were made from a blend of wool and nylon serge fabric. The jacket was made of more rugged 288.2 g/m^2 (8.5 oz/yd^2) cotton sateen weave. The five-harness sateen weave was considered “rip-proof” and was developed specifically for mountain troops.[28] The shirt used a blend of wool and nylon fibers. However, evidence suggests that soldiers did not benefit from these improvements, as the Army was still utilizing old stocks of WWII-era uniforms, and the M1951 uniform system was not sent to the Korean War. Instead, the water-repellent, cotton oxford M1943 field jacket was used during most of the Korean War, even though, with artificial fur layers underneath, it provided inadequate protection during the harsh winters. The winter uniform the soldiers did wear during the Korean War consisted of a pair of wind-resistant cotton trousers over the regular wool trousers and a wool flannel shirt. The summer uniform consisted of a jacket and trousers made from the rugged HBT cotton fabric. [27]

During the time of the Korean War and into the Vietnam War, investigation into developing a clothing-based insect repellent was being conducted. A blend of chemicals called M1960 was adopted for this purpose, and was over 90% effective in protecting soldiers from fleas, ticks, mosquitoes, and chiggers for up to one week of combat wear. Chiggers spread the fatal disease of scrub typhus, and mosquitoes spread malaria. Intended to combat these threats, M1960 was a spray-on repellant and was not durable to laundering. Due to its lack of durability and its trend of causing skin irritations, M1960 was not fully adopted, and the search for an improved clothing-based insect repellent continued. [29]

In 1957, soldiers entered the Vietnam War wearing uniforms that were the same as, or similar to, those worn in WWII—although the combat environments were drastically different. To alleviate soldiers' discomfort in wearing the M1951 uniform in the hot and humid climate of Vietnam, in 1963 a tropical uniform was issued. The performance requirements of this uniform were that it had to provide increased breathability and mosquito/malaria protection while, at the same time, reducing weight. The result was a uniform in 186.5 g/m^2 (5.5 oz/yd^2) cotton poplin that was lightweight, more breathable, and dried faster; it did not, however, provide mosquito protection, and it was not durable in the jungle environment. Developing a uniform fabric that provided increased comfort while still being durable and providing protection from insects presented a struggle throughout the entire war. Over eight million of these uniforms were supplied to the soldiers in the first four years of procurement. [30, 31]

The uniform became water repellent with the addition of a “Quarpel” treatment. This is an acronym for “Quartermaster Repellent,” the name given to the finish by its inventor at Natick Laboratories. This durable finish provides the uniform with repellency to water and organic liquids, as well as to some chemicals. [30, 32] However, due to reduced comfort, this treatment was not incorporated in the long term.

Nylon was used extensively in uniforms during the Vietnam War. Staple lengths of nylon or polyester were blended with cotton to improve its performance by reducing weight and absorbency while improving strength and durability. To improve mosquito repellency, the Army developed two experimental uniforms: the T61-1 and the T61-2. These uniforms used a blend of nylon and cotton fibers. Two types of BDUs using fabric that had improved mosquito repellency were tested in Vietnam. Both were made from a 203.4 g/m^2 (6 oz/yd^2) blend of 50% cotton and 50% nylon termed “Nylon/cotton”. [30]

In 1961, the official position of the U.S. Army was that disruptive camouflage patterns on clothing did not provide a distinct advantage compared to a solid color that was similar to the soldier's environment. However, soldiers regularly engaged in combat saw the need for patterned camouflage and witnessed its benefit to the South Vietnamese soldiers who used it. The first camouflage uniforms and patterns were based on these soldiers' experiences. Mass-production of camouflage uniforms was made possible by utilizing nearby Japan, Thailand, Taiwan, and Korea for production. Later, in 1967, the "woodland" camouflage pattern was developed and issued. [30] As seen in Figure 3, this was a "splotch" pattern and provided protection against infrared detection. By the end of the war in 1975, the solid uniform had been phased out and camouflage patterns had become standard. [30]

Figure 3 Vietnam Camouflage Pattern

Blends were first researched in 1951 and then again in 1953; but at that time, there were no synthetic fibers available that would produce a fabric able to outperform the 100% wool that was then in use. The reason a blend was so necessary was not only to improve the performance of the uniform, but also to prevent issues with wool shortages during war time—such as those that the Army experienced during WWII and the Korean War, when wool was difficult to obtain. During the Vietnam War, an extensive research effort was undertaken to develop an alternative to the 100% wool fabric. The goals for the new fabric were that is should have a reduced maintenance and laundering cost, and be more comfortable than wool, while still providing the same (or an increased) levels of strength and tear and abrasion resistance. The research team expected that the new fabric would be more expensive but would be much more durable, therefore compensating for the increased cost. Several blends, such as wool/polyester, wool/acetate, and wool/nylon, were evaluated and compared with the 100% wool standard. [33]

At the conclusion of the investigation in 1967, most of the experimental blends performed as well as or better than the 100% wool standard in terms of air permeability, comfort, appearance, hand, weight, tear resistance, and strength; furthermore, the polyester blends performed better with regard to abrasion resistance. Results of the study found that the polyester and wool blends were most durable and were preferred by the soldiers. These blends behaved differently in the cutting and sewing operations. First, the polyester and wool blends absorbed less moisture, making them less pliable by steam and ironing. This meant that using the same patterns as had been used with the 100% wool fabrics would not result in garments of the same shape; garments and seams would pucker. New patterns were created and sewing machines were adjusted to compensate for these issues. [33]

After Vietnam, the focus of future Army uniform development was centered on using commercially available synthetic fibers to produce a uniform that was streamlined, and both comfortable and durable, while still being cost effective and providing a smart military appearance. [9] Since 1992, the U.S. and other NATO (North Atlantic Treaty Organization) countries abide by the uniform requirements set forth in Standardization Agreement (STANAG) 2333. This agreement identifies the general requirements that the uniform and all specialty gear must meet in order to be effective and allow the soldier to "perform all combat and training activities," while enabling the soldier to "carry out these activities in good mental and physical condition." [34] STANAG 2333 provided guidance for uniforms concerning such characteristics as camouflage, flammability, durability, care, and maintenance.

The Woodland Battle Dress Uniform was developed and began to be issued to soldier in 1982. In addition to the considerations discussed above, the primary objective of this uniform was to protect against enemy detection in both day and night combat. Experience in the Vietnam War taught the U.S. the importance of using disruptive patterns for concealment of soldiers, as well as vehicles, shelters, and other equipment. During this time, the two major threats of enemy detection came from visual identification in daylight and visual detection with the assistance of night vision goggles at night; the latter made use of near infrared (NIR) detection to measure the amount of reflected light. Per the requirements in STANAG 2333, a camouflage uniform would have to be developed that would provide concealment from visual and near infrared detection at a distance of about 350 meters. As seen in Figure 4, the four colors in the woodland camouflage—black, light green, dark green, and brown—were chosen for their low visual and spectral contrast to the woodland or jungle combat environments.

Figure 4 Woodland Camouflage Pattern

The pattern of the camouflage was based on a 1948 tropical camouflage pattern developed to protect against sniper detection; this was a small pattern and did not have a long range of effectiveness, so the pattern was increased by 60% to extend the concealment range to 250 meters. [35] To provide against NIR detection, a special blend of dyes and pigments had to be used that were designed to match the woodland or jungle environment. [35, 36] The Woodland BDU was first issued in two weights: a lighter, 100% cotton ripstop for warmer climates, and a heavier blend of 50% cotton and 50% nylon twill for cooler environments. Because of durability issues, in 1996 these were replaced with one lighter-weight nylon–cotton ripstop for all climates. Colorfastness was a huge hurdle to overcome in the development of this camouflage pattern. For this reason, the four colors of the woodland camouflage pattern were a slightly darker than what would provide the best protection against being detected. This allowed for the color change that inevitably occurs in mass production; the final colors are generally lighter than the standard. Additionally, this provision allowed for the fading that would undoubtedly occur in laundering the uniforms. Over time, then, the uniform will fade into the target shades and spectral reflectance, rather than begin to fade out. To prevent shortages in a time of need, consideration was given to ensuring that the textile industry could produce this fabric in large quantities if needed. The uniform was also QUARPEL treated to become water and oil resistant.

In 1981, the Army developed a desert camouflage pattern, see Figure 5. This was a six-color pattern dubbed the “chocolate chip cookie” pattern. It was based on an earlier 1962 pattern, with spots of light tan with light green, light brown, dark brown, and white with black spots. The black dots were added to mimic rocks in the desert environment.

Figure 5 Six-Color Desert Camouflage Pattern

This pattern was never very popular with soldiers, and after it was used in the 1990–1991 Operation Desert Storm, it was dropped because it was not considered military enough. After the start of the 2003 Iraq war, the remainder of the unwanted chocolate chip uniforms were given to the new Iraqi Army, providing both easy identification and needed camouflage. [12] The six-color desert pattern was replaced with a three-color desert pattern (Figure 6) that more closely matched the desert environment in Iraq. This pattern was dubbed the "coffee-stain." Because this pattern only used three colors instead of six, it was actually cheaper to produce. Sand and rock samples from the Middle East were used to develop the new desert pattern and colors.

Figure 6 Three-color Desert Camouflage Pattern

A soldier's only protection against wet conditions is provided by separate rain gear. To add functionality to the soldier's battle dress uniform (BDU), scientists at the U.S. Army Natick Soldier Center researched the possibility of adding a durable water-repellent finish to both sides of the uniform fabric. They evaluated both the effectiveness of the finish as a water repellent and also how the finish impacted the soldiers' comfort. It is well known that many of the durable water repellant finishes available today perform exceptionally well at repelling water, but they can also reduce the breathability of the garment to which it is applied, thus reducing the wearer's comfort. Three proprietary nanotechnology-based durable water repellant finishes were applied and evaluated for their effectiveness in repelling water, their durability, and their effect on fabric breathability. Although lab testing showed that the breathability of the fabric was not changed, during field testing, soldiers wearing uniforms treated with the experimental finishes reported that they were much less comfortable than the untreated uniforms. This was attributed to the fact that the finish reduced the fabric's ability to wick moisture and sweat away from the soldiers' skin, decreasing the uniform's comfort in a hot environment. It took many years to incorporate a water repellant finish into the BDU fabric, and this time it is issued as an alternate uniform and not available as a standard issue. This is a very good example of an improvement to the uniform that was not universally adopted because, while it would provide additional functionality, it reduced the soldiers' comfort.[37]

As a lesson learned by previous uniform improvements like the durable water repellant finish, the efforts put forth in this study will seek to identify how durability and comfort are affected by the addition of a conductive network. Identifying any negative impact of the network early in the development process will allow efforts to minimize these impacts be concurrent with optimizing the network performance.

Today, the BDU had been transformed into the Advanced Combat Uniform (ACU). The most obvious difference between the BDU and the ACU is the updated camouflage pattern as seen in Figure 7. The new universal camouflage pattern is a three-color small-scale digital pattern, very unlike the previous camouflage patterns. This pattern is meant to be the 80% solution to combat that takes place in both desert and urban environments. Research to develop this new pattern began in 2001 and originated with twelve patterns. The base fabric for the ACU is still an intimate nylon/cotton blend woven in a ripstop pattern however; this fabric is treated with a wrinkle-resistant finish that provides the soldier with reduced maintenance during use. Another distinct change is that the uniform shape and fit has been revamped with a focus on allowing mobility, while still enhancing durability and protection.

Figure 7 Universal Camouflage Pattern

2.2 The Future of the U.S. Army Uniform

Future developments in the U.S. Army uniform will be focused on providing the soldier with additional performance capabilities while still providing a durable and easy-to-procure uniform. Areas of research include improved camouflage capabilities, reducing the weight and bulk of the uniform, providing the uniform with protection from ultra-violet rays, developing a uniform that is self-cleaning, impregnating uniform material with blood-clotting agents, and developing a biodegradable/disposable uniform. [3]

A short-term improvement to the BDU may be to use antimicrobial technologies to protect the soldier from microbes that can negatively affect health, comfort, body odor ,and safety. Several chemicals are being evaluated for this use, including silver, copper, tin, Triclosan, and Chitosan. Currently, X-static is a silver-coated textile fiber used in U.S. military socks and t-shirts, though it is not yet being applied to the BDU. It is important to reduce the amount of bacteria on the body because these bacteria can cause a smell that would reduce the soldier's ability to remain undetectable from the enemy. [3, 38]

To protect soldiers against insect bites that are uncomfortable and can spread diseases, the Army requires that soldiers apply a thin layer of DEET-based insect repellent. The problem with skin-applied insect repellents is that they have a strong odor and have to be reapplied frequently. Using insect repellents that can be applied to clothing will circumvent these issues while still providing protection from insect bites. The Army has been investigating the potential for clothing-based insect repellents since the 1940s, as has been noted above. Permethrin is based on pyrethrin, a natural insecticide found in some flowers that paralyze insects. Permethrin was first developed in the 1970s; it is a synthetic, durable insecticide that can be applied to clothing, and it repels, paralyzes, and kills insects. The chemical can be applied at the manufacturer's level or it can be sprayed on by the soldier. This solution has been more successful than the M1960 because it is more durable and does not cause immediate skin irritations. However, due to health concerns for factory workers at plants that apply the permethrin to the fabric, as well as for soldiers who could wear treated uniforms for more than 20 years, the Army decided against allowing permethrin application at the factory level. The downside of spray application is that it reduces the level of effectiveness and durability of the insecticide. In December of 2008, the Army Uniform Board decided that enough research had been conducted to assure them that there was a safe factory application method and that soldiers would not suffer long-term health consequences from the factory impregnation of permethrin. The use of spray application permetherin should be phased in to the manufacture of the U.S. Army ACU by 2012. [29]

Electronic textiles (e-textiles) can be defined broadly as electronics and interconnections that are woven or knit directly into a fabric. These electronics can be wires or fibers that transfer data, provide power, communication, sense chemicals, etc. The advantage to the combination of electronics and textiles is that the result is often lighter in weight and more flexible than the traditional, separate versions. [39, 40]

Land Warrior and Objective Force Warrior are two ongoing soldier enhancement programs that the Army is developing. The goal of this program is to develop materials and equipment that will provide additional communication and protection capabilities to the combat fighter while also reducing equipment weight, bulk and profile. e-textiles will play a pivotal role in these programs to provide connection and power supply for the multiple electronic devices worn and used by the soldier. Utilizing e-textiles to provide in this way will eliminate or at least reduce the number of cables and equipment required and result in a reduction of the overall weight and bulk of the OFW and FFW system. [41]

The ability to incorporate electronic equipment or power supply into fabric or clothing opens up many new possibilities for end items and can provide a benefit to the soldier in more advanced ways than the technology is providing benefits to the private sector.[40] For example, there is technology that integrates conductive elements directly into a fabric to allow the fabric to change color in response to an electronic signal; this technology could be used to develop uniforms that are able to adapt the camouflage pattern to provide more concealment in multiple environments and reduce the types of uniforms that have to be packed and carried. [41] Many of the e-textile technologies that are promising can be used by medical personnel, fire fighters and policemen and other first responders.

There are wearable e-textile applications that allow biometric identification to be used in a wearable form to identify friend-from-foe. This technology incorporates fingerprint and iris scanning, digital cameras and GPS capability into handheld or wearable equipment that enables the soldier to take the identification capability anywhere. [41]

Since 1989, the Army has been working to incorporate small ruggedized electronics and computers in a wearable format that attach directly to the body or uniform for use in combat environments. The computers would provide the individual soldier with increased communication and data exchange with command control and other units, GPS awareness as well as provide a resource for maps and manual. The benefit to having information and communication capability be in a wearable format is that the soldiers hands are freed up and bulk and weight that the soldier needs to carry is reduced. To achieve this Microvisions Nomad™ wearable computer and later the Thermalite® wearable computer were developed. The US Army reserve has used this wearable ruggedized computer in Iraq. Equipment and vehicle repair technicians as well as medical personnel benefit from these wearable computers as it provides them access to unlimited amount of repair manuals or medical references. [42, 43]

The above mentioned computers and electronics are wearable and lighter in weight but they are not completely integrated into the textile material and so wearable e-textile technology continues to be an additional component that the soldier has to wear and carry. The OFW and FFW seeks to take this technology a step further and incorporate wearable electronics directly into the clothing make the equipment low profile and as light weight as possible.

An early example of this are e-textiles that have the ability to act as keypads or switches and can be located in clothing or other convenient textile surfaces. The keypads can be printed, coated or embroidered onto the fabric or woven directly into the fabric. Fabric keyboards, can use optical fibers embedded in the fabric that are pressure sensitive. When pressed, these fibers bend under the pressure and send a signal back to the processor indicating the key stroke. Another method for creating a keypad on a textile is to use electrically conductive yarns such as resistive Kevlar and stainless steel filaments embroidered onto a fabric. [44] A fabric keyboard would be much lighter and less bulky than a traditional keypad and can be folded or rolled up for convenient storage and transportation.

A more complex example of incorporating an electronic device into material is the Universal Serial Bus (USB) and a BUS . The USB was particularly suited to converting into a narrow woven fabric. Traditional USB transmission mediums, power wires and drain materials were used and were located within a double plain weave narrow fabric transforming the once bulky and stiff USB cable into a more flexible e-textile cable that can be used to connect various electronic equipment that is worn on the soldiers body. Another technology that used similar methods to incorporate electronics and textiles was the soft double loop antenna. This is a VHF antenna that is typically rigid and during use prevents the soldier from retaining a low profile for concealment. Integrating the electrically and optically conductive yarns within a tubular narrow fabric allows the antenna to become more flexible and body conformal. Ultimately this technology was incorporated onto the modular lightweight load carrying equipment vest. [45]

Fabrics that are used for electromagnetic shielding and static control utilize conductive yarns as part of the weaving process. [1] A step closer to fully integrating electronics and textiles is the Army’s portable and flexible woven electronic acoustic array fabric that uses either triangulation or beam forming techniques to determine the position of a sound source such as a gunshot or vehicle movement. Multiple power and grounding lines were developed into e-yarns that were woven into the fabric in a predetermined pattern along with a majority of non conductive yarns. Connection points between the e-yarns to create the conductive network were formed using traditional soldering methods. Microphones were attached to the network in specific locations depending on whether triangulation or beam forming techniques were used. The result was an acoustic sensor that was easy to deploy, flexible and light-weight. [5, 46]

The previously mentioned SBIR solicitation takes this technology a step further and seeks to use conductive and non conductive yarns in a woven fabric and have the ability to cut and sew the broad goods into a garment and still retain network conductivity. SBIR solicitations are competitively awarded to smaller, high-tech innovative businesses. This is a method the US government uses to leverage early stage commercial research to enhance their own efforts. Infoscitex Corporation, based in Waltham, MA was awarded the developmental funding for the SBIR to develop a conductive fabric that could be cut and sewn into garments such as the Army BDU jacket. Phase I of the SBIR program was awarded in November 2006; this is the developmental phase and is used to prove out the concept proposed by the awardee through small scale testing. If the idea has merit, a Phase II option can be awarded noncompetitively. This is more of a demonstration phase to prove if the concept can be brought into commercialization as Phase II takes the concept out to the marketplace. [47]

Infoscitex teamed with the College of Textiles at North Carolina State University (NCSU) to design and weave several prototype BDU fabrics using electrically conductive yarns (e-yarns) located throughout the weave to create a fabric that could be cut and sewn into a garment, such as the BDU jacket, using traditional methods. Infoscitex developed a technology that would allow the network to be revived by making electrical connections to link the e-yarns across seams to form continuous network paths. This would allow the garment to retain its conductive network post cutting and sewing operation. [6, 48]

The garment constructed with a continuous network had to be made from the standard BDU fabric that conforms to MIL-DTL-44436. This is a 104x54, nylon/cotton ripstop weave. As seen in Figure 8, a ripstop pattern is mainly a plain weave with the ripstop square pattern formed by locating the reinforcement ribs (two yarns woven as one) at every 24th warp and every 13th filling yarn. [49]

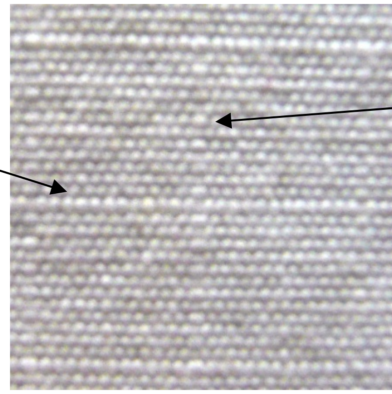

Figure 8 Standard Rip-Stop BDU Fabric (greige)

A portion of the yarn typically used to weave the BDU fabric was modified to be electrically conductive by wrapping it with extremely fine gauge insulated copper filaments. Copper was used as a first attempt at conductivity in this study because it is highly conductive, less expensive and more stable than other electrically or optically conducting fibers or polymers. These were termed ‘e-yarns’ and were incorporated into the BDU fabric by inserting them into the warp and filling direction at each rip-stop reinforcement rib. This results in approximately eight e-yarns per inch in both the filling and warp direction.

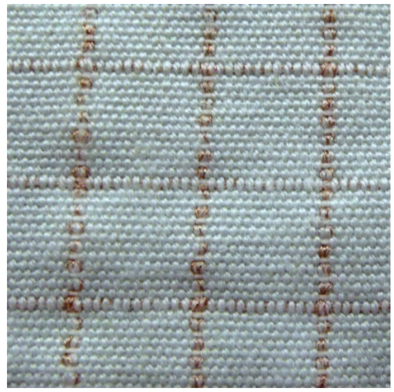

Figure 9 Experimental BDU Fabric with e-yarn in Ripstop Location (greige)

Fabric utilizing the e-yarns located at the reinforcement ribs was woven as required in MIL-DTL-44436, pgh 3.7.1, and resulted in fabric that is exhibited in Figure 9. During a conductivity trial, this fabric made a limited amount of electrical connections.[50] It was determined that this was because the float lengths of the fabric were short and the warp and filling yarns traveled moved frequently from the face to the back of the fabric. The yarn followed a wave or a crimp pattern reducing the conductivity of the yarn. To improve conductivity, the weave would have to be modified to reduce the number of times the e-yarn travels from the face to the back of the fabric and thus straightening the e-yarn. The standard MIL-DTL-44436 weave pattern was modified to increase the e-yarn float length to span five and seven yarns, these are identified as weave #'s 2 and #3. Two more weave designs were developed with varying float locations. The warp and filling float in weaves #1, #2 and #3 are located on the front and on the back of the fabric, and weave #4 and #5 were created to keep the warp and filling floats of weave #3 and #4 on one side of the fabric. These ripstop rib floats that have been extended to improve conductivity are identified as maximum float lengths are identified throughout this thesis as $float_{max}$ See Table 1 for weave design descriptions:

Table 1 Weave Constructions

Weave Design ID	#1	#2	#3	#4	#5
$Float_{max}$ Length	2	5	7	5	7
Warp & Filling $Float_{max}$ Location	Both sides	Both sides	Both sides	Same side	Same side
# of filling interlacings in one repeat	24	16	12	16	12
# of warp interlacings in 1 repeat	26	18	14	18	14

Infoscitex performed conductive testing that showed Weave #5 had the best performance in terms of cross-seam conductivity during trial, making connection almost 100% of the time, while Weaves #2 and #4 made connections less often.[50] Weave #5 performed the best because the e-yarns had the longest $float_{max}$ and the least amount of crimp and because the warp and filling e-yarn $floats_{max}$ were located on the same side of the fabric. This allows for an increased amount of connection points to create the network on the garment. Because Weave #5 was the most successful in conductivity testing it was then successfully constructed into a BDU jacket.[50] The Phase I contract of this SBIR was completed in November 2007 and in September 2009 a Phase II contract was awarded to Infoscitex.

Although Weaves #1-5 were evaluated through the Phase I of the SBIR for their ability to form a conductive network, fabric properties relating to performance and comfort were not evaluated. The work in this thesis will provide enough data to develop an understanding of how the durability and comfort of the BDU fabric will be affected by the addition of the electrically conductive network.

CHAPTER 3 OBJECTIVE

The primary objective of this study is to determine how the addition of an electrical conductive network will impact the performance of the Battle Dress Uniform (BDU) fabric in terms of durability and soldier comfort. The project is set up to measure the effect of the conductive network on such properties as fabric weight, thickness, tear resistance, breaking strength, elongation, air permeability, and thermal transmittance – all properties that directly relate to the fabric's durability and comfort. A secondary objective will be to propose solutions to overcome any negative production or performance impact that the addition of the electrical conductive network may cause.

CHAPTER 4 EXPERIMENTAL

The experimental design was structured to identify and understand the change in fabric comfort and durability properties caused by the addition of an electronic network using the weave designs identified in Phase I of the SBIR. The change in ripstop yarn type (nylon/cotton or e-yarn) and weave design ($float_{max}$ length and location) are the factors considered to be main effects on the properties of the experimental samples. Several resultant fabric properties were studied and statistical analysis was used to identify significant differences between the factors as well as their interactions. Ideally, a full factorial design would have been conducted but because the samples without the e-yarn were already woven and the warp beam was set up to run e-yarn in the ripstop, a modified design was used. The main factors and levels for this study are identified in Table 2.

Table 2 Fabric Sample Factors and Levels

Sample Identification	Yarn Type 2 levels	$Float_{max}$ Length 3 levels	$Float_{max}$ Location 2 levels
1	Cotton	2	Opposite sides
1E	e-yarn	2	Opposite sides
2	Cotton	5	Opposite sides
2E	e-yarn	5	Opposite sides
3	Cotton	7	Opposite sides
3E	e-yarn	7	Opposite sides
4	Cotton	5	Same side
4E	e-yarn	5	Same side
5	Cotton	7	Same side
5E	e-yarn	7	Same side

The three factors identified in Table 2 and their associated levels were chosen for use in this study because efforts from Phase I of the SBIR identified them as the most suitable. Referencing Table 2, Sample 1 is considered as the baseline or benchmark sample as it represents the current Army BDU fabric, while Sample 5E is considered as the most promising of the designs from Phase I of the SBIR

The resulting fabric properties that were chosen for evaluation have a direct effect on the durability and/or the comfort of the fabric. The fabric properties that were evaluated are yarn count, crimp, weight, thickness, air permeability, stiffness, tear and tensile strength, abrasion resistance and thermal transmittance.

To identify those factors that have a statistically significant effect on the above properties, one way analysis of variation (ANOVA) was used. To estimate the amount of variability associated with the production of the samples, two replicates were woven. The weave designs were chosen randomly however, due to the limitations on changing the warp beam, only those weave designs with the electronic network were eligible. Out of those, Samples 2E and 5E were chosen. Because of the small number of samples in this study, a confidence level of 90% ($\alpha = 0.10$) is being used.

4.1 Raw Material

As required by MIL-C-444436, the nylon/cottonyarn is an intimate blend of 50% combed cotton and 50% high tenacity semi-dull nylon. Nylon staple length is required to be 1 to 1 1/2 inches long and the size of the individual staple fibers is required to be 1.6 to 1.8 denier. Yarn size is not provided for the warp or filling direction however, the warp yarn is required to be 2-ply while the filling direction can be 2-ply or singles. [49] The warp yarn used in this study is a 42/2, 50%/50% nylon/cotton yarn. The filling yarn used is a 16/1 nylon/cotton yarn. Actual size determinations as well as tensile strength and elongation testing were conducted following the applicable ASTM test methods. After the fabric is woven it is dyed and then roller or screen printed with the Universal Camouflage pattern and a wrinkle resistant finish is applied.

The electrically conductive yarn is in the experimental stages and therefore does not fall under any specification requirements. The yarn is a nylon/cotton blend wrapped with four very fine filaments of copper and is depicted in Figure 10

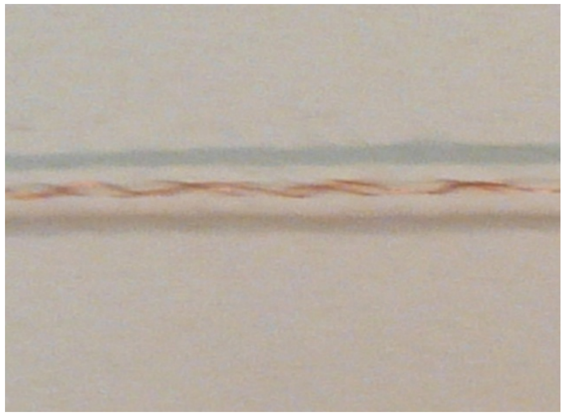

Figure 10 e-Yarn

Many packages of e-yarn and nylon/cotton yarn were used to create the warp beam prior to the start of this study. As a result the yarns were randomized throughout the warp beam. The nylon/cotton filling yarn was inserted using only one package for all samples. Four different cones of the remaining e-yarn were used to insert the conductive network into the filling ripstop ribs; these were identified as cones A, B, C and D. The exact history of the four cones is unknown; however, they were all made from larger packages that were used to make the warp beam and came from the same manufacturing lot. Testing to determine yarn size, break force, elongation and modulus was conducted on these four cones and can be considered representative of the e-yarn used in both the warp and filling ripstop ribs. Actual size determinations as well as tensile strength, elongation and modulus testing were conducted following the applicable ASTM test methods.

4.2 Fabric Formation

All fabric samples were woven on a Picanol Flexible Rapier Loom with a Picanol accumulator/prewinder yarn feed system that utilized a microprocessor for many of the functions relating to programming. Samples were woven over the course of two days and in a random order. The nylon/cotton fabric samples were woven previous to the start of this study, while the e-yarn samples were woven during January 2009. Fabric samples were woven in lengths ranging from only 66 cm (26 inches) to 91 cm (1 yard) due to the limited amount of e-yarn on hand. In this study it was important to compare the characteristics of both sides of the fabric, mainly due to the distinction of $floats_{max}$ being located on both sides (Weave patterns 1, 2 and 3) or only on one side (Weave patterns 4 and 5). To differentiate the two surfaces, all fabric samples were labeled with the side of the fabric facing up on the loom as the "face" of the fabric and the reverse is considered the "back" of the fabric. Samples were evaluated in the greige state to fully understand the effect of the change in yarn type, $float_{max}$ length and location since the subsequent dyeing and finishing processes have a significant effect on the fabric properties and could mask or skew the evaluation data.

This study covers the five variations of ripstop weave patterns including the regular/baseline weave. For sample identification, the weaves are identified as 1 through 5, and when the samples contain the conductive network the weave # is followed by an "E". Each of the five weave patterns was produced with and without the conductive network. As stated earlier, to ensure that the weaving and testing were consistent, two random replicates were woven as well. These samples are identified as described above but end in "R" to identify them as a replicate. Also, one additional sample was woven using the most promising weave pattern #5 with the e-yarn only in the warp direction. This will allow us to examine the option of putting in a reduced amount of e-yarn in the fabric while still creating a functioning network. This modified sample was identified as "5M". Samples will be referred to their corresponding identification label for the remainder of this thesis. See Table 3 and Figures 11-15 for details of the samples woven and the corresponding weave designs.

Table 3 Sample Descriptions

Weave Design	Yarn used in the ripstop locations	$Float_{max}$ Length	$Float_{max}$ Location	Filling e-Yarn Cone	Sample Identification
1	nylon/cotton	2	both sides	n/a	1
2	nylon/cotton	5	both sides	n/a	2
3	nylon/cotton	7	both sides	n/a	3
4	nylon/cotton	5	same side	n/a	4
5	nylon/cotton	7	same side	n/a	5
1	e-yarn	2	both sides	A	1E
2	e-yarn	5	both sides	B	2E
3	e-yarn	7	both sides	C	3E
4	e-yarn	5	same side	B	4E
5	e-yarn	7	same side	C	5E
2	e-yarn	5	both sides	C	2ER
5	e-yarn	7	same side	D	5ER
5	e-yarn only in the warp direction rip stop locations	7	same side	D	5M

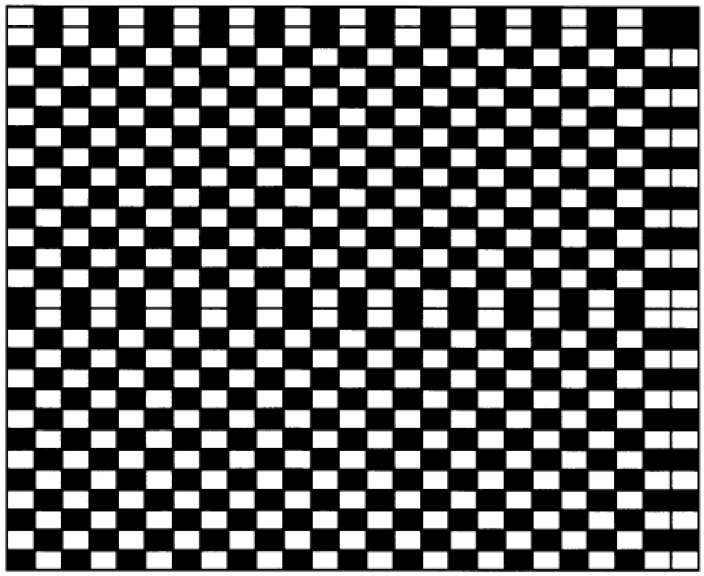

Figure 11 Weave Construction 1 Design Plot

[50]

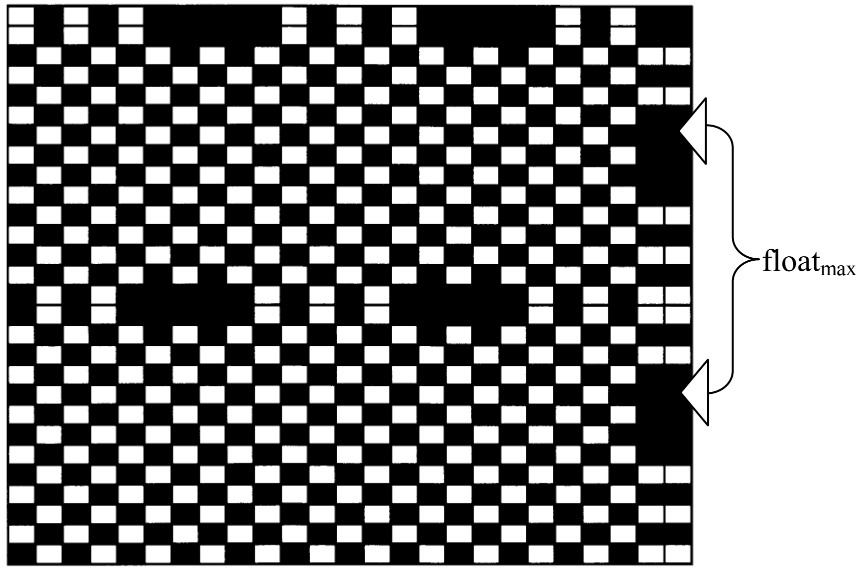

Figure 12 Weave Construction 2 Design Plot [50]

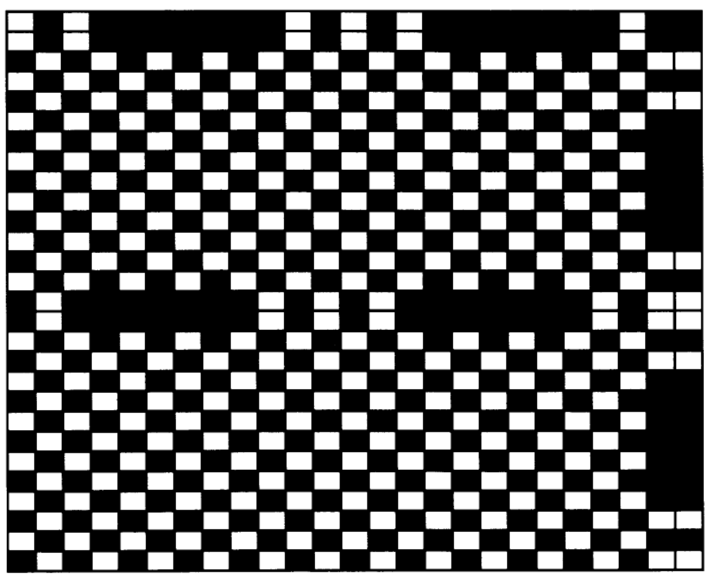

Figure 13 Weave Construction 3 Design Plot [50]

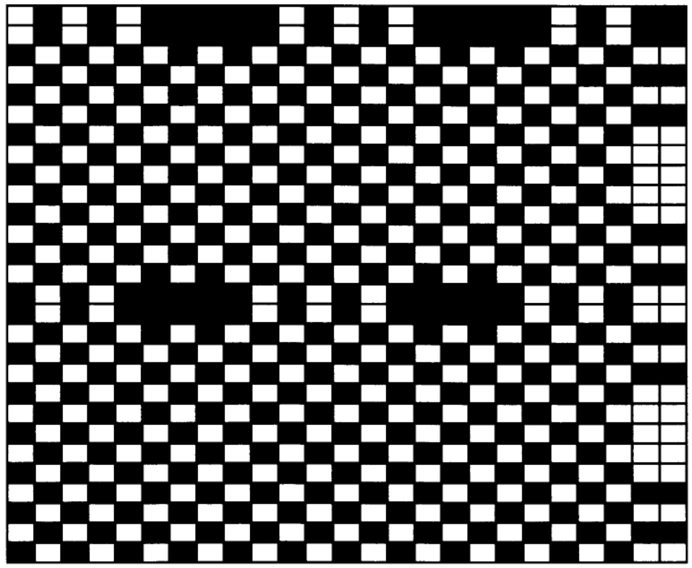

Figure 14 Weave Construction 4 Design Plot [50]

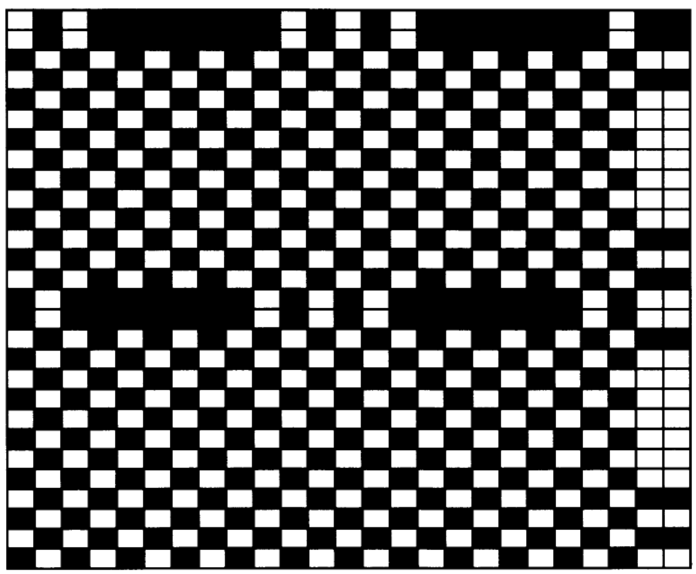

Figure 15 Weave Construction 5 Design Plot [50]

The weave factor for each of the five weave patterns was calculated using the following formula: [51]

$$M1 = \frac{N_1}{i_2}$$

$$M2 = \frac{N_2}{i_2}$$

Where:
M_1 = warp weave factor
M_2 = filling weave factor
N_1 = number of warp ends per weave repeat
N_2 = number of filling yarns per weave repeat
i_1 = number of filling intersections per repeat
i_2 = number of warp intersections per repeat

The weave factor is a measure of the amount of interlacing in the fabric and the inverse of the weave factor is fabric tightness. A decrease in the length of the $float_{max}$ leads to a higher weave factor and a tighter fabric. The yarn intersections are where the yarn changes its presence from the face to the back of the fabric. The tightest fabric is a plain weave fabric because the maximum amount of warp and filling direction yarn intersections/interlacings occur. This would result in a weave factor and tightness factor of 1. Fabric tightness affects many properties such as the elongation and air permeability of the fabric. As the tightness decreases, the elongation of the fabric will also decrease because the amount of crimp required to weave the fabric has decreased. The air permeability of a fabric will increase with decreasing tightness because there are less intersections and more open area in the fabric. [2]

Samples were woven to meet the requirements of MIL DTL 4436 and be as similar to the current BDU fabric (in the greige state) as possible except for the three factors of yarn type, $float_{max}$ length and $float_{max}$ location. Samples 1 through 5 were woven prior to the start of this study. Samples 1E through 5E were woven in random order, and then samples 2ER, 5ER and 5M were woven. The weaving process was difficult at times because the warp e-yarns would abrade against the other warp yarns and cause break outs and weaving would have to be stopped until the warp ends could be tied in again. Because the e-yarn was coarse, it would abrade against the nylon/cotton yarns and cause them to break out as well. This difficulty was overcome by keeping a close watch on the warp sheet and removing any copper slubs before they reached the heddles. Pictures of the face and back of the resulting thirteen fabric samples are shown in Appendix A.

4.3 Testing

Construction and performance properties of the fabric samples were tested with the focus on assessing their durability and comfort. Many of the tests performed in this study are requirements in MIL DTL 44436. Due to cost and time constraints it was necessary to modify some of the testing and in those instances, the variations from the standard method will be detailed. Except for a few instances, testing was performed under standard atmospheric conditions of 21˚C +/-2˚C and a relative humidity of 65% +/-5%. Due to fluctuations, there were times when the atmospheric conditions were slightly out of the acceptable range. All testing except for thermal resistance testing was conducted in the NCSU Dame S. Hambly Physical Testing Laboratory; the thermal resistance testing was conducted in the NCSU Textile Protection and Comfort Center (TPACC). All test samples were left in standard conditions for at least one week prior to testing to allow sufficient time for the conditioning. In all cases, specimen were cut from the middle 80% of the fabric width and care was taken to ensure that maximum representation of the length and width of each fabric sample was achieved.

A majority of the test methods used in this experiment are those required by MIL-C-44436. As previously stated, fabric properties measured were yarn count, thickness, weight, tear and tensile strength, abrasion resistance, stiffness, air permeability and thermal resistance. Test Methods used to measure these properties are identified in Table 4.

Table 4 Test Methods Used in this Study

Test #	Title
ASTM D 3883	Standard Test Methods for Yarn Crimp and Yarn Take-up in Woven Fabrics
ASTM D 3776	Standard Test Method for Mass per Unit Area (Weight) of Fabric
ASTM D 1777	Standard Test Method for Thickness of Textile Materials
ASTM D 1388	Standard Test Method for Stiffness of Fabrics
ASTM D 5034	Standard Test Method for Breaking Strength & Elongation of Textile Fabrics (Grab Test)
ASTM D 1424	Standard Test Method for Tearing Strength of Fabrics by Falling-Pendulum Type (Elmendorf) Apparatus
ASTM D 737	Standard Test Method for Air Permeability of Textile Fabrics
ADTM D 4966	Abrasion Resistance to Textile Fabrics (Martindale Abrasion)
ASTM D 1518	Standard Test Method for Thermal Transmittance of Textile Materials

These tests were selected because together, their results will provide a good indication of how the addition of the electrically conductive network and resulting $float_{max}$ length and location changes will affect the fabric's comfort and durability.

Comfort is a difficult property to asses because it is a combination of many individual fabric properties such as stiffness, cover factor, breathability, thickness, weight and thermal transmittance. When a soldier is performing a critical mission in theater, comfort becomes a safety issue. If the uniform becomes uncomfortable, there is always the risk that the soldier will alter it or not wear it properly to alleviate the discomfort, thus reducing the level of protection it provides..

The durability of a fabric is its ability to perform appropriately when subjected to conditions that approximate its actual end use. [52] Several test methods can be used to do this, most involving the application a physical or mechanical force until fabric failure. It is difficult to assess the durability of a fabric in a laboratory environment because most testing involves the application of one type of force at a time, rarely is this the case in the actual use of the BDU.

4.3.1 Thread Density

Thread density was measured in each direction of the fabric. This is an important parameter of fabric construction because it influences many properties such as air permeability, thermal resistance, weight, thickness, tensile and tear properties. The BDU specification, MIL DTL 44436 has a stated requirement for a minimum of 41 yarns/cm (104 yarns/inch) in the warp direction and 21.5 yarns/cm (54 yarns/inch) in the fill direction. To meet this requirement weaving parameters were set accordingly.

ASTM D 3775 Standard Test Method for Warp (End) and Filling (Pick) Count of Woven Fabric is the method required by MIL DTL 44436 to measure this parameter. Due to the high thread density of this fabric, it can be difficult to count the yarns per square area accurately, even using the ravel method. To improve the accuracy of the measuring process, an alternative method where the number of repeats in a certain length of fabric is counted and multiplied by the number of yarns within the repeat and then converted to thread density per cm. Since the fabric is a ripstop pattern with grid like squares, the pattern repeat is easily defined and counted over a long length of fabric. The number of repeats in a given length was converted to yarns per cm by the following equation:

$$D_1 = \frac{R \times 25}{L}$$

$$D_2 = \frac{R \times 28}{L}$$

Where:

D_1 = warp density (1/cm)

D_2 = pick density (1/cm)

R = number of repeats

L = length of fabric measured (cm)

4.3.2 Fabric Weight (Mass per Unit Area)

Fabric weight relates to both the comfort and durability of the fabric and is also used during testing to determine other fabric properties. The heavier a fabric is, generally the more durable it is. However, a heavier fabric will cling more to the body when a wearer is sweating, decreasing comfort. MIL DTL 44436 has an accepted weight range requirement of 203.4 to 237.342 g/m^2 (6 to 7 oz/yd^2) and ideally test results would show that the fabric with an electrically conductive network would remain within these requirements.

ASTM D 3776 Standard Test Method for Mass per Unit Area (Weight) of Fabric, Option C - Small Swatch of Fabric was used to determine the weight of the fabric. Ten specimen dimensioned 10x7.5cm each were cut from the fabric samples to ensure full representation of the length and width of each fabric sample. Each test specimen was weighed on the Mettler DeltaRange PM480 Scale, Serial# L57461 and the mass recorded out to three significant figures. ASTM D 2776 requires that each test specimen be weighed to within 0.1% of its mass; however, this was not possible because no scale in the physical testing laboratory was that accurate. These test results were then used to calculate weight of each fabric using the following equation from ASTM D 2776

$$\frac{g}{m2} = M \times \frac{10{,}000}{LW}$$

Where:
M = mass of specimen in grams
L = length of specimen in cm
W = width of specimen in cm

4.3.3 Yarn Crimp

Yarn crimp is an important parameter of fabric construction to measure because it affects the tensile, elongation and air permeability properties of the fabric. There are several factors that will affect the yarn crimp in the fabric including weave pattern and amount of yarn tension during weaving. ASTM D 3883 Standard Test Methods for Yarn Crimp and Yarn Take-up in Woven Fabrics was used to determine the amount of yarn crimp in the warp and filling direction. The test method required a marked specimen length of 250 mm but in this case 305 mm was used. Ten yarn specimen were very carefully individually raveled from this length. Two of the ten specimen were yarns from the ripstop rib and the remaining eight were from the plain weave of the fabric. There are three options in this test method that can be used to straighten out the crimped yarn, a Crimp tester, a CRE type tensile tester or hand tension. Option A, the method to measure crimp by hand was used, although it is considered the least accurate. The individual yarns were carefully straightened with hand tension and measured to the nearest 1mm. Yarn crimp was calculated using the following equation found in ASTM D 3883.

$$C = 100\frac{Y - F}{F}$$

Where:
C = yarn crimp %
F = distance between marks on fabric (305 mm)
Y = distance between marks on yarn removed from fabric

4.3.4 Thickness

Thickness is a property that can affect the warmth, weight and stiffness of a fabric. A change in thickness can have an effect on abrasion resistance, air permeability, and stiffness. Additionally, thickness directly affects the thermal insulation of the uniform as the thicker it is the warmer the garment is. Thickness of a fabric is a function of yarn size, weave design, thread density in the fabric and can change during subsequent dyeing and finishing operations. MIL STD 44436 does not have a specified thickness minimum or maximum requirement so Sample 1 will be used as a baseline when evaluating the thickness of the experimental samples.

ASTM D 1777 Standard Test Method for Thickness of Textile Materials, Testing Option 1 was used to measure the thickness of the samples. This option uses a dead weight and a 38 mm diameter anvil to lower a 28.7 mm diameter presser foot and apply 4.14 kPa of pressure to the fabric sample. This standardized amount of pressure is required to produce consistent thickness values. Because of this, it is important to note that the tested thickness is not the actual thickness of the fabric when worn as clothing. Thickness was measured on ten specimen obtained diagonally across the length and width of the fabric. Care was taken to gradually lower the presser foot down onto the fabric in a consistent manner to obtain reliable and accurate thickness values. Thickness of the fabric while being worn as a BDU is not the same as the thickness of the fabric when being tested. This is because the anvil of the thickness tester provides a standard amount of pressure. An Ames Logic Basic Model

BG1110-1-04 thickness tester with digital read out conforming to the ASTM requirements was used. Thickness values were recorded after five seconds out to 0.02 mm as required by Testing Option 1.

4.3.5 Stiffness (Flexural Rigidity)

Stiffness is very a very important factor in determining comfort. Fiber type, fiber denier, yarn and fabric construction all contribute to the stiffness properties of a fabric. The stiffness of a fabric affects its hand and appearance and contributes to the comfortability of a garment. If a fabric is very stiff, it will have a neater and crisper appearance. However, if the fabric is overly stiff, it may cause chafing or irritation to the soldier. Conversely, if a fabric is too pliable, it will cling to the soldier when it is moist and become uncomfortable. [53] Stiffness is determined by the type of fibers in the yarn are as well as yarn geometry and fabric construction. Flexural rigidity is a way to measure the stiffness of a fabric because it measures the degree to which a fabric bends under its own weight. Stiffness is not a required test method for the standard BDU fabric and so there is no required level of minimum or maximum stiffness, however, since preliminary yarn testing showed that the e-yarn is stiffer than the standard yarn, fabric stiffness will be measured. The test results will be evaluated comparatively using the results of Sample 1 as a baseline.

To measure how stiff the samples are in comparison to the standard, ASTM test method ASTM D 1388 Option A, the cantilever test, was used. In this test, the length of the fabric overhang is read off the apparatus and converted into bending length by the following equation from ASTM D 1388:

$$C = \frac{O}{2}$$

Where:
C = bending length in mm
O = length of overhang in mm

Weight is an important factor in calculating stiffness from bending length because two fabrics of can have the same overhang length but if one fabric is heavier than the other, it will feel stiffer because it has a greater resistance to bending. The following equation is a result from the modification of the ASTM D 1388 equation used to convert bending length into flexural rigidity reported in units of torque, µjoule/meter into µjoule/cm.

$$G = (1.421 \times 10^{-5} \times W \times C^3)100$$

Where:
G = flexural rigidity in µjoule per meter

W = fabric mass per unit area in grams per centimeter^2

C = bending length in mm.

ASTM D 1388 requires that four warp and four fill direction samples be tested. The equipment used was a commercially available motorized cantilever bending tester manufactured by IDM Industries. This apparatus uses a motorized feed unit to slide the sample off the ledge at a constant rate of 115 mm/min. The apparatus was leveled and ensured to be within calibration before testing began.

4.3.6 Breaking Force and Elongation

During actual use of the BDU, the fabric does not usually encounter the forces necessary to cause a failure in the fabric, however, strength and elongation testing is an important factor in evaluating the durability of the fabric during use. It measures the force required in one direction to pull the fabric to failure as well as the amount of elongation the yarns experienced while under load.

Several fabric construction parameters affect the breaking strength and elongation of a fabric, fiber strength, yarn construction and strength, weave, direction of test and fabric density all have an effect on the strength and elongation of a fabric. [54] The fabric samples have a weave that is primarily plain and so ASTM D 5034 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test) was used to test the breaking strength and elongation of the fabric samples. The grab is a more realistic and efficient method of determining these properties compared to the ravel strip method because, the fabric that overhangs the jaw plates plays a role in the strength properties of the material. This is called "fabric assistance" and occurs because the additional fabric outside the jaws helps to absorb the load. However, elongation results from this type of test may not be as meaningful as those from strip tests because of the fabric assistance effect and because the fabric within the jaw elongates at a different rate than fabric outside the jaws. [55]

The test method requires that five specimen be tested in the warp direction and another eight in the filling direction. Due to the limited amount of fabric samples only five specimen were used in the warp and filling direction. A constant rate of extension (CRE) tester, the Q-Test/B Elite™ Controller was used. The jaws were lined with rubber to prevent fabric slippage during the test. The BDU standard requires that the fabric have a minimum break force of 890 newtons (200 lbs) in the warp direction and 400 newtons (90 lbs) in the filling direction.

4.3.7 Tear Strength

Tear strength or resistance to tear is a very important factor in the durability of the BDU. The weave of the fabric was designed to impart tear resistance through the use of warp and filling ribs that weave two yarns together and improve the tear resistance of the mostly plain weave fabric.   During a tear, these ripstop ribs improve tear resistance by working together to sustain the load until they eventually rupture. The two yarns that are woven together as the ripstop rib will tear together and as result in a higher tearing strength because they are not interlaced as much. [54] There are cases where tear strength is considered the most important property of a fabric.

Tearing strength is determined by the mobility of the yarns in the fabric. This is the fabric's ability to allow individual yarns to slide past one another and pack or jam together resulting in an increased tear force. Yarn type, fabric density, weave pattern and $float_{max}$ length all are factors that contribute to the tear strength of a fabric. When a group of yarns is constricted and cannot move, the tear strength is decreased, sometimes to a point that is equal to the break strength of just one yarn. [56] In contrast to break force, tearing force is only concentrated on a few yarns in the fabric at any one time. [54]

ASTM D 1424 Standard Test Method for Tearing Strength of Fabrics by Falling Pendulum Type (Elmendorf) Apparatus with a mounted slit cutter and a maximum capability of 6400 grams was used to measure the force needed to propagate a tear in the fabric. The Elmendorf apparatus can almost be considered to be an impact tear force as the time to tear is generally less than 1 second.[55] Tear strength in fabrics varies during the test because as the yarns move and shift the load increases. At the point where the yarns cannot move or shift any further, the load required to continue the tear peaks, the fabric becomes jammed and the yarns break. Then the load is reduced but maintained and a different group of yarns begin to move and shift continuing the process until fabric is ripped in two.

This test is more realistic than other methods of tear because it is much faster and approximates a tear occurring through actual use. The indicator reading on the Elmendorf should be between 20 and 80% of the load capability to maintain accuracy. Test results outside of the tester capability are cause to move to the next higher load capability. Five specimen in the warp and another five in the filling direction were tested. When the test is performed in the warp direction, the yarns that are actually being tested and torn are the filling yarns. This is called a filling torn sample. When the test is performed in the filling direction, the warp yarns are being tested and the sample is identified as warp torn. The equation to determine the tearing force is as follows:

$$Tearing\ force = R_s \times \frac{C_s}{100}$$

Where:

R_s = scale reading

C_s = full scale capacity (6400 grams/force)

MIL DTL 44436 requires that the BDU fabric have a Elmendorf tear strength of at least 3175 grams (7 pounds) in the warp direction and 2258 grams in the filling direction (warp yarns).

4.3.8 Martindale Abrasion Resistance

Abrasion occurs on fabrics through the wearing or laundering of a garment. Fabric wear is the amount of deterioration imparted to the fabric because of fiber or yarn breakage, cutting or loss of fibers. Resistance to abrasion is one of the most important tests that can be performed to determine the wear of a fabric.

Typically clothing such as the BDU would experience abrasion in a flat and/or flexing configuration. Flat abrasion is when two fabric surfaces rub against one another and in this type of wear it is the crowns or high points of the yarn cross-overs that suffer the most damage. Flex abrasion is when the fabric is bent and straightened, folded and unfolded, like at the inside of the elbows or abdomen area. This would also take place during laundering.

There are several fabric construction properties that affect abrasion resistance including fiber type, yarn and fabric structure. As mentioned before, the yarn used in the BDU fabric is an intimate blend of nylon and cotton stable fibers. The addition of nylon in the BDU fabric improves its abrasion resistance, which is good because although staple yarns can hide abrasion and make wear less obvious, they are generally less abrasion resistant than filament yarns.

ASTM D 4966 Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method) was used to assess the flat abrasion resistance of the fabric samples. The six-head James H. Heal & Co Ltd Nu-Martindale Abrasion & Pilling Tester SN#403/97/2073 and the lighter 9kPa mounting weights were used. The abradant was the standard fabric identified in the test method, a new piece of plain weave worsted fabric mounted on top of the standard felt padding. The test method requires three specimens to be tested but due to time constraints, one specimen was tested for the face and back of each fabric sample. The specimen were mounted with a disk of polyurethane foam and run for 30,000 cycles and checked after every 10,000 cycles. There are several different factors to consider when selecting an abrasion test: motion, abradant, pressure applied, sample tension, wet or dry, lint removal, how to determine an end point. [56] Pictures and visual evaluations were used to assess the degree of abrasion on the samples. Option 1 was used for evaluation, the specimens were run until two yarn breaks occurred or to 30,000 cycles, whichever came first.

Because of its tight weave structure the BDU fabric is known to very abrasion resistant and durable however, there is no specified test to determine the abrasion resistance of the fabric. In field trials, durability and resistant to abrasion and wear have been conducted by having soldiers complete a lengthy obstacle course where they have to climb, slide or crawl through various structures. At the end of the trial, the BDUs are examined for their abrasion resistance and durability [35] As this was not an option, flat abrasion testing was conducted and Sample 1 will serve as a baseline and standard for the performance of the experimental samples.

4.3.9 Air Permeability

Air permeability is used to describe the breathability of a fabric and directly affects its comfort by controlling convective heat loss and moisture evaporation and protects from wind penetration. Several basic fabric construction properties have an effect on the ability of air to flow through the openings (pores) of a fabric; thickness, weave pattern, yarn crimp, yarn construction (twist), cover factor and type of finishing will have a positive or negative impact on breathability.

ASTM D 737 Standard Test Method for Air Permeability of Textile Fabrics was used to measure the air permeability (breathability) of the fabrics. This test method measures the amount of perpendicular air flow through a known area of fabric and adjusts that rate to obtain a prescribed air pressure differential between the face and back fabric surfaces. This air flow rate is then converted into air permeability described as air flow in cubic feet per minute passing through one square foot of fabric ($ft^3/min/ft^2$).

A manually operated Frazier High Differential Pressure Air Permeability Tester was used to measure the air permeability of the fabric samples. This equipment measures the air flow in cubic feet per minute passing through one square foot of fabric under a pressure drop equal to a ½" of water. The equipment was ensured to be level and within calibration before testing began. The height of the meriam red oil in the vertical manometer is recorded and converted into $ft^3/min/ft^2$ through the use of the Frazier Precision Instrument conversion table. Further conversion is needed to convert that into the SI units of $cm^3/s/cm^2$. [55] The fabric was tested face-up on the Frazier Tester, then tested in the face-down configuration. Air Permeability readings were taken in a broad distribution across the length and width of the sample. Eleven air permeability readings were taken in the face-up direction and five in the face-down configuration. Test location was positioned to obtain a thorough representation of the fabric.

As wind resistant fabric, the BDU specification, MIL STD 44436 requires that the end state BDU fabric have a maximum air permeability value of 7.62 $cm^3/s/cm^2$ (15 $ft^3/min/ft^2$) for regular uncoated BDU fabric and 5.08 $cm^3/s/cm^2$ (10 $ft^3/min/ft^2$) for water repellent or wrinkle free finished fabrics. The fabric samples used in this study are greige and as such do not have the same degree of air permeability as the finished fabrics. The dyeing processes washes and abrades the fabric, reducing its weight and cover, thus increasing it air permeability, while tentering, calendaring will change the thread density of the fabric and flatten the yarns to decrease the openings between the yarns and result in a decrease in air permeability. While the MIL DTL 44436 requirements will be considered, the most important comparisons will be between the baseline Samples 1 and the experimentals. The differences between these will be looked at closely to determine the impact on soldier comfort.

4.3.10 Thermal Transmittance

The transfer of dry heat away from the body, through clothing is the major route for body heat loss. [57] Just like any article of clothing, the BDU creates a micro climate for the wearer. Unlike civilians who have the ability to change their clothing at any point to compensate for changes in the weather or activity level, the soldier wears the uniform through it all. The BDU needs to perform well in warmer and cooler conditions, although extreme temperatures call for the use of alternate uniforms. The BDU is worn by soldiers performing office duties as well as those out on the battle field. It is not uncommon for a soldier to have long periods of rest followed by periods of extreme exertion and then to rest again. [33]

Thermal resistance is the measure of a fabrics ability to stop heat flow through the fabric. Thermal transmittance is a measure of the amount of heat that is transferred from one side of the fabric, to the other and takes into account the temperature on both sides of the fabric. Thermal insulation is a measure of how well the fabric layer prevents heat loss through conduction, convection or radiation. Thermal insulation occurs through the use of dead air spaces in the fabric and between the skin and the fabric. In textile fabric, generally the thickness of the fabric determines its insulation and to a lesser degree the density and porosity of the fabric. There are three primary factors that affect the thermal comfort of any garment: air temperature, relative humidity and wind speed. Other variables are the amount of activity that the soldier is engaged in and the insulation value of the uniform. [58] Clo is a unit of measure for thermal resistance defined as the insulation required to keep a resting man comfortable in an environment at 21°C, air movement less than 0.1 m/s. It has been reported that an increase or decrease in clo value of 0.1 is the minimum change that can be detected by the human body. Thickness and density of the fabric are major factors in determining it's thermal resistance. [57, 59] MIL STD 44436 does not have a specified thermal resistance requirement so Sample 1 will be used as a guide when evaluating the thermal properties of the experimental samples.

ASTM D 1518 is used to determine several thermal transmission coefficients for a fabric exposed to a set of tightly controlled thermal and environmental conditions. The requirements identified in ASTM D 1518 were modified for this study. A 12.7 cm (ASTM requires a minimum of 15.25 cm square) square fabric specimen was place face-up on the guarded hot plate. The plate was set to 35°C with the guard ring set to 35.4°C to help maintain the hot plate temperature. As soon as the specimen was in place the timer was started. After 3 minutes, a reading on the amount of watts needed to maintain the 35°C temperature plate was taken. The equipment takes one full minute and during this time, the equipment chamber temperature and %RH was recorded. Then this process was repeated four more times and the temperature was recorded at 3, 6, 9, 12 and 15 min. The ASTM requires that the measurements be taken every three minutes for a total of thirty minutes but due to time constraints this was not possible for every specimen although some were tested for the full time.

The recorded readings are the amount of power required to maintain the hot plate at 35°C while covered with the fabric. These readings are converted into watts/m°C by the following equation:

$$W = \frac{R}{P - T} \times 0.01$$

Where:
W = watts/m°C
R = reading
P = plate temperature (body temperature)
T = recorded temperature in the test chamber

The resulting value was converted into clo using the following equation

$$Clo = \frac{\left(\frac{1}{W}\right)}{0.155}$$

Where:

W = watts/m°C

Use of clo as a unit of measure was chosen because it is a generally accepted unit of measurement for the insulation properties of clothing.

4.4 Statistical Software, Analytical Model Used

The thirteen fabric samples with three different factors were evaluated for the fabric construction and performance variables identified in Table 4. The effect of each of the factors and their interactions were studied using statistical analysis in JMP software. First the effect of each of the factors and levels was evaluated individually. Then comparisons were made between the baseline sample and the best experimental, the varying levels of conductive network and finally between the replicates and the experimentals. Since the sample sizes used for this evaluation was limited, a p-value of 0.10 was used to determine if the factor or interaction had a statistically significant effect on the property.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Raw Material

The individual results for the characterization of the nylon/cotton yarn is located in Appendix B, Tables B1 and B2, the e-yarn data is located in Tables B3 through B6. Average results for the nylon/cotton yarn are in Table 5 and the average results for the e-yarn is located in Table 6.

Table 5 Nylon/cotton Yarn Characterization

Characteristic		Std nylon/cotton warp	Std nylon/cotton filling
Denier		263.50	334.24
Break force (gf)	M	578	700
	SD	54	54
Break Strength (gf/denier)	M	2.19	2.09
	SD	0.205	0.006
Elongation (%)	M	15.42%	17.23
	SD	2.41	3.06

Table 6 e-Yarn Characterization by Cone

Characteristic		Avg All	A	B	C	D
Denier		730.18	701.0	681.0	783.3	755.40
Break force (gf)	M	681	683	587	752	695
	SD	51	49	25	70	61
Break Strength (gf/denier)	M	0.933	0.974	0.861	0.960	0.920
	SD	0.070	0.070	0.037	0.089	0.081
Elongation (%)	M	12.71	13.58	12.02	12.42	13.02
	SD	2.21	1.87	1.75	2.52	2.69

As expected, the e-yarn is much larger/heavier than the nylon/cotton yarns. The e-yarn has an average denier of about 730 compared to the nylon/cotton warp yarn that has an average denier of 263.5 and the nylon/cotton fill yarn that has an average denier of 334.24. It is important to note that although the e-yarn denier is much greater than the regular nylon/cotton yarn it is not double the size, the increase in denier is largely due to the addition of the copper yarn that have a much greater density then the nylon and cotton fibers.. The deniers of the three types of yarn used in this study are obviously significantly different from each other and will result in different fabric properties.

An All Pairs Tukey-Kramer Test revealed that the e-yarn and nylon/cotton warp yarns have different break strengths while the nylon/cotton filling and the e-yarns are statistically similar. See Figure 16 for the comparison circles that resulted from this test.

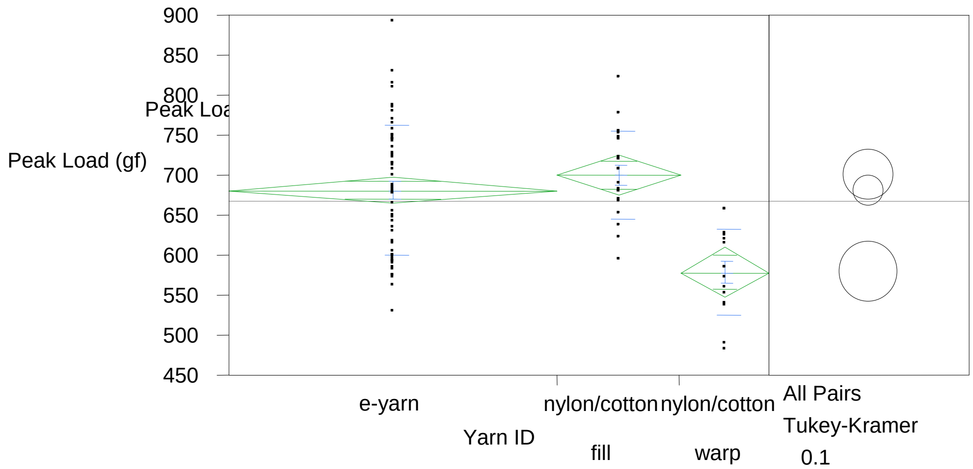

Figure 16 Effect of Yarn Type on Yarn Strength

When looking at the percent elongation of the three types of yarn used in this study, the e-yarn is significantly less extensible from the nylon/cotton warp and fill, see Figure 17 for a description of the data that shows that the e-yarn has less elongation than both the nylon/cotton warp and fill yarns. Comparison circles show that the e-yarn elongation is significantly different from the nylon/cotton warp and filling yarns. This will probably result in lower overall fabric elongation and lower yarn crimp for these yarn vs. the nylon/cotton yarns.

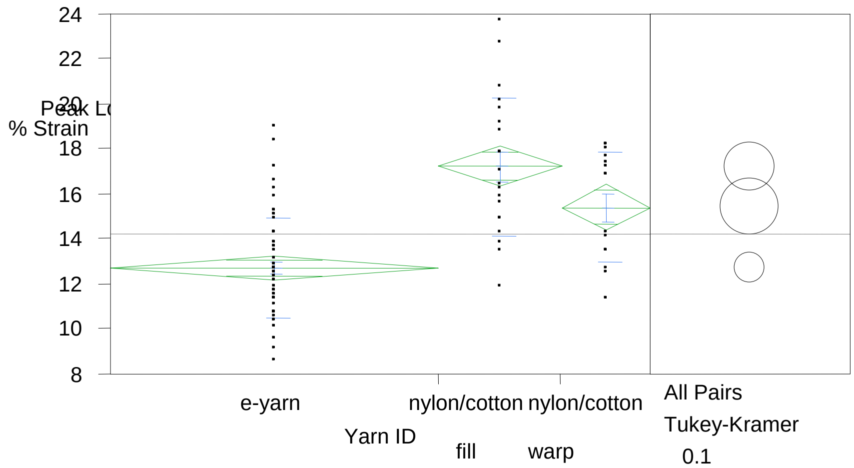

Figure 17 Effect of Yarn Type on Yarn Elongation

5.2 Weave Factor and Fabric Tightness

As the float$_{max}$ length in the nylon/cotton fabric construction increases the weave factor also increases and causes the fabric tightness to decrease as shown by the results in Table 7. The change from having all the floats$_{max}$ located on both sides of the fabric (Weaves 1, 2 and 3) to only one side of the fabric (Weaves 4 and 5) did not cause difference in the warp or fill direction weave factor and tightness. This is because the warp float$_{max}$ were relocated to the same side by adjusting the interlacing, not changing the number of interlacings.

Table 7 Weave and Tightness Factors for Nylon/Cotton Samples

Sample ID	M_1	Warp Tightness Factor	M_2	Filling Tightness Factor
1	1.042	0.959	1.077	0.939
2	1.130	0.885	1.144	0.883
3	1.218	0.869	1.194	0.860
4	1.130	0.885	1.144	0.883
5	1.218	0.869	1.194	0.860

5.3 Summary of Data

Table 8, provides a summary of the average value for each tested property grouped by sample identification. Tables of individual data from each property tested are in Appendix E, Tables E1-E11.

Table 8 Summary of Property Averages by Sample ID

Property	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
Warp Density (1/cm)	39.93	40.43	41.67	40.36	40.44	39.92	40.52	40.44	39.84	40.27	40.45	40.29	40.40
Pick Density (1/cm)	23.25	23.33	22.78	23.25	23.53	22.72	22.78	22.97	22.68	23.33	22.81	22.95	24.16
Warp Crimp (%)	26.8%	24.9%	24.8%	25.6%	25.1%	24.8%	23.8%	22.7%	23.4%	23.1%	24.3%	23.3%	25.1%
Fill Crimp (%)	5.4%	5.5%	5.6%	5.8%	6.5%	5.4%	4.8%	5.4%	4.7%	5.2%	5.7%	5.0%	5.4%
Thickness (mm)	0.62	0.74	0.86	0.81	0.86	0.70	0.84	0.95	0.85	0.91	0.95	0.90	0.90
Weight (g/m2)	229.446	229.668	228.963	230.955	231.413	257.033	263.058	258.443	260.250	258.951	255.561	258.567	247.223
Stiffness, (ujoule/cm)	0.720	0.837	0.756	0.821	0.843	1.126	1.217	1.252	1.139	1.256	1.295	0.015	1.005
Breaking Force, Warp (newtons)	1171	1157	1142	1138	1120	1142	1150	1123	1125	1120	1162	1134	1092
Breaking Force Fill (newtons)	621	642	645	622	623	630	672	608	659	624	624	605	662
Warp Elongation (%)	60.0%	57.8%	56.4%	56.8%	56.7%	54.8%	54.6%	53.4%	53.5%	52.0%	54.9%	54.0%	51.5%
Fill Elongation (%)	25.3%	26.5%	27.9%	25.9%	26.9%	24.8%	26.7%	26.1%	25.9%	24.7%	26.5%	26.1%	27.3%
Warp Elmendorf Tear (gf)	4838	5350	6272	5747	6387	4544	5286	5978	5446	5715	5286	5421	5760
Fill Elmendorf Tear (gf)	3085	3494	4723	3930	4966	2624	3802	3942	3872	3814	2906	3763	5478
Air Perm, Face-up ($cm^3/s/cm^2$)	2.524	4.840	6.940	4.779	6.671	3.128	5.546	8.087	5.663	7.971	6.067	8.223	8.245
Air Perm Face-down, ($cm^3/s/cm^2$)	2.652	4.712	6.630	4.843	6.976	3.034	5.175	7.510	5.513	7.527	5.346	7.392	7.333
Thermal Transmittance Face-up (clo)	0.459	0.478	0.474	0.470	0.483	0.467	0.466	0.463	0.464	0.479	0.471	0.482	0.501
Thermal Transmittance Face Down (clo)	0.451	0.469	0.467	0.449	0.460	0.449	0.458	0.464	0.452	0.460	0.458	0.456	0.471

5.4 Data Analysis and Discussion

The effect of the three factors, yarn type, $float_{max}$ length and $float_{max}$ location, and their associated levels was understood through the use of One-Way Analysis of Variance (Fit Y by X) using SAS JMP® 7.0 software. The Fit Y by X test is used to understand the relationship between two variables, one a predictor and the other a response. In this study the predictors used are the factors of yarn type, $float_{max}$ length and location. The responses are the fabric properties. The results from the test will show the effect that the different levels within each factor has on the individual fabric properties. This test assumes that the fabric samples and the resulting measurements are independent, that the measurements are random and normally distributed and that the variances between the samples are equal. It is clear that the measurements are independent, however, identifying if the data is normally distributed is difficult, especially because the sample sizes are small for this study so it is assumed that the data is distributed normally.[60] A one-way ANOVA was preferred over a fit model for two reasons; first a fit model could not be used because a full factorial design was not used in setting up the test. Second, compared to Fit Model, the Fit Y by X is a conservative estimate of the differences of the mean results for each of the levels because all the error is assigned as random error between and within the variables. This is a more conservative analysis because the fit model method assigns variation to each factor (treatment) and therefore may not detect the more subtle differences between factor levels.

The null hypothesis in this study is that the evaluated factor does not have an effect on the measured fabric property and that there is no difference between the groups of data.
The alternative hypothesis of this study is that the evaluated factor did have an effect on the measured fabric property and that there is a difference between the groups of data.

The alpha (α) used in this study is 0.10 and is the probability threshold for a decision to retain or reject the null hypothesis. $\alpha = 0.10$ was used because the sample size of the study is relatively small and is generally used in experimental models. A p-value of less than 0.10 indicates that there is a less than 10% probability that the sample means are from the same distribution. The main factors that were evaluated for their effect on the measured properties were yarn type (with or without the network), $float_{max}$ length and $float_{max}$ location. Table 9 provides a summary of the measured properties grouped by factor and level. Factors of yarn type and $float_{max}$ length were created with all samples excluding Sample 5M, which will be compared separately later. The factor of $float_{max}$ location was evaluated using all samples excepting Samples 1, 1E and 5M. The analysis was performed this way to provide a balanced way to compare the levels of $float_{max}$ location since Samples 1 and 1E have no counterpart that have the $floats_{max}$ located on only one side.

Table 9 Summary of Property Averages by Factor

	Yarn Type		Float $_{max}$ Length			Float$_{max}$ Location	
Property	e-yarn	nylon/cotton	2	5	7	both sides	same side
Warp Density (1/cm)	40.27	40.57	39.93	40.32	40.59	40.48	40.27
Pick Density (1/cm)	23.05	23.27	23.09	22.97	23.29	22.98	23.32
Warp Crimp (%)	**23.62%**	**25.42%**	**25.76%**	**24.40%**	**23.78%**	24.1%	24.1%
Fill Crimp (%)	**5.20%**	**5.79%**	5.44%	5.32%	5.57%	5.4%	5.5%
Thickness (mm)	**0.872**	**0.780**	**0.660**	**0.840**	**0.897**	0.868	0.868
Weight (g/m2)	**258.8**	**230.1**	243.2	247.9	247.3	247.139	248.027
Stiffness, all directions, (ujoule/cm)	**1.259**	**0.795**	**0.923**	**1.061**	**1.127**	**1.071**	**1.117**
Warp Breaking Force (newtons)	1137	1144	1157	1146	1128	1147	1127
Fill Breaking Force (newtons)	630	631	626	643	621	637	627
Warp Elongation (%)	**53.90%**	**57.53%**	**57.41%**	**55.43%**	**54.50%**	55.3%	54.6%
Fill Elongation (%)	25.82%	26.49%	**25.06%**	**26.27%**	**26.36%**	26.7%	25.9%
Warp Elmendorf Tear (gf)	**5382**	**5719**	**4691**	**5423**	**5955**	5635	5743
Fill Elmendorf Tear (gf)	**3532**	**4040**	**2854**	**3601**	**4242**	**3733**	**4069**
Air Perm, Face-up ($cm^3/s/cm^2$)	**6.384**	**5.151**	**2.826**	**5.379**	**7.579**	**6.296**	**6.661**
Air Perm Face-down, ($cm^3/s/cm^2$)	**5.928**	**5.232**	**2.864**	**5.147**	**7.217**	**5.923**	**6.497**
Thermal Transmittance Face-up (clo)	0.470	0.473	0.463	0.470	0.476	0.470	0.476
Thermal Transmittance Face Down (clo)	0.457	0.459	0.450	0.457	0.462	0.463	0.456

Highlighted values in Table 9 indicate that the resulting p-value was greater than 0.10 and that the null hypothesis was rejected. This means that the evaluated factor did have a statistically significant effect on the measured fabric property and that there is a difference between the averages of the groups. However, only the bold values exhibit a more than 5% difference between the factor levels. A difference of 5% or greater is being used to define a practical difference. Of particular interest is how the change from the standard BDU fabric to the conductive BDU fabric will compare to the baseline fabric as well as the current requirements in MIL- DTL 44436.

All resulting F-ratio's and p-values from JMP® testing are documented in Appendix C. Since ANOVA depends upon equal variances between the factor levels, a Levene Test to determine equal variances was conducted on each data set. Levene was chosen because it does note assume a normal distribution. When the Levene test determined the variances between the levels within a factor to be unequal, The F-ratio and p-value resulting from the Welch ANOVA testing was used to determine if the averages were significantly different. In all cases, where ANOVA identified a statistical difference with unequal variances, the follow-on Welch ANOVA testing also identified the differences as statistically significant. Graphs of the most important properties resulting from the one-way ANOVA data was created in JMP® in included in this report. These graphs show the individual data points for the factor levels as well as means diamonds to illustrate the differences between the mean and the median of each group. The top and bottom points of the means diamond indicates the upper and lower 90% confidence points. The JMP software assumes that the variances between the groups are equal, but this assumption was verified by the Levene Test. When the variances were found to be unequal, the Walsh ANOVA test was used to determine the p-value. The horizontal line within the diamond shows the mean value of the data. The width of the diamond is proportional to the number of data points within the group. This is important as many times when the data was grouped by the factor levels, the sample size of each group varied. For the factor of $float_{max}$ length, comparison circles were generated using HSD Tukey-Kramer analysis. The size of the circle indicates the amount of variance in the group, the larger the circle the more variance. The location of the circles to the horizontal line indicates how close that group was to the average (grand mean) of all the samples together. The proximity of the circles to each other shows how similar the groups are to each other, separation of the circles point out a difference between the averages.

The All-pairsTukey-Kramer comparison circles show how the levels within each factor are different. However, it was desired to dig deeper and determine the comparisons between each sample for a particular fabric performance property so JMP® was used to run a paired student's t test to make individual comparisons between two Sample IDs. The data resulting from this test is summarized in a connecting letters report. This testing will clearly show which samples are statistically similar and different according to a particular fabric property. The connecting letters report first puts the samples in order of descending test result. Then samples with similar test averages are grouped together and assigned a letter (A, B, C, etc). Where the letters connect across the row, no statistical difference is noted. When the letters are not connected across the row, these samples are identified as have statistically different test averages.

In Section 5.6, Sample 5M (partial network) will be compared to Sample 5 (no network) and Samples 5E and ER (full network) to determine if there is any advantage to putting less network in the BDU fabric. When applicable, baseline Sample 1 will be compared to the best performing sample in terms of conductivity, Sample 5E and 5ER. This is one of the most important evaluations this study will attempt to make because this is the weave pattern and network configuration that is the best performing in terms of electrical conductivity. The conductive performance is optimized in Samples 5E/5ER because the longer $float_{max}$ lengths create a straighter line for the e-yarns and locating all the $float_{max}$ on one side enables more interconnect sites to create the continuous network .

Comparison of the two replicates against their associated experimentals is located in Appendix D. This comparison was performed to determine if the 2ER and 5ER samples were truly were a replicate of the entire weaving process. As previously stated, Samples 2E and 5E were replicated after all other samples were woven.

5.5 Explanation of Test Results Properties

5.5.1 Thread Density

The on loom setting for pick density was 39.27 picks/cm (52.36 picks/cm). The on-loom warp density was set to 20.5 ends/cm (52 picks/inch); the warp sheet consisted of 3432 ends through a 67" wide reed, drawn 3 ends/dent. The finished BDU fabric is required to have 41 picks/cm (104 picks/inch) and 20.5 ends/cm (52 ends/inch). During the measurement of the warp and pick density, no problems were encountered. Since the number of yarns measured over a length of fabric was so large (range was 476 – 2375 yarns) only one determination was made in each direction on each fabric. Raw data for this test in listed in Appendix E, Table E1 and the average results for each sample is listed in Table 8. As seen in Table 9, yarn type, $float_{max}$ length and $float_{max}$ location did not have an effect on the thread density of the fabric.

5.5.2 Yarn Crimp

During the measurement of warp and filling crimp, no problems were encountered. Individual data resulting from these tests is listed in Appendix E, Table E2A&B. Table 8 provides the average warp and filling crimp for each of the thirteen fabric samples. There is a large difference in the warp and filling crimp because the two different yarn types behave differently in weaving. The shedding motion during weaving causes the large degree of crimp in the warp direction while the filling yarn is essentially inserted straight through the open shed. If the fabric samples had not been evaluated in greige state but rather in the finished form, the difference between the two directions might not have been so extreme. The finishing processes, especially drying on a tenter frame, will stretch the fabric in the warp and fill directions causing a change in the measured warp and filling crimp.

As seen in Table E2A&B the distribution of the crimp test results show a high amount of sample variation with %CVs ranging from about 24.5% in the warp direction and 5.5% in the filling direction. This can probably be attributed to two reasons: first, the manual method of measuring crimp (option A) was used and is known to be the least accurate of the three allowed options in the test method. If a CRE tensile tester or a crimp tester was used, this cause for variation could have been mitigated. Second, the within sample variation can be attributed to the fact that out of the ten measurements on each fabric sample, two were from the ripstop ribs and the remaining eight were taken from the plain weave within the ripstop ribs. These two weaves result in very different crimp because their yarns interlace differently in the fabric. As seen in Table 9, only factors of yarn type and $float_{max}$ length had a statistically significant effect on the % crimp.

Factor: Nylon/cotton vs. E-yarn (conductive network)

The warp crimp was 7.11% less when the e-yarn (M = 23.62%, SD = 1.12) was used than when the nylon/cotton (M = 25.42%, SD = 0.91%) was used in the ripstop ribs. A similar effect was observed in the filling crimp as it was 10.21% less when the e-yarn (M = 5.2%, SD = 1.3%) was used than when only the nylon/cotton yarn (M = 5.79%, SD = 0.73) was used in the ripstop ribs

Yarn type affects yarn crimp because in this case, the e-yarn has less stretch or extensibility than the nylon/cotton yarn. Again, the method of manually measuring the crimp might have something to do with the results as well. Although efforts were made to be careful and precise during the test, since the nylon/cotton and e-yarn do not stretch at the same tension level, it is harder to ensure that the test is performed consistently between the two groups.

Factor: Float$_{max}$ Length (2, 5 or7)

The warp crimp was greatest when the float$_{max}$ length equaled two (M = 25.76%, SD = 1.65) than when it equaled five (M = 24.40%, SD =0.95), and was lowest when the float$_{max}$ length equaled seven (M = 23.78%, SD = 1.21). Analysis shows that the differences between each factor was statistically significant.

Float$_{max}$ length has a significant effect on the warp crimp because as the float$_{max}$ length increases, the number of interlacings decreases. Less interlacing in the fabric allows the yarn to travel in a straighter path and reducing the length of the yarn required to go through the weave. When the yarn travels a straighter, shorter path through the fabric, the amount of crimp is less. The reason filling crimp is not shown to be statistically different when grouped by float$_{max}$ length is because in this weave the filling yarn travels a much more straight path through the fabric and therefore is not as influenced by $float_{max}$ length as the warp direction yarns.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

Sample 1 and Sample 5E/5ER were found to have statistically different warp crimp. The percent of warp crimp was 13.37% less in Sample 1 (M = 26.76%, SD = 0.204) than in Sample 5E/5ER (M = 23.18%, SD = 0.77). This will lead to an effect on fabric breaking strength and elongation at break.

5.5.3 Fabric Thickness

No problems were encountered during the thickness measurements. Individual data are listed in Appendix E, Table E3. MIL-DTL-44436 does not have a thickness minimum or maximum requirement so to determine the effect of yarn type, $float_{max}$ length and $float_{max}$ location, Sample 1 will be used as the baseline. As previously shown in Table 9, only yarn type and $float_{max}$ length had a statistically significant effect on the thickness of the fabric. Sample 1 was the least thick with a value of 0.62 mm and Sample 3E and 2ER had the highest thickness of 0.95 mm. The %CV of the within sample data ranges between 1.27% and 9.3%.

Factor: Nylon/cotton vs. E-yarn (conductive network)

Fabric thickness increased 11.80% when the e-yarn (M = 0.872 mm, SD = 0.094) was used than when only the nylon/cotton yarn (M = 0.780 mm, SD = 0.097) was used in the ripstop ribs. Although the e-yarn is only located in the ripstop ribs (15% of the fabric) this addition had an effect on the thickness measurement because the diameter of the presser foot on the thickness gage is larger than the weave repeat and only measured the areas of greatest thickness. The fact that the main body of the fabric remains unchanged in thickness is not accounted for.

Factor: Float_{max} Length (2, 5 and 7)

The change in float_{max} length had an effect on the thickness of the fabric as well.
The fabric thickness was the least when the float_{max} length equaled two (M = 0.660 mm, SD = 0.052) than when it equaled five (M = 0.840 mm, SD =0.012) and was highest when the float_{max} length equaled seven (M =0.897 mm, SD = 0.052). The change in float_{max} length from two to five caused a 27.27% increase in thickness while the change in float_{max} length from two to seven caused a 35.88% increase overall.

The increase in thickness because of float_{max} length increase is because the floating yarns are not as tied down into the fabric, they are raised up on the surface of the fabric making the fabric thicker. The longer the float_{max}, the more these particular yarns are raised above the main body of the fabric surface. The pressure foot on the thickness gauge is 28.7 mm in diameter and only uses 4.14 kPa of pressure. As previously stated, the size of the presser foot is larger than the repeat of the pattern and so the thickness being measured is of the ripstop rib thickness, not of the full fabric thickness. It is important to note that while the thickness has increased significantly with the increase in float length, this is not an all-over effect. The thickness of the fabric is only increased at the $float_{max}$ locations (15% of the fabric weave construction) and therefore is a localized effect only.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

A one-way analysis of variance (ANOVA) was performed to determine if the difference in thickness between the two fabrics was significant. The fabric thickness increased 46.13% from the standard (M = 0.62 mm, SD = 0.013) to the experimental (M = 0.906, SD = 0.046). As previously stated, this increase in thickness is only found in the ripstop locations and is not representative of the entire fabric area.

5.5.4 Fabric Weight (Mass per Unit Area)

There were no issues measuring the weight of the fabric samples. Individual data is listed in Appendix E Table E4. Table 8 provides the average weight for each of the thirteen samples. This data is very consistent as within each sample there is less than 2% coefficient of variation and all but two samples have less than 1.5% variation. As noted in Table 9, the only factor that had a statistically significant effect on the weight of the fabric was the change in yarn type. The $float_{max}$ length and location factors did not have a significant effect on the weight of the fabric.

MIL-DTL-44436 has a requirement for finished BDU fabric to be between 203 and 237 g/m^2 (6-7 oz/yd^2) making all of the conductive samples out of specification tolerance. However, the weight requirement is for finished fabric though and the fabric in this study is greige state and subsequent dyeing and finishing processes may alter this weight.. To determine the effect of the three experimental factors, the weight of Sample 1 will be used as a baseline. Sample 1 was the lightest with a mass per unit area of 229.446 g/m^2 and the heaviest fabric was Sample 2E at 263.058 g/m^2.

Factor: Nylon/cotton vs E-yarn (conductive network)

From the average data shown in Table 9 it is obvious that the addition of the e-yarn had a significant effect on the weight of the BDU fabric. The fabric weight was 12.50% greater when the e-yarn ($M = 258.838$ g/m^2, $SD = 4.138$) was used than when only the nylon/cotton yarn ($M = 230.089$ g/m^2, $SD = 2.633$) was used in the ripstop ribs. The difference in averages between the two groups of samples is understandable since the e-yarn denier is two to three times greater than the standard nylon/cotton. A graphical description of the two groups of data is in Figure 18.

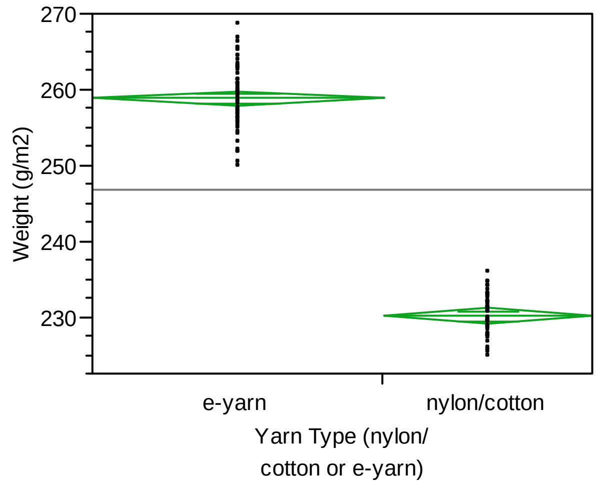

Figure 18 Effect of Yarn Type on Fabric Weight

5.5.5 Fabric Stiffness

There were no issues during this testing. Table 8 provided the average stiffness readings for each of the thirteen samples. The averages are from all four directions tests, face-up, face-down and each of the ends are combined as required by the reporting method stated in ASTM D 1388. Individual results are located in Appendix E, Table E5. The variation within each sample is large and ranged from about 23% to 44%. This is likely due to the fact that the direction of test impacts the test results. Table 9 identifies that only the two factors of yarn type and $float_{max}$ length had a statistically significant effect of the fabric's stiffness.

Factor: Nylon/cotton vs. E-yarn (conductive network)

The two different types of yarn did have an effect on the stiffness of the samples as the addition of the e-yarn made the fabric much stiffer. Figure 19 shows a description of the data.

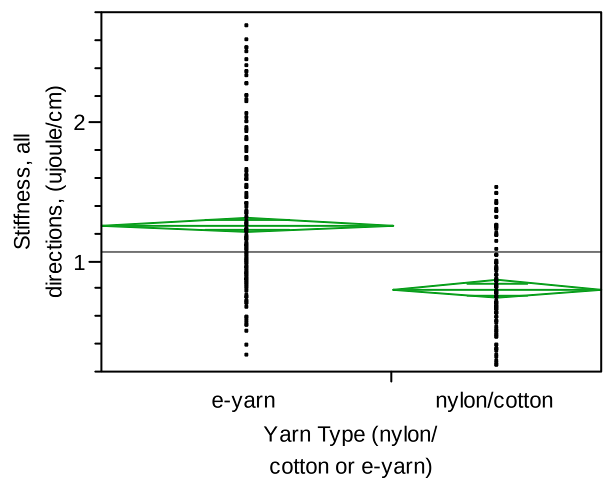

Figure 19 Effect of Yarn Type on Stiffness

The fabric stiffness was 58.31% greater when the e-yarn (M =1.26 μjoule/cm, SD = 0.0049) was used than when only the nylon/cotton yarn (M = 0.80 μjoule/cm, SD = 0.0028) was used in the ripstop ribs. This is easily explained by the fact that the e-yarn stiffness and denier is much greater than the nylon/cotton yarn stiffness and size.

Factor: Float$_{max}$ Length (2, 5, or7)

The change in float$_{max}$ length also affected the stiffness of the fabric. The fabric was the softest when the float$_{max}$ length equaled two (M = 0.009 μjoule/cm , SD = 0.004) than when it equaled five (M = 0.0106 μjoule/cm, SD = 0.004) and was the stiffest when the float$_{max}$ length equaled seven (M = 0.0113 μjoule/cm, SD = 0.005). Comparing the float$_{max}$ length of two with the float$_{max}$ length of five and a float$_{max}$ length of seven, the all pairs Tukey-Kramer comparison circles in Figure 20 shows that the differences between each factor was not found to be statistically significant. The difference between a float$_{max}$ length of two and seven produces a 22.1% increase in stiffness and as can be seen in the comparison circles in Figure 20, was the only difference found to be statistically significant.

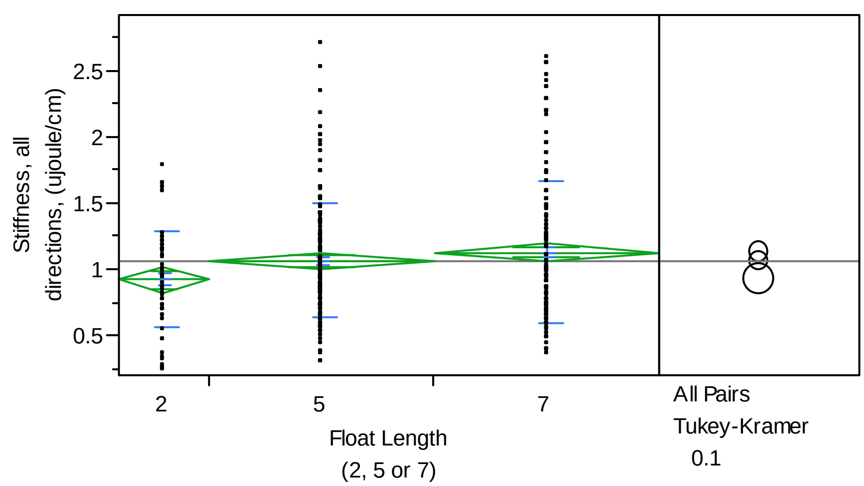

Figure 20 Effect of Float$_{max}$ Length on Stiffness

Generally, stiffness increases with shorter $float_{max}$ lengths because the smaller the $float_{max}$ length, the greater the number of interlacings. The fact that the stiffness increased when $float_{max}$ lengths increased is opposite the general convention. The only explanation for this is that as the $float_{max}$ length increases the floats in the e-yarn samples become stiffer and allow the fabric to be more rigid. When the stiffer e-yarn is in the sample with a $float_{max}$ length of two, the yarn is not allowed to be stiff because it is bent due to interlacing into the fabric.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The difference in stiffness between the standard fabric and the experimental fabric was found to be significant. The fabric stiffness almost doubled (increase of 93.4%) from the baseline Sample 1 ($M = 0.0072$ μjoule/m, $SD = 0.0009$) to Samples 5E/5ER ($M = 0.0139$ μjoule/m, $SD = 0.0009$).

Comparisons for Each Sample Pair using Students' t

The connecting letter report for this testing is shown in Table 10. This testing shows that while a majority of the nylon/cotton samples performed similarly, Baseline Samples 1 and Sample 3 are significantly different from the rest as is Sample 5ER. The e-yarn samples were less similar in stiffness and fell into three groupings and this is probably related to the varying cones of e-yarn used. Sample 5M with a partial network overlaps groups with and without the conductive network. This makes sense because when tested in the warp direction, with the e-yarn. It would behave more like the samples with a network. When tested in the filling direction, where no e-yarn was present, the sample would behave more like samples without a conductive network.

Table 10 Stiffness (μjoule/cm)

Level						Mean
5ER	A					1.5279375
2ER		B				1.2952500
5E		B				1.2558750
3E		B				1.2523438
2E		B				1.2166250
4E		B	C			1.1387500
1E		B	C			1.1264375
5M			C	D		1.0058438
5				D	E	0.8432188
2				D	E	0.8371563
4				D	E	0.8210000
3					E	0.7555625
1					E	0.7195938

5.5.6 Fabric Break Force (warp and fill direction)

There were no problems associated with this testing. The individual data for each direction is located in Appendix E, Table E6A&B. Average results for each sample in each test direction are located in Table 8 and Table 9 shows that while yarn type did not have a significant effect on the warp or fill direction break force, $float_{max}$ length affected both the warp and fill direction and a change in $float_{max}$ location only has a statistically significant effect on the warp direction testing.

The data was consistent within each sample group with the warp direction testing having less than 3% CV and the fill direction testing having no more than about 5% CV. MIL DTL 44436 has a minimum breaking force requirement for the finished BDU fabric of 890 newtons (200 lbs) in the warp direction and 400 newtons (90 lbs) in the fill direction. This requirement as well as the breaking force of the baseline Sample 1 will be used to determine if the breaking force of the experimental samples was practically significant.

Factor: $Float_{max}$ Length (2,5 or 7)

The increase in $float_{max}$ length had a negative effect on the breaking force of the fabric in both the warp and fill directions. Looking at the warp direction test first, the break force was the greatest when the $float_{max}$ length equaled two (M = 1157 N, SD = 27) than when it equaled five (M = 1146 N, SD =26), and was lowest when the $float_{max}$ length equaled seven (M =1128 N, SD = 0.28). The change in $float_{max}$ length from two to five and then from five to seven caused a slight decrease in break force in each change with an overall loss of 2.5%. Figure 21 is a graphical representation of the one-way analysis showing that as the $float_{max}$ length increases, the force required to break the fabric decreases. The Tukey-Cramer comparison circles show that the change from $float_{max}$ length of two to seven and five to seven can be considered statistically different.

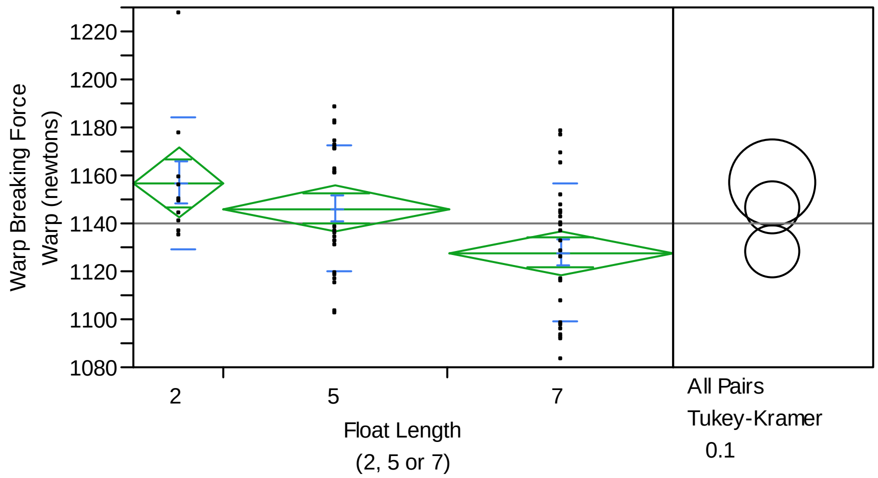

Figure 21 Effect of Float$_{max}$ Length on Warp Break Force

Now, looking at the filling direction data, the same effect was not observed. The break force was the greatest when the float$_{max}$ length equaled five (M = 643 N, SD = 28), a float$_{max}$ length of two (M = 626 N, SD =12) was lower and when the float$_{max}$ length equaled seven (M =621 N, SD = 24) the breaking strength was the weakest. It is important to note however, that these are slight differences –less than 4% overall. Figure 22 is a description fill direction breaking force data and the comparison circles show only a difference between the float$_{max}$ length of five and seven.

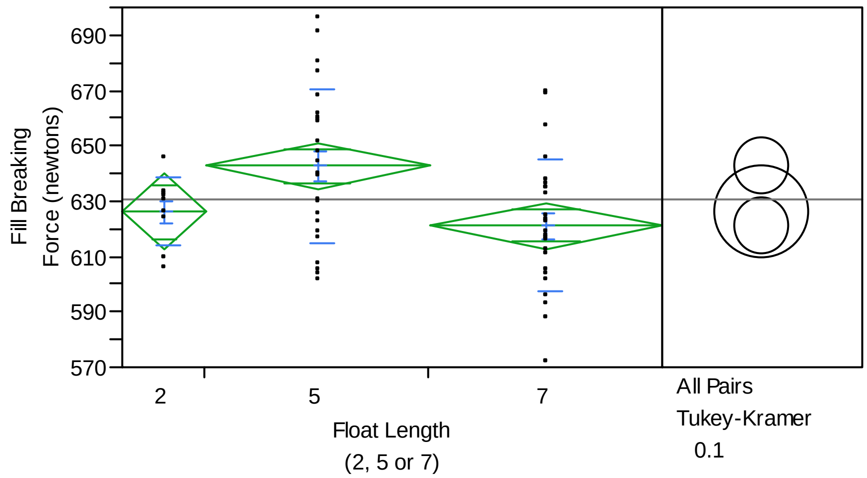

Figure 22 Effect of Float$_{max}$ Length on Fill Break Force

The expected change in break force is a reduction in strength as the float$_{max}$ lengths get longer and the number of yarn intersections/interlacings is reduced. The intersection points in the weave bind the yarns together, for example, every filling yarn holds a warp yarn at each intersection along its length. The number of intersections in the fabric is what causes the yarn strength in the fabric to be much higher than when it is in the free state. When the number of intersections in the fabric is reduced, the number of binding sites on the yarn is also reduced and the strength of the fabric is decreased. The warp direction of the fabric behaved this way but the fill direction did not. The effect observed in the filling direction might be due to the fact the filling direction samples had much more within sample variation. The warp direction samples had less than 1% within sample variation and the fill direction samples had just under 4.4% variation. This increased amount of variation might be due to the fact that the four different cones of filling e-yarn were used during weaving. Multiple cones were also used to make the warp beam but these were spread out more randomly throughout the warp and any cone to cone variation in strength was cancelled out by the randomization. In the filling direction, there was no randomization to mitigate the effects of the different cone strength. As shown in 4.1 section the four different cones had varying break strength. The average break strength of e-yarn was 681 gf but the %CV was just over 24%. This could account for the fill direction break test results not decreasing with increasing $float_{max}$ length.

Although each of the factor levels had a significant effect on the breaking force of the samples, it is important to determine exactly which of the factor levels are different from each other. In both directions the increase in $float_{max}$ length from two to five did not produce a statistically significant difference however the increase from five to seven did. The total increase from two to seven did make a difference in the warp direction but not in the fill direction. As stated before, it is a little more confusing why the filling direction break force would increase and then decrease. The only explanation is that can be offered at this time is that the different cones of e-yarn used to weave the samples played a part in the results.

Looking at the data in terms of filling e-yarn cone used, a one-way analysis of the filling direction break force revealed that the different cones of e-yarn used did have a statistically significant effect on the break force. See Figure 23 for a graphical representation of the data.

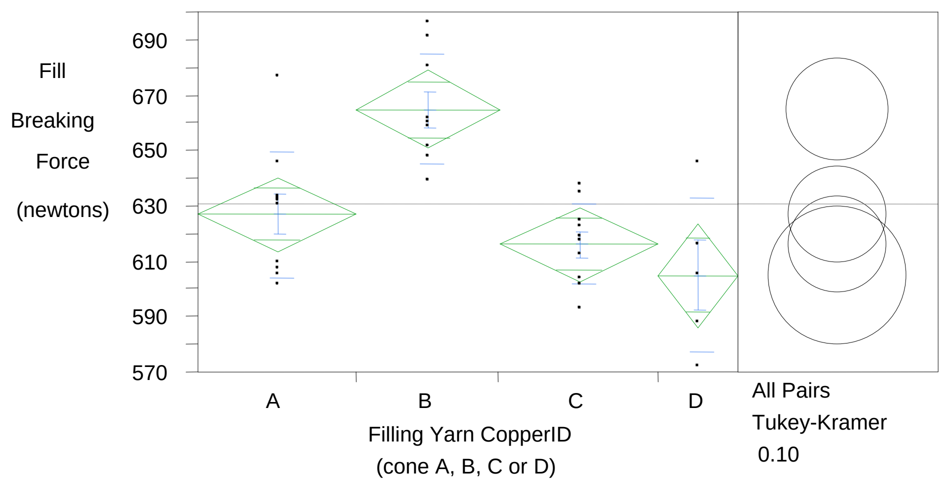

Figure 23 Effect of Cone ID on Filling Break Force

Samples using Cone D yarn had the lowest break force (M = 605 N, SD = 23), samples using Cone C were about 10 N stronger (M = 616 N, SD = 14) and samples using Cone A were about another 10 N stronger (M = 627 N, SD = 23). Samples using Cone B were about 40 lbs stronger (M = 665 N, SD = 20). Comparison circles in Figure 23 show that while Cones A, C and D are not statistically different, Cone B's effect on the fabric break strength is. As shown in Table 3, the samples that used Cone B were 2E and 4E and these are two with the highest filling break strength. Samples 2E and 4E also have a $float_{max}$ length of 5 and this explains why the expected decrease in filling break force as $float_{max}$ length increases was not observed.

Factor: Float$_{max}$ Location (same or both sides)

The change from locating the float$_{max}$ on both sides of the fabric to only one side of the fabric only caused a statistically significant difference, not practically in the warp direction of the test. The warp direction breaking force was slightly decreased (less than 2%) when the floats$_{max}$ were located on both sides of the fabric (M = 1147 N, SD = 28) than when they were moved to be located on the same side of the fabric (M = 1127 N , SD = 26). The decrease in the force required to break the fabric in the warp direction when the float$_{max}$ location was changed from one side to another is very minimal and not really understood at this time. Figure 24 is a visual description of this effect.

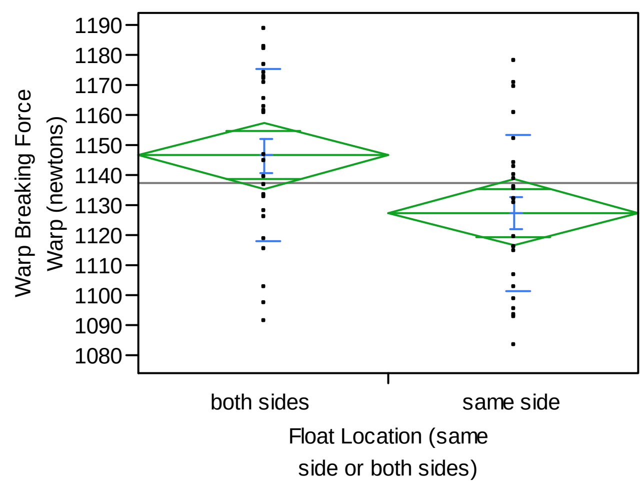

Figure 24 Effect of Float$_{max}$ Location on Warp Break Force

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The difference in warp break force is decreased only about 4% from the baseline sample (M = 1171 N, SD = 33) then when the best conductivity samples (M = 1127 N. SD = 34). Although the ANOVA testing found this to be statistically different, there was no practical difference found and the break force of the samples is still about 27% greater than the minimum requirement in MIL DTL 44436. Similar comparisons can be made in the filling direction. The change in filling break force is a minimal loss of about 1% from the baseline samples (M = 621 N, SD = 11) to the best conductivity samples (M = 615 N, SD = 23) and is not considered practically significant.

Comparisons for Each Sample Pair using Student's t

The connecting letters report for the warp break force is shown in Table 11 and the filling break force is shown in Table 12. Looking at the warp direction first, this testing shows that there is much overlap between the Samples. Samples 1, and2, 3, 4, 1E, 2E and 2ER have significantly different average warp break force values compared to Samples 5, 3E, 4E, 5E and 5M. This difference can probably be attributed to the differences in $float_{max}$ lengths. The filling break force is found to have more statistically significant differences between the samples that although no pattern as to the effect of yarn type, $float_{max}$ length or location can be readily ascertained.

Table 11 Warp Break Force (N)

Level						Mean
1	A					1171.1761
2ER	A	B				1161.6086
2	A	B	C			1156.7832
2E	A	B	C	D		1149.8653
1E	A	B	C	D		1142.3923
3	A	B	C	D		1141.7695
4	A	B	C	D		1138.2999
5ER		B	C	D		1134.3855
4E			C	D	E	1124.6883
3E				D	E	1123.1760
5				D	E	1119.8843
5E				D	E	1119.7953
5M					E	1092.4832

Table 12 Filling Break Force (N)

Level					Mean
2E	A				672.23749
5M	A	B			662.25123
4E	A	B			658.69265
3		B	C		644.72524
2		B	C		642.45924
1E			C	D	630.04611
5E			C	D	623.72963
2ER			C	D	623.64067
5			C	D	623.46274
4			C	D	622.03931
1			C	D	621.19415
3E				D	608.42775
5ER				D	604.86917

5.5.7 Fabric Elongation

The percent elongation of the fabric samples was tested along with the break force. The individual results for the percent elongation in the warp and filling direction are in Appendix

E, Table E7A&B. Table 8 shows the average percent elongation for each of the thirteen samples. The warp and filling elongation were only affected by the factors of yarn type and $float_{max}$ length and found to have a statistically significant effect. The highest percent elongation was 60% in the warp direction and 28% in the fill direction. The lowest was 51% in the warp direction and 25% in the fill direction. The variation of the within sample data was moderate, in the warp direction the %CV was 5.5% at most and in the fill direction it was a little greater at 7.81%.

Factor: Nylon/cotton vs. E-yarn (conductive network)

The change from nylon/cotton to the e-yarn in the ripstop ribs did have an effect on the elongation of the fabric samples. The warp direction elongation at break was 6.31% less when the e-yarn (M = 53.90%, SD = 0.31) was used than when only the nylon/cotton yarn (M = 57.53%, SD = 0.376) was used in the ripstop ribs. The fill direction elongation at break was very close regardless of whether the e-yarn (M = 25.82%, SD = 1.4) was used than when only the nylon/cotton yarn (M = 26.49%, SD = 1.6) was used in the ripstop ribs. A decrease in % elongation with the incorporation of the e-yarn is expected for two reasons. First, the warp and filling crimp in the fabric decreased 7.11% and 10.21% respectively when the e-yarn was added to the ripstop locations. Second, in the yarn testing, the e-yarn was determined to be much less extensible than the nylon/cotton yarn. See Figures 25 and 26 for a description of the two groups of warp and filling elongation data.

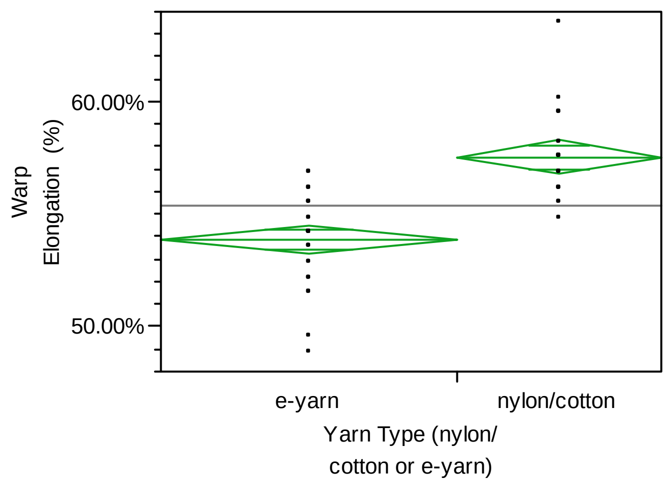

Figure 25 Effect of Yarn Type on Warp % Elongation

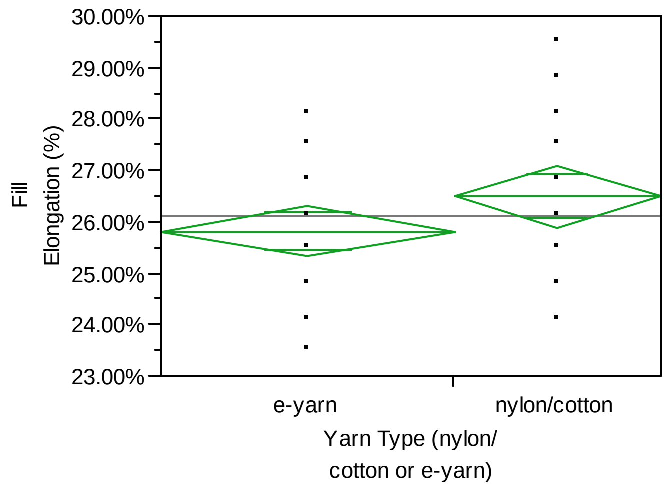

Figure 26 Effect of Yarn Type on Filling % Elongation

Factor: $Float_{max}$ Length (2, 5 or 7)

The change in $float_{max}$ length had an effect on the fabric elongation at break as well. Looking at the warp direction first, the elongation steadily decreased with increasing $float_{max}$ length. The elongation was the greatest when the $float_{max}$ length equaled two (M = 57.41%, SD = 3.20) than when it equaled five (M = 55.43%, SD =2.01) and was lowest when the $float_{max}$ length equaled seven (M = 54.50%, SD = 2.38). The change in $float_{max}$ length from two to five caused a 3.44% increase in elongation while the change in $float_{max}$ length from two to seven caused a 5.06% increase overall. Figure 27 shows a graphical representation of the one-way analysis on the warp direction showing that as the $float_{max}$ length increases, the fabric thickness increases. Comparison circles indicate that while a $float_{max}$ length level of two and five and two and seven are statistically different from each other, there is no difference between $float_{max}$ lengths of five and seven.

The reason that the $float_{max}$ length had an effect on the percent elongation is because as the $float_{max}$ length increases the number of yarn intersections in the fabric decreases, making the yarn path through the fabric in a straighter line. This put less crimp in the yarn and crimp removal is the first event in the sequence of textile break and elongation testing. Only after all the crimp is removed from the woven yarn will the crimp interchange be triggered and lead to the actual elongation and breaking of individual yarns. The less crimp in the fabric, the less elongation the fabric will initially experience.

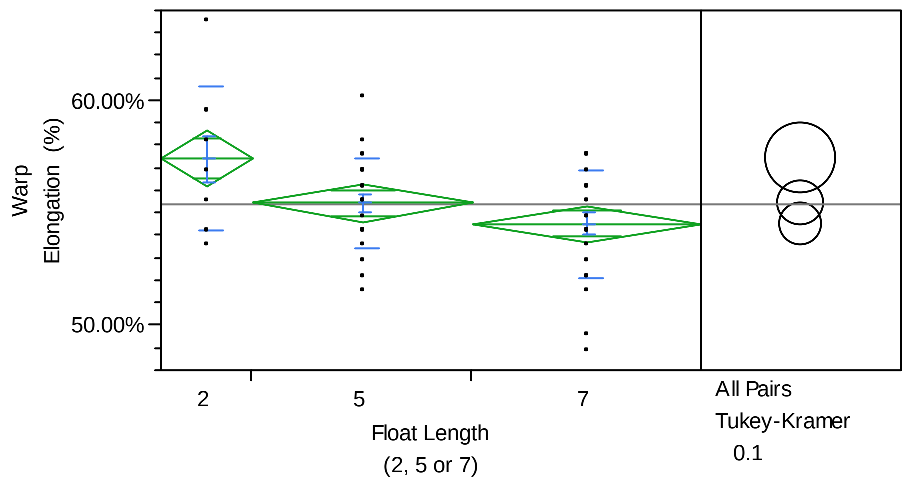

Figure 27 Effect of Float$_{max}$ Length on Warp % Elongation

Next, considering the filling direction test data, the same effect of a decrease in elongation as float$_{max}$ length increases was not observed. The elongation was the lowest when the float$_{max}$ length equaled two (M = 25.06%, SD = 1.6) was used than when it equaled five (M = 26.27%, SD =1.2) or seven (M =26.36%, SD = 1.5). The change in float$_{max}$ length from two to five caused a 4.8% increase in elongation while the change in float$_{max}$ length from five to seven remained mostly unchanged. Figure 28 is a graphical representation of the one-way analysis on the warp direction showing that this effect. Comparison circles indicate that while a float$_{max}$ length level of two and five and two and seven are statistically different from each other, there is no difference between float$_{max}$ lengths of five and seven. While this effect was unexpected, it is probably due to the change in e-yarn cones than due to the effect of the float$_{max}$ length. Looking only at the elongation data from samples without the conductive network and comparing how the $float_{max}$ length affected those samples, an increase in $float_{max}$ length caused an increase in the elongation at break measured in the sample.

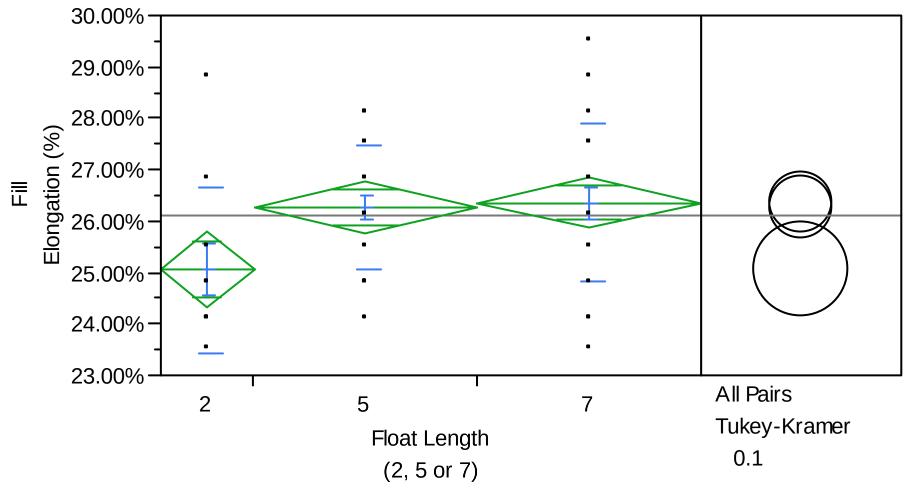

Figure 28 Effect of $Float_{max}$ Length on Filling % Elongation

Factor: $Float_{max}$ Location (same or both sides)

The change in $float_{max}$ location has an effect on the filling percent elongation but not the warp. The filling elongation was decreased just over 3% when the $float_{max}$ was located on both sides of the fabric (M = 26.7%, SD =1.32) than when they were moved to be located on the same side of the fabric (M = 25.9% , SD =1.3) This decrease in elongation at break caused by the relocation of $floats_{max}$ from both sides is considered very minimal and is not understood at this time. Figure 29 shows a description of the two groups of data.

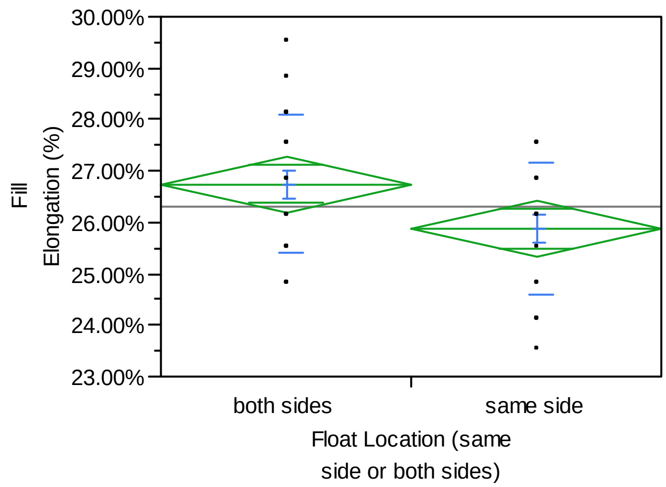

Figure 29 Effect of Float$_{max}$ Location on Filling % Elongation

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The difference in fabric elongation was found to be significant in only the warp direction. The fabric elongation decreased 11.7% from the baseline fabric (M= 60.02%, SD = 1.64%) to the experimental (M = 53.00%, SD = 0.74).

Comparisons for Each Sample Pair using Student's t

The connecting letters report for the warp elongation is shown in Table 13 and the filling elongation is shown in Table 14. Looking at the warp direction, Sample 1 is statistically different from all other samples as is 5M. The remaining nylon/cotton samples are statistically different from most of the e-yarn samples. Within the e-yarn samples there are some statistical differences that can be somewhat attributed to float length. Looking at the filling elongation, the reasons for the differences are less obvious and require more investigation, although the lack of more clearly defined statistical differences may be due to the different cones of e-yarn used.

Table 13 Warp Elongation (%)

Level									Mean
1	A								0.60020000
2		B							0.57800000
4		B	C						0.56800000
5		B	C	D					0.56660000
3		B	C	D	E				0.56420000
2ER			C	D	E	F			0.54920000
1E				D	E	F			0.54800000
2E					E	F			0.54640000
5ER						F			0.54000000
4E						F	G		0.53480000
3E						F	G		0.53440000
5E							G	H	0.52000000
5M								H	0.51460000

Table 14 Filling Elongation (%)

Level						Mean
3	A					0.27880000
5M	A	B				0.27320000
5	A	B	C			0.26940000
2E	A	B	C			0.26680000
2ER	A	B	C			0.26520000
2	A	B	C	D		0.26450000
3E		B	C	D	E	0.26140000
5ER		B	C	D	E	0.26125000
4		B	C	D	E	0.25860000
4E		B	C	D	E	0.25860000
1			C	D	E	0.25320000
1E				D	E	0.24800000
5E					E	0.24660000

5.5.8 Fabric Tear Strength

There were a few issues with the Elmendorf Tear Test as it was performed. The BDU has very high tear strength and as such, fifty out of the sixty-five filling torn (test conducted in the warp direction) test results were higher than 80% of the rated capacity of 6400 grams of the Elmendorf Tear Test. ASTM D 1424 requires that when this occurs, an apparatus with the next higher load capacity be used. In this study this was not possible because the physical testing lab did not have another Elmendorf Tear Tester and this requirement could not be met. The reason fabrics with tear strengths above the 80% capacity need to be moved to the next highest loading is because some degree of accuracy is lost at the higher levels.

The BDU fabric specification requires that the finished BDU fabric have a tear strength of at least 3175 gf (7 lbs) for the filling torn samples (warp direction test) and 2258 gf (5 lbs) for the warp torn samples (fill direction test). The variation of each sample was a little higher than expected. As noted in Table 9, only the factors of yarn type and $float_{max}$ length had a statistically significant effect on the filling and warp torn strength of the fabric samples. The %CV within the filling torn samples had a maximum of 12.79%CV and all but one set of the warp torn samples had a %CV of less than 12.6%. Individual tear strength data is shown in Appendix E, Table E8A&B. The range of filling torn data is from 4544 gf to 6387 gf. The range of the warp torn data is 2624 gf to 5478 gf. All samples exceed the MIL DTL 44436 specification requirements.

Factor: Nylon/cotton vs. E-yarn (conductive network)

The change in yarn type definitely had a negative effect on the tear strength of the fabric. The filling torn strength was 5.89% lower when the e-yarn (M = 5382 gf, SD = 101) was used than when only the nylon/cotton yarn (M = 5719 gf, SD = 120) was used in the ripstop ribs. The warp torn strength was 12.58% lower when the e-yarn (M = 3532gf, SD = 623) was used than when only the nylon/cotton yarn (M = 4040 gf, SD = 777) was used in the ripstop ribs. Figure 30 and 31 is a description of the two groups of data.

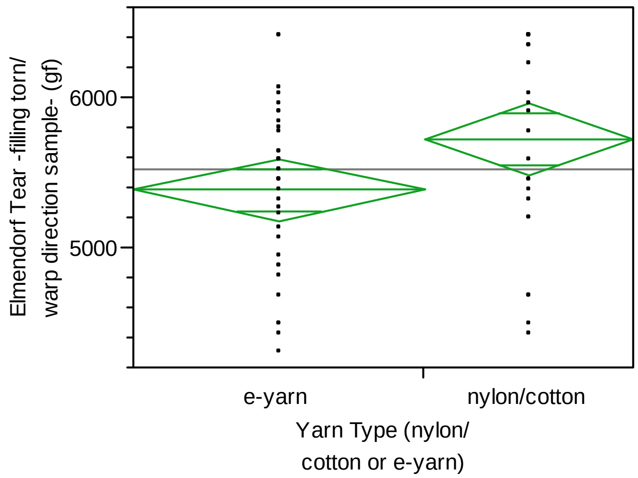

Figure 30 Effect of Yarn Type on Tear Strength (filling torn/warp direction)

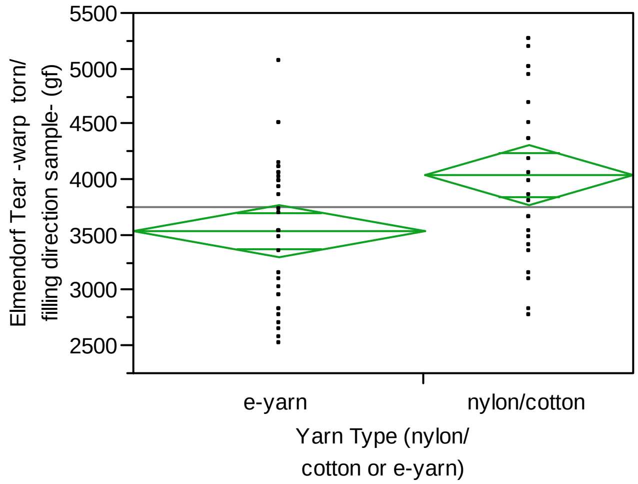

Figure 31 Effect of Yarn Type on Tear Strength (warp torn/fill direction)

Initially, the expectation was that since the e-yarn is a larger diameter, that the tear strength would increase with the addition of the e-yarn conductive network. This was not the case and can be attributed to the fact that the surface of the e-yarn is much more rough and coarse than the nylon/cotton yarn and increases yarn to yarn friction during the tear test. Higher yarn to yarn friction reduces mobility of the yarns, and mobility is key to tear strength because if the yarns are able to slide and move past one another and share the load as a group. The more yarns that are able to bundle together in the delta zone of the fabric tear will increase fabric tear strength. Since the nylon/cotton yarns are more smooth and flexible they are able to move and slide to allow for a higher tear strength. Even though the addition of the e-yarn caused the fabric tear strength to decrease, the average of the e-yarn samples in either direction is still 12.5% higher in tear strength than the baseline Sample 1 and 64% higher than the MIL-DTL-44436 minimum requirement.

Factor: Float$_{max}$ Length (2, 5 or 7)

The change in float$_{max}$ lengths also had an effect on the tear strength of the fabric samples. Taking the filling torn data first, the tear strength steadily increases with increasing float$_{max}$ length. The tear strength was the weakest when the float$_{max}$ length equaled two (M = 4691 gf, SD = 371) than when it equaled five (M = 5423 gf, SD =371) and was highest when the float$_{max}$ length equaled seven (M =5955 gf, SD = 508). The change in float$_{max}$ length from two to five caused a 15.6% increase in tear strength while the change in float$_{max}$ length from two to seven caused a 26.93% increase overall. Figure 32 is a graphical representation of the one-way analysis on the filling torn data showing that as the float$_{max}$ length increases, the fabric tear strength also increases. Comparison circles indicate that the three levels of float$_{max}$ length are statistically different from each other.

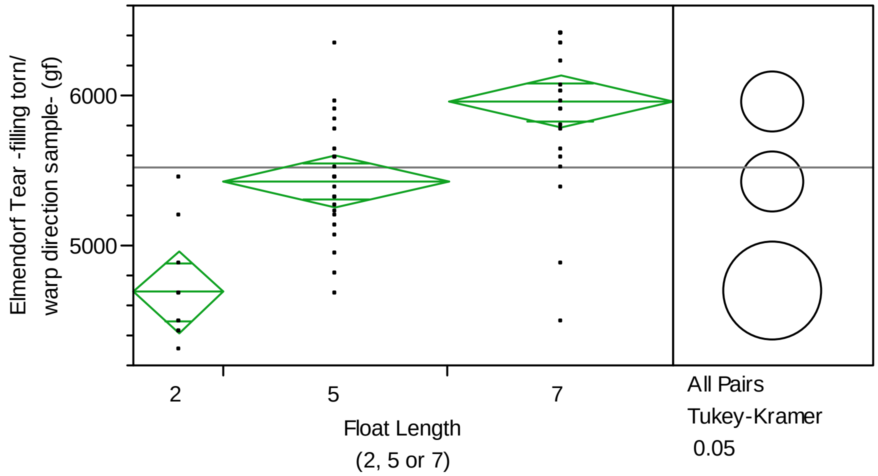

Figure 32 Effect of Float$_{max}$ Length on Tear Strength (filling torn/warp direction)

Looking at the warp torn data, the same effect was observed –as float$_{max}$ length increased, so did tear strength. Again, the tear strength was the weakest when the float$_{max}$ length equaled two (M = 2851 gf, SD = 325) than when it equaled five (M = 3601 gf, SD =455) and was highest when the float$_{max}$ length equaled seven (M =4242 gf, SD = 674). The change in float$_{max}$ length from two to five caused a 26.15% increase in tear strength while the change in float$_{max}$ length from two to seven caused a 48.61% increase overall. Figure 33 is a graphical representation of the one-way analysis on the warp torn samples showing that as the float$_{max}$ length increases, the fabric tear strength also increases. Comparison circles indicate that the three levels of float$_{max}$ length are statistically different from each other.

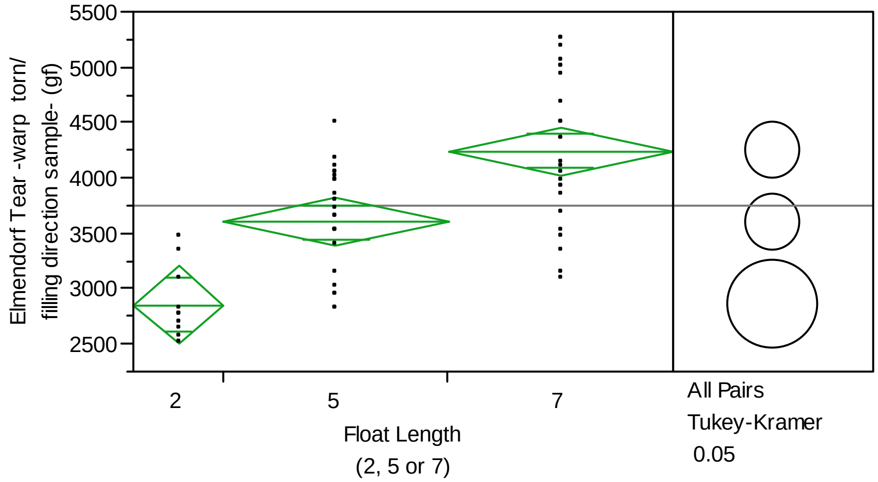

Figure 33 Effect of Float$_{max}$ Length on Tear Strength (warp torn/filling direction).

As previously described, an increase in float$_{max}$ length decreases the number of yarn intersections in the fabric. The decrease in yarn intersections is a decrease in the number of sites on the yarn that get bound or pinched during a tear test. This allows the yarns to move more freely during the tear test and bundle together to break or tear as a group resulting in higher tear strength.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The difference in tear strength in both directions was found to cause a significant increase to the tear strength. The filling torn strength was 15.08% higher in the warp direction when looking at the experimental (M = 5568 gf, SD = 168) as compared to the baseline (M = 4838 gf, SD = 452). The warp torn samples performed similarly and was 22.02% higher in the experimental(M = 3789, SD = 175) than in the baseline fabric (M = 3085, SD = 248). This is due to the effect of $float_{max}$ length on the tear strength property.

Comparisons for Each Sample Pair using Student's t

The connecting letters report for the filling torn tear strength is shown in Table 15 and the warp torn tear strength is shown in Table 16. Both test directions seem to be somewhat ordered according to $float_{max}$ length and location and supports previous conclusions that longer $float_{max}$ lengths cause better tear performance.

Table 15 Filling Torn Tear Strength (gf)

Level							Mean
5	A						6387.2000
3	A						6272.0000
3E	A	B					5977.6000
5M		B	C				5760.0000
4		B	C	D			5747.2000
5E		B	C	D			5715.2000
4E			C	D			5446.4000
5ER			C	D			5420.8000
2			C	D			5350.4000
2ER				D	E		5286.4000
2E				D	E		5286.4000
1					E	F	4838.4000
1E						F	4544.0000

Table 16 Warp Torn Tear Strength (gf)

Level						**Mean**
5M	A					5478.4000
5		B				4966.4000
3		B				4723.2000
3E			C			3942.4000
4			C			3929.6000
4E			C			3872.0000
5E			C			3814.4000
2E			C			3801.6000
5ER			C			3763.2000
2			C	D		3494.4000
1				D	E	3084.8000
2ER					E	2905.6000
1E					E	2624.0000

5.5.9 Fabric Air Permeability

There were no issues during air permeability testing other than initially, the fabric samples were only tested face-up. Later, this was corrected and testing was conducted on the samples in a face-down configuration. This explains why the samples sizes for both directions of test are not the same. Looking at the two groups of data (face-up and face-down test configuration) using the one-way ANOVA no statistical difference was noted between them. The BDU specification requires that the finished fabric have a maximum air permeability of 7.62 $cm^3/s/cm^2$ (15 $ft^3/min/ft^2$). The individual data for all thirteen samples in the face-up and face-down direction is located in Appendix E, Table E9A&B and the average data is located in Table 8. Sample 1 had the least amount of air permeability and Sample 3 had the highest value in the face-up test configuration and Sample 5E had the most permeability in the Face-down configuration. The within sample variation was moderate for this test, a maximum of 6.8% CV in the face-up test and 6.2% CV when tested face-down. Not all the samples met the maximum air permeability requirement and as was explained in Section 4.3.9 this is to be expected because the fabric was tested in the greige state. Subsequent dyeing, printing, and finishing processes can and are commonly used to adjust the air permeability of the fabric into specification requirements. As seen previously in Table 9, all three factors of yarn type, $float_{max}$ length and $float_{max}$ location were determined to have an impact on air permeability.

Factor: Nylon/cotton vs E-yarn (conductive network)

The air permeability of the fabric was 23.94% greater when the e-yarn (M = 6.384 $cm^3/s/cm^2$, SD = 0.194) was used than when only the nylon/cotton yarn (M = 5.151 $cm^3/s/cm^2$, SD = 0.230) was used in the ripstop ribs. Figure 34 graphically shows this data. The change in yarn type from standard nylon/cotton to the e-yarn caused an increased the air permeability of the fabric perhaps because the copper component on the surface of the e-yarn is not tightly wrapped. This may cause the group of samples with the e-yarn to have increased air permeability because the cover of the fabric is decreased.

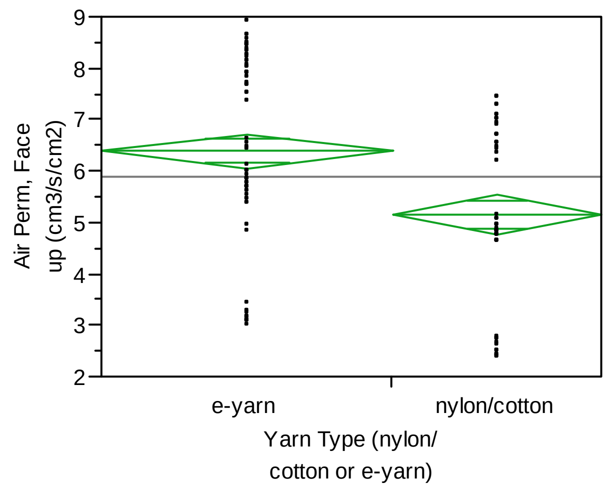

Figure 34 Effect of Yarn Type of Air Permeability, (face-up)

Factor: Float$_{max}$ Length (2, 5 or7)

Increasing float$_{max}$ length caused an increase in air permeability regardless of whether the fabric was tested face-up or face-down. Taking the face-up data first, the air permeability steadily increased with increasing float$_{max}$ length. The air permeability was the lowest when the float$_{max}$ length equaled two (M = 2.826 cm^3/s/cm^2, SD = 0.131) than when it equaled five (M = 5.379 cm^3/s/cm^2, SD =0.083) and was highest when the float$_{max}$ length equaled seven (M =7.579 cm^3/s/cm^2, SD = 0.083). The change in float$_{max}$ length from two to five caused a 90.3% increase in air permeability, a further increase to a float$_{max}$ length of seven caused an additional increase of 40.89%. The overall change in float$_{max}$ length from two to seven caused a total increase in air permeability of 168%. Figure 35 is a graphical representation of the one-way analysis on the face-up air permeability testing showing that as the float$_{max}$

length increases, the fabric permeability also increases. Comparison circles indicate that the three levels of $float_{max}$ length are statistically different from each other.

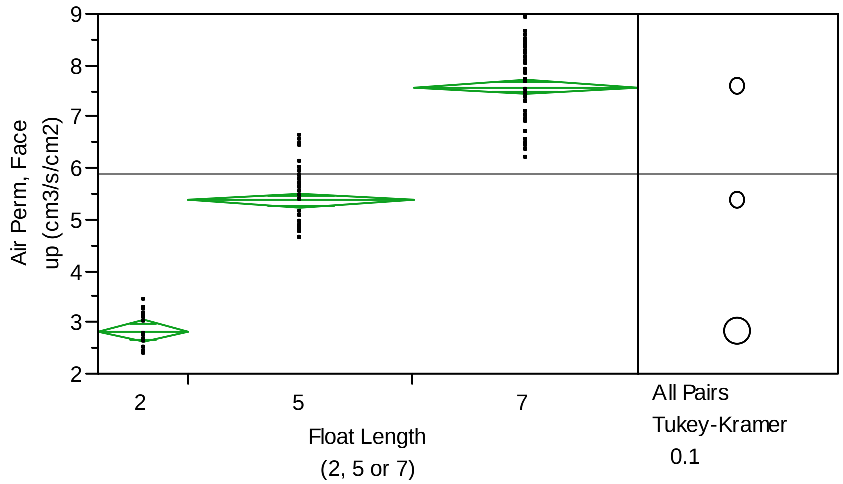

Figure 35 Effect of $Float_{max}$ Length on Air Permeability, (face-up)

The face-down test results show a similar effect as the face-up . The air permeability was the lowest when the $float_{max}$ length equaled two (M = 2.864 $cm^3/s/cm^2$, SD = 0.226) than when it equaled five (M = 5.147 $cm^3/s/cm^2$, SD =0.359) and was highest when the $float_{max}$ length equaled seven (M =7.217 $cm^3/s/cm^2$, SD = 0.470). The change in $float_{max}$ length from two to five caused a 79.7% increase in air permeability, a further increase to a $float_{max}$ length of seven caused an additional increase of 40.21%, resulting in a total increase in air permeability of 152% for the $float_{max}$ length increase of two to seven. Figure 36 is a graphical representation of the one-way analysis on the face-up air permeability testing showing that as the $float_{max}$ length increases, the fabric permeability also increases.

Comparison circles indicate that the three levels of $float_{max}$ length are statistically different from each other

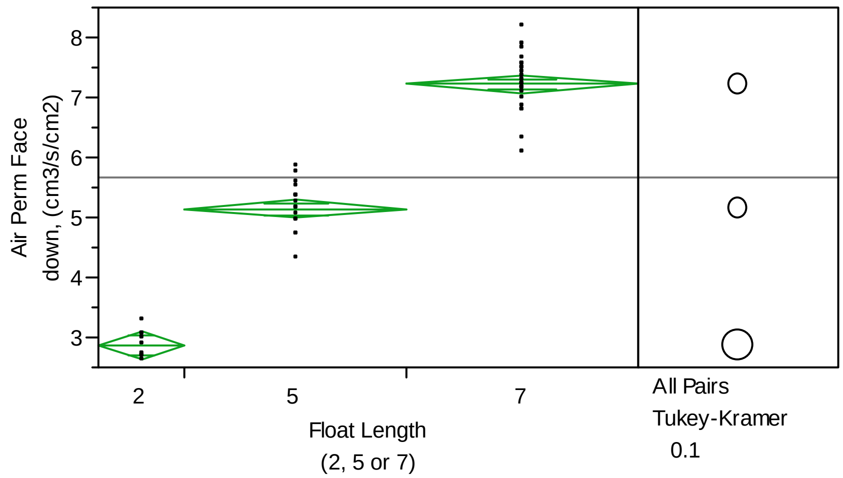

Figure 36 Effect of $Float_{max}$ Length on Air Permeability, (face-down)

For both the face-up and face-down testing the increase in $float_{max}$ length resulted in an increase in the air permeability of the fabric samples because longer $float_{max}$ lengths leads to less interlacings and a more open fabric. More fabric openings allow more air to flow through the fabric. However, to maintain the fabric as “wind resistant” the dyeing, printing and finishing processes can be used to decrease the air permeability to a desired level.

Factor: $Float_{max}$ Location (same or both sides)

The air permeability of the fabric was also increased when all $float_{max}$ were located to one side of the fabric, instead of on both sides of the fabric, however this was only observed in the face-down testing.. Air permeability was increased 9.69% when the $floats_{max}$ were on both sides of the fabric (M = 5.923 $cm^3/s/cm^2$, SD =1.095) to when they were moved to be located on the same side of the fabric (M = 6.497 $cm^3/s/cm^2$, SD =1.104). Figure 37 is a graphical representation of the ANOVA results.

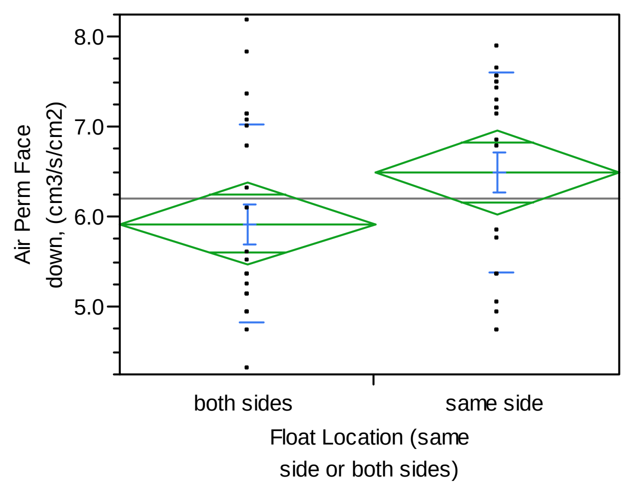

Figure 37 Effect of $Float_{max}$ Location on Air Permeability, (face-down)

The reasoning behind why the location of the $floats_{max}$ had an effect on the air permeability of the fabric is not fully understood at this time. One explanation could be that in the face-down configuration, there are more of the looser raised $floats_{max}$ facing the airstream to impede the airflow through the fabric.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The one-way ANOVA test found that the difference in air permeability between the baseline sample and the experimental sample was significant in both the face-up and face-down configuration. Looking at the face-up data first, the air permeability of the fabric was 181.3% greater for the experimental fabric (M = 8.010 $cm^3/s/cm^2$, SD = 0.148) than for the baseline fabric (M = 2.524 $cm^3/s/cm^2$, SD = 0.368). In the face down testing, the air permeability was increased 190.8% from the baseline fabric (M = 2.565 $cm^3/s/cm^2$, SD = .047) to the experimental (M = 7.460 $cm^3/s/cm^2$, SD = 0.208). This increase in air permeability is likely due to the increase in $float_{max}$ length and can be controlled using fabric finishing techniques such as calendaring and tentering.

Comparisons for Each Sample Pair using Student's t

The connecting letters report for air permeability, face-up is shown in Table 17 and the face-down results are shown in Table 18. The differences between in both directions show that the samples are not very similar and seem to be ordered by $float_{max}$ length and location.

Table 17 Air Permeability, face-up ($cm^3/s/cm^2$)

Level										Mean
5M	A									8.2453547
5ER	A	B								8.2231873
3E	A	B								8.0874119
5E		B								7.9710329
3			C							6.9402481
5				D						6.6710064
2ER					E					6.0669444
4E						F				5.6633127
2E						F				5.5455483
2							G			4.8403474
4							G			4.7789252
1E								H		3.1283764
1									I	2.5243144

Table 18 Air Permeability, face-down ($cm^3/s/cm^2$)

Level									Mean
5E	A								7.5265763
3E	A								7.5103202
5ER	A								7.3924634
5M	A	B							7.3325190
5		B	C						6.9761547
3			C						6.6304585
4E				D					5.5128514
2ER				D					5.3462263
2E				D	E				5.1745212
4					E	F			4.8425411
2						F			4.7117302
1E							G		3.0337955
1								H	2.6517770

5.5.10 Thermal Resistance

The differences between the standard ASTM test method and the one used in this study were previously noted in Section 4.3.10 and there are no other deviations or issues to report. Individual results for this test are located in Appendix E, Table E10A&B. Averages of each sample's thermal resistance in the face-up and face-down test configuration are shown in Table 8. MIL DTL 44436 does not have a requirement for clo value, so Sample 1 will be used as a baseline to determine the effect that the three fabric construction factors had on the thermal resistance of the fabric.

As previously stated, a clo value of 0 is equivalent to wearing no clothes, a 0.6 clo is summer weight fabric and 1.0 is winter weight fabric. A clo of 4.0 is the maximum and is equivalent to wearing extreme cold weather gear. As explained in Section 4.3.10, thermal resistance is the measure of a fabrics ability to stop heat flow through the fabric. Thermal transmittance is a measure of the amount of heat that is transferred from one side of the fabric, to the other and takes into account the temperature on both sides of the fabric. Thermal insulation is a measure of how well the fabric layer prevents heat loss through conduction, convection or radiation. Use of clo as a unit of measure was chosen because it is a generally accepted unit of measurement for the insulation properties of clothing. Looking at the data in Table E11A&B, the variation within each sample was acceptable, with the maximum %CV is 5.69% when the fabric is tested face-up and 3.57% when the fabric is face-down. As shown previously in Table 9, only the factors of $float_{max}$ length and location had a significant effect on the thermal resistance of the fabric samples. Surprisingly, yarn type was shown to have no significant effect on the thermal resistance of the fabric. This may be due to the fact that the e-yarn is used in less than 15% of the weave and that the portion of copper in the yarn is minimal. Further reading shows that although copper readily absorbs heat it does not transfer it easily.

Factor: $Float_{max}$ Length (2, 5 or 7)

$Float_{max}$ length had a significant effect on the thermal resistance of the fabric regardless of whether testing was conducted face-up or face-down. Looking at the face-up data first, the thermal resistance steadily increased with increasing $float_{max}$ length. The thermal resistance was the lowest when the $float_{max}$ length equaled two (M = 0.463 clo, SD = 0.011) than when it equaled five (M = 0.470 clo, SD =0.0176) and was highest when the $float_{max}$ length equaled seven (M =0.476 clo, SD = 0.0164). The change in $float_{max}$ length from two to five caused a slight increase in thermal resistance, and the overall increase in $float_{max}$ length from two to seven resulted in a total increase of 2.85%. Figure 38 is a graphical representation of the one-way analysis on the thermal resistance. Comparison circles indicate that while $float_{max}$ length levels of two to seven and five to seven are statistically different, there is no difference between the $float_{max}$ lengths of two and five.

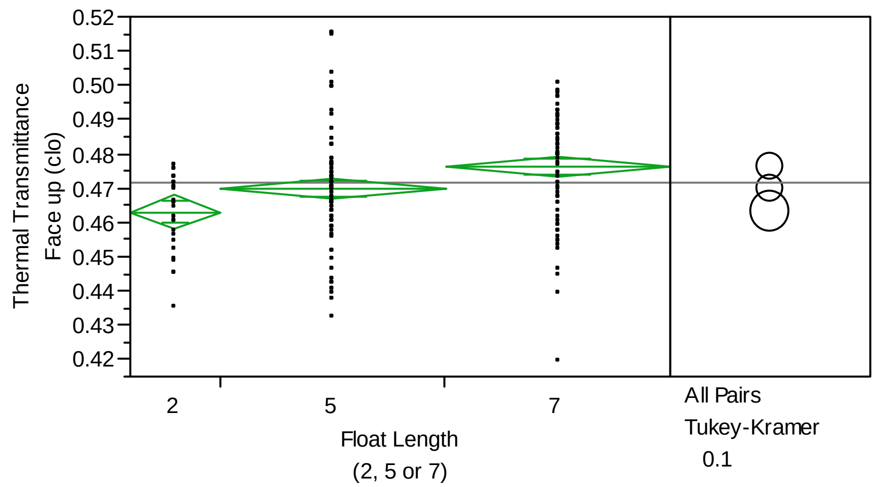

Figure 38 Effect of $Float_{max}$ Length on Thermal Resistance, (face-up)

Face-down testing resulted in similar effects. Again, the thermal resistance was the lowest when the $float_{max}$ length equaled two (M = 0.450 clo, SD = 0.012) than when it equaled five (M = 0.457 clo, SD =0.0156) and was highest when the $floa_{max}$ length equaled seven (M =0.462 clo, SD = 0.0145). The change in $float_{max}$ length from two to five caused a slight increase in air permeability, and the overall increase in $float_{max}$ length from two to seven resulted in a total increase of 2.54% or 0.012 clo, well under the 0.1 clo that can be detected by the human body.. Figure 39 is a graphical representation of the one-way analysis on the thermal resistance test in the face-up configuration. As observed previously in face-up testing, the comparison circles indicate that while $float_{max}$ length levels of two to seven and five to seven are statistically different, there is no difference between the $float_{max}$ lengths of two and five

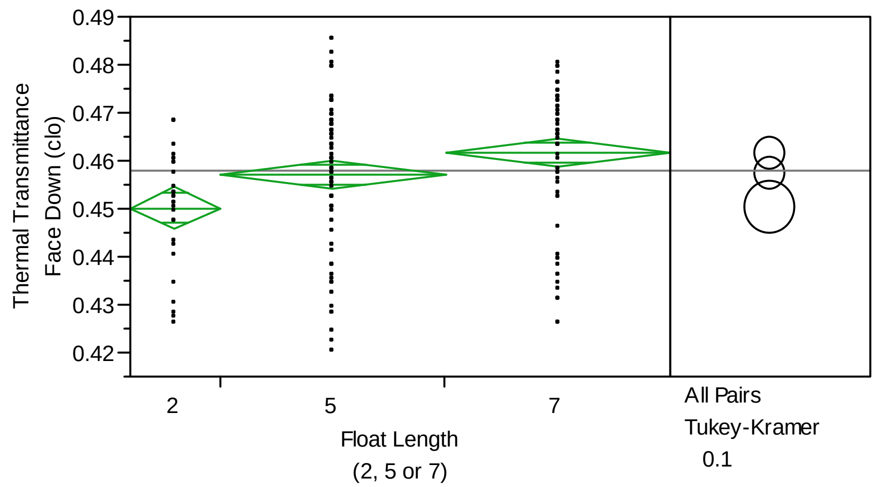

Figure 39 Effect of Float$_{max}$ Length on Thermal Transmittance, (face-down)

The change in float$_{max}$ length has a significant effect on the thermal transmittance because as the float lengths increase, the fabric becomes thicker in localized areas. Fabric thickness is a main determiner of thermal resistance and all other parameters being the same, thicker fabric will provide greater resistance to thermal transmittance.. However, in this case the increase in fabric thickness is localized to only the ripstop locations. Also, it has been reported that a minimum difference in clo of 0.1 can be detected by the human body, and the differences between the clo values of the different levels of float$_{max}$ length are much lower than that. It is for this reason that the factor of float$_{max}$ length with the levels used in this study is found to not have a practical effect on the thermal resistance of the BDU fabric.

Factor: $Float_{max}$ Location (same or both sides)

The factor of $float_{max}$ location also had an effect on the thermal resistance of the fabric although the effect was not the same when testing was conducted in the face-up or face-down configuration. Looking at the face-up data first, the thermal resistance was increased slightly, only 1.20% from when the $float_{max}$ were located on both sides (M = 0.470 clo, SD = 0.0189) of the fabric to when they were moved to be only on one side (M = 0.476 clo, SD = 0.0154) of the fabric. In the face-down test the thermal resistance decreased (1.59%) from when the $float_{max}$ were located on both sides (M = 0.463 clo, SD = 0.0153) of the fabric to when they were only on one side (M = 0.456 clo, SD = 0.0144). Figures 40 and 41 show a description of this data.

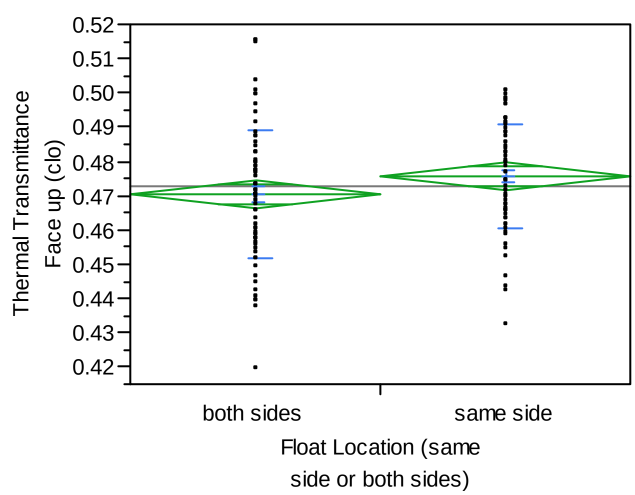

Figure 40 Effect of $Float_{max}$ Location on Thermal Resistance, (face-up)

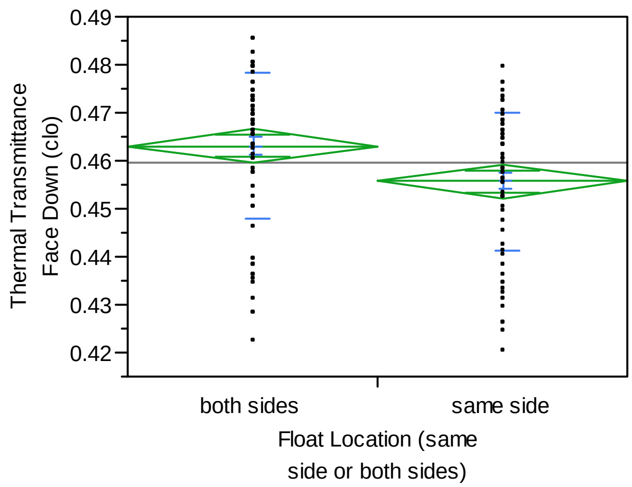

Figure 41 Effect of Float$_{max}$ Location on Thermal Transmittance, (face-down)

The opposite effect that was found in the face-up or facedown configuration supports the ANOVA analysis that showed float$_{max}$ location has an impact on thermal resistance. When tested in the face-up configuration, six out of eleven samples with float$_{max}$ lengths of five or seven have loose float$_{max}$ on the back side. Figure 42 is an example of this. From this Figure it is clear that the float$_{max}$ on the back make the fabric less smooth because they are slightly raised. So, when the samples are tested in the face-up configuration, the floats$_{max}$ act as a "spacer" between the main part of the fabric and the hot plate. This allows more air to be trapped between the hot plate and the fabric and so provides more insulation, increasing the clo value of the fabric. When the samples are tested in the face-down configuration, there are more instances of the fabric being in close contact with the hot plate and transmission of the heat is easier.

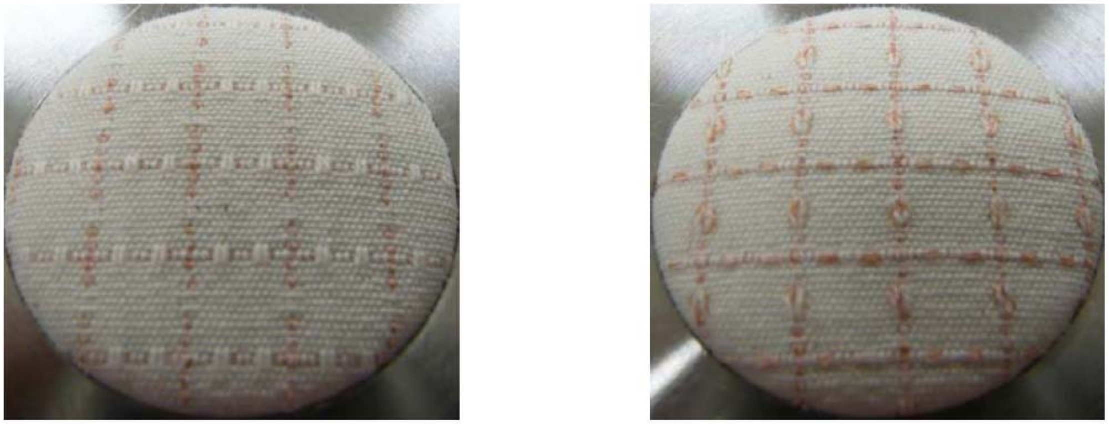

Figure 42 Difference in Surface Between Face (left) and Back (right) $Float_{max}$

Seeing that the configuration of the test made a difference in the test results, analysis was performed to determine if it was statistically significant. The average clo value of all the fabric samples that were tested in a face-up configuration is 0.473 and in the face-down configuration it is 0.459; this is a difference of 0.014 clo total. This difference in clo is still not enough to make a perceptable difference of 0.10 in comfort whether the fabric is constructed into a garment with the $float_{max}$ inside or out.

Comparisons for Each Sample Pair using Student's t

The connecting letters report for thermal resistance, face-up is shown in Table 20 and the face-down results are shown in Table 19. When the fabric is face-up, it is clear that samples using weave pattern 5, (where the $floats_{max}$ is located on the face and the $float_{max}$ length is greatest) have the most thermal resistance, although in the face-down testing the reasoning is effect is not observed. In the remaining samples, here is much overlap between the groups of samples. It is important to note however that the maximum difference in either direction is much lower than 0.1 clo, which has been identified as the minimum difference in clo that can be felt by the human body.

Table 19 Thermal Resistance, face-up (clo)

Level							Mean
5M	A						0.50120000
5		B					0.48266667
5ER		B					0.48233333
5E		B	C				0.47926667
2		B	C	D			0.47800000
3		B	C	D	E		0.47426667
2ER		B	C	D	E		0.47133333
4			C	D	E	F	0.47046667
1E				D	E	F	0.46706667
2E					E	F	0.46553333
4E					E	F	0.46353333
3E					E	F	0.46286667
1						F	0.45913333

Table 20 Thermal Resistance, face-down (clo)

Level						Mean
5M	A					0.47120000
2	A	B				0.46893333
3	A	B	C			0.46653333
3E	A	B	C			0.46413333
5		B	C	D		0.46046667
5E		B	C	D		0.46040000
2ER			C	D	E	0.45806667
2E			C	D	E	0.45793333
5ER			C	D	E	0.45646667
4E				D	E	0.45166667
1				D	E	0.45120000
4					E	0.44926667
1E					E	0.44913333

5.5.11 Martindale Abrasion Testing

There were no issues with the Martindale abrasion testing. All samples were able to remain in testing until 30,000 cycles with only pilling and fuzzing noted. Pictures were taken of the original samples, at 10K , 20K and 30K cycles. These are located in Appendix E, Table 11A-N. During the test, only fuzzing and pilling was noted, and was observed to be more severe on the samples with the e-yarn and with longer $float_{max}$ lengths.

Upon further microscopic analysis of the samples after they were removed from the Martindale specimen holders, it was found that although no yarns were fully broke, many of the individual conductive filaments on the e-yarns were. Four conductive filaments are wrapped around the nylon/cotton yarn to form the e-yarn. Table 21 shows the number of e-yarns in each specimen that have individually broken filaments. The approximate number of instances of e-yarn in the ripstop ribs that are exposed on a Martindale sample is about 5 warp and 5 fill e-yarns for a total of 10 e-yarns with about 4 individual copper yarns on each e-yarn. This was a subjective test and ANOVA was not performed on the test results. From looking at the actual samples and the number of broken conductive filaments, the table was created. From this information it is clear that the addition of the e-yarn and the change in $float_{max}$ length, specifically the warp e-yarns were the two factors that affected the ability of the yarn to resist abrasion. The factor of $float_{max}$ location did not provide a noted effect.

Table 21 Martindale Abrasion Results

Sample ID	Number of filament breaks (Face, Back)	Level of Fuzz and Pill (1-5*) (Face, Back)	Pass/Fail (Face, Back)
1	n/a	5, 5	P, P
2	n/a	5, 5	P, P
3	n/a	4, 4	P, P
4	n/a	5, 4	P, P
5	n/a	5, 5	P, P
1E	0, 0	5, 5	P, P
2E	11, 0	3, 3	F, P
3E	13, 0	3, 3	F, P
4E	0, 5	4, 3	P, F
5E	0, 4	4, 2	P, F
2ER	11, 0	3, 2	P, F
5ER	0, 4	4, 2	P, F
5M	0, 10	4, 2	P, F

* Rating of 1 is the lowest and a rating of 5 is the highest

Factor: Nylon/cotton vs. E-yarn (conductive network)

The addition of the copper network did not negatively impact the Martindale abrasion resistance until the float$_{max}$ lengths were increased. The e-yarn cause the abrasion resistance of the Martindale samples to be reduced because the conductive filaments are very fine and were easily abraded away. The nylon/cotton yarn within the e-yarn and the regular nylon/cotton yarns were worn in many spots but did not break.

Factor: Float$_{max}$ Length (2, 5 or 7)

The length of floats$_{max}$ did reduce the Martindale abrasion resistance of the samples, especially in the warp float$_{max}$ and in the e-yarn samples. Typically a longer float$_{max}$ length would increase the fabrics ability to resist surface abrasion because tighter weaves are more severely crimped than looser weaves making the crown of the yarn on the surface of the fabric passing over another yarn is more pronounced. When the float$_{max}$ length is longer the crown of the float in the fabric is less rounded and more flat and is more able to withstand abrasion forces because a larger length of the yarn is in contact with the abradant. This was not the case in the samples studied and the reason is that the yarn floats$_{max}$ were loosely woven into the fabric and were able to move around with the abrasion test. The warp floats$_{max}$ were particularly looser and more raised than the fill direction floats$_{max}$. This caused abrasion on the surface of the yarn in contact with the Martindale abradant and the underside of the surface that is in contact with the body of the fabric. The stiffness of the e-yarns also lead to their abrasion on the test. Their surfaces are much more rough than the nylon/cotton yarn and the fine conductive filaments are much more fragile. When the float$_{max}$ length is short, the e-yarn is tied down into the fabric and unable to move and abrade against each other. This protects the fine filaments in the e-yarn from abrasion.

Comparison of Baseline Sample 1 and Sample 5E/5ER (best conductivity)

The baseline fabric exhibited a high level of resistance to Martindale abrasion up to 30,000 cycles. The experimental sample did not perform nearly as well. At the end of the 30,000 cycles, the experimental sample showed excessive signs of wear with a high level of pilling and fuzzing. Several of the conductive copper filaments on the e-yarns were also broken, eliminating the fabrics ability to have a functioning conductive network. Since Sample 5E/5ER has the $float_{max}$ located on only one side of the fabric, this negative effect can be avoided or at least mitigated by keeping the $float_{max}$ on the inside of the garment to protect the network.

5.6 Comparison of Varying levels of Network

This section will compare how the addition of varying levels of e-yarn conductive network affects the fabric test properties to determine if a reduced level of conductive network would provide less of a change in fabric properties compared to the full network. The fabric properties of Samples 5, 5M, 5E and 5ER are compared in this section. Sample 5 has no electrically conductive network, Sample 5M has a partial network with the conductive yarns only in the warp direction and Samples 5E and 5ER have the full network as the conductive yarns are located in both the warp and fill ripstop ribs. See Table 22 for details of the fabric construction.

Table 22 Levels of e-Yarn in Fabric Samples

Sample ID	Warp Rib Yarn Type	Fill Rib Yarn Type	Network
5	nylon/cotton	nylon/cotton	none
5E	e-yarn	e-yarn	full
5ER	E-yarn	e-yarn	full
5M	e-yarn	nylon/cotton	partial

Table 23 shows the average test results for each group tested; the highlighted values were found through ANOVA to have a statistical difference. Samples 5E and 5ER were averaged together (considered as one sample) and compared to Sample 5 and 5M. Since the differences between fabric samples having no network and a full network have been previously discussed, only those test properties that have been found to be statistically different and have a difference of 5% or greater between the partial or full network with be discussed. These properties are yarn crimp, stiffness, and filling break force and elongation as well as warp torn tear strength.

Table 23 Summary Table of Means by Level of Conductive Network

Fabric Property	No network (Sample 5)	Partial network (Sample 5M)	Full network (Sample 5E/ER averaged)
Warp Density (1/cm)	39.7	39.6	39.6
Pick Density (1/cm)	23.8	23.2	23.0
Warp Crimp (%)	25.1%	25.1%	23.2%
Fill Crimp (%)	6.5%	5.4%	5.1%
Thickness (mm)	0.86	0.90	0.91
Weight (g/m2)	231.413	247.223	258.759
Stiffness, all directions, (ujoule/cm)	0.8432	1.0058	1.392
Warp Breaking Force (newtons)	1120	1092	1127
Fill Breaking Force (newtons)	623	662	614
Warp Elongation (%)	56.7%	51.5%	53.0%
Fill Elongation (%)	26.9%	27.3%	25.4%
Warp Elmendorf Tear (gf)	6387	5760	5568
Fill Elmendorf Tear (gf)	4966	5478	3788
Air Perm, Face-up ($cm^3/s/cm^2$)	6.671	8.245	8.097
Air Perm Face-down, ($cm^3/s/cm^2$)	6.976	7.333	7.460
Thermal Transmittance Face-up (clo)	0.483	0.501	0.481
Thermal Transmittance Face Down (clo)	0.460	0.471	0.458

5.6.1 Yarn Crimp

The difference between a partial or full network in the fabric had a statistically and practically significant effect on only the amount of warp crimp in the fabric, The percent of warp crimp was equal when the fabric had no network (M = 25.08%, SD = 0.52) or a partial network (M = 25.08%, SD =0.94) and decreased 7.58% when the full network (M = 23.18%, SD = 0.76%). Using the comparison circles in Figure 43 to compare the levels of conductive network, there is no difference between the warp crimp in samples with no network and a partial network. The full network is significantly different than samples with no network and partial network.

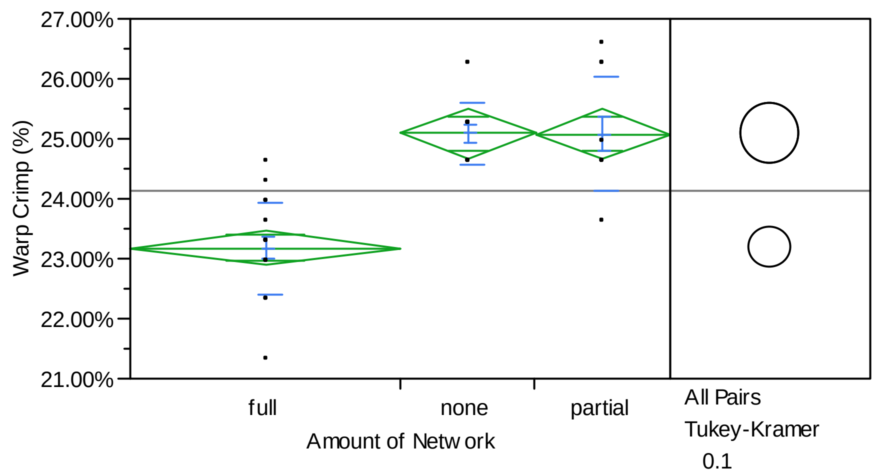

Figure 43 Effect of Level of e-yarn in Sample on Property of Warp Crimp %

The decrease in the crimp could have been caused by the decrease in warp and pick densities when the e-yarn was added to the weave. Also, at least two out of the ten individual yarns sampled for this test were the e-yarn from the ripstop ribs. These yarns have much less extensibility and since the % crimp was measured using hand tension only, this may have also played a factor in decreasing the amount of crimp.

5.6.2 Fabric Stiffness

The stiffness of the fabric samples was affected by the addition of a partial or full network. Understandably the fabric was the softest when the no network was in the fabric (M = 0.8432 μjoule/cm , SD = 0.309) and 19.29% stiffer when the partial network (M = 1.006 μjoule/cm, SD = 0.248). Stiffness was increased another 38.39% when the full network was added (M = 1.392 μjoule/cm, SD = 0.0.560) for a total effect of 65.07% increase in stiffness. In this case, Figure 45 shows that the only significant differences found between the levels of conductive networks are between no network and a full network or a partial network and a full network. No difference was found to exist between the stiffness of samples without a network and with only a partial network. This shows that stiffness is a fabric property that could remain unchanged for the most part if only a partial network was added to the fabric.

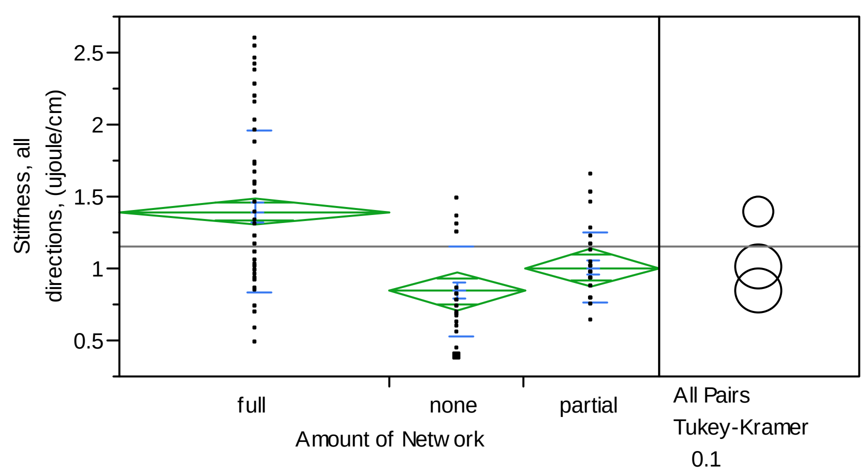

Figure 44 Effect of Level of Conductive Network on Stiffness

5.6.3 Filling Break Force

The filling break force was significantly and practically affected by the amount of e-yarn in the fabric. The lowest break force was observed when the full network (M = 614N, SD = 23) was in the fabric. Using only a partial network (M = 662 N, SD = 15) increased the break force 7.40%. Then looking at the samples with no network (M = 623 N, SD = 10), surprisingly, the break forces of these lie between those of the full and partial network. Figure 45 shows this data graphically. Comparison circles show that there is no statistical difference between the samples without and with a full network, the filling break force of those with a partial network is statistically different from the rest. In the samples with the partial network, there is no e-yarn in the filling direction.

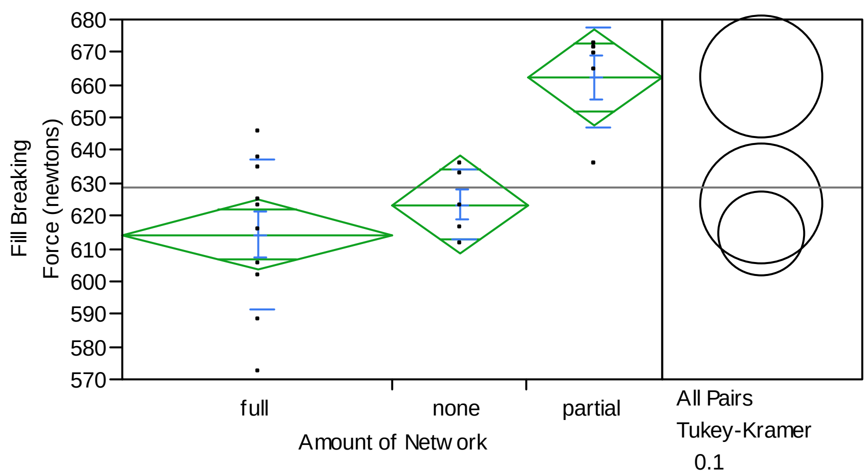

Figure 45 Filling Break Force

5.6.4 Filling Elongation

The filling elongation showed a similar effect as the filling break strength. The lowest elongation was observed when the full network (M = 25.31%, SD = 0.376) was in the fabric. Using only a partial network (M = 27.32, SD = 0.50) increased the break force 7.35%. Then looking at the samples with no network (M = 26.94, SD = .50), again, the elongation values of these lie between those of the full and partial network. Figure 46 shows this data graphically. Comparison circles show that there is no statistical difference between the samples without and with a full network, the filling elongation of those with a partial network is statistically different from the rest.

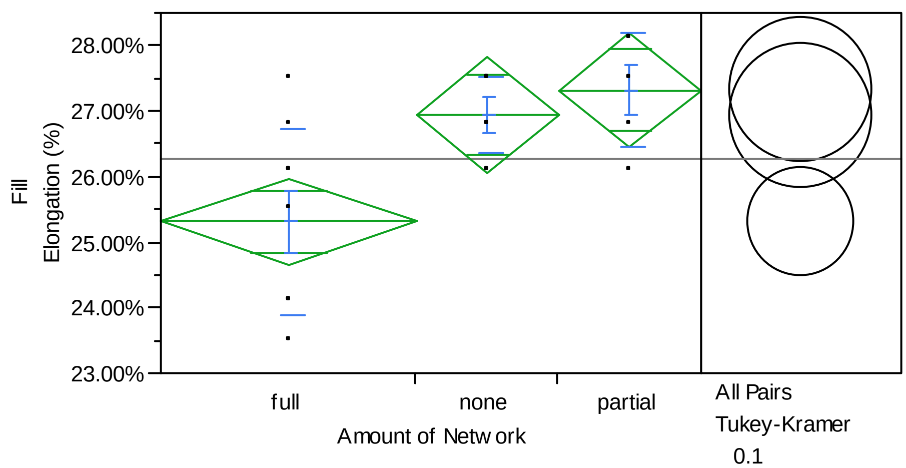

Figure 46 Filling Elongation

5.6.5 Tear Strength (warp torn/filling direction)

Warp torn fabric tear strength properties were affected by the addition of the conductive network. The tear strength of fabric without a conductive network (M = 4966 gf, SD = 302) was actually increased 10.31% with the addition of a partial network (M = 5478 gf, SD = 375) Then the tear strength was reduced 30.84% and was the weakest when a full network (M = 3789 gf, SD = 650) was added into in the fabric. Figure 47 is a graphical representation of the one-way analysis on the filling direction data. Comparison circles indicate the warp torn tear strength was affected by the change from having no network to a partial or full network. There was no statistical difference observed between the stiffness of samples with a partial network or full network.

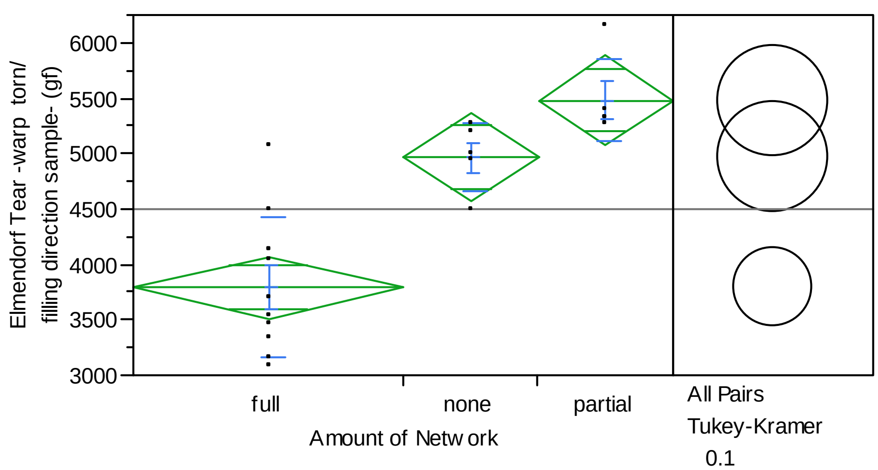

Figure 47 Effect of Level of Network on Warp Torn Tear Strength

The reason for the initial increase in tear strength with the addition of the partial network may be due to the fact that the e-yarn friction issue does not come into play because the network is not in both the warp and filling directions. This is clear when the partial network in increased to a full network and the e-yarn is put in both directions. Although the breaking strength of the e-yarn is much higher than the nylon/cotton yarn, perhaps the friction of the e-yarn located in both directions prevents the yarns from having full mobility during the tear test. This prevents the yarns from moving and slinging past one another to finally break as a group. Using only a partial network instead of a full network allows more yarn mobility and results in a higher tear strength. It is important to note that although the samples with the full network had the lowest tear strength, the results are still about 68% greater than the MIL DTL 44436 minimum requirement.

5.7 Summary

There are some negative and positive impacts on durability and comfort when comparing the baseline sample to the experimental fabrics. The increase in thickness and weight may be a problem for the soldier when he is perspiring as thicker fabric is generally less breathable than thinner fabric. However, this study has found that the air permeability of the experimental weave, Samples 5E/5ER was not reduced by the increase in thickness, it was increased. This is mainly because the increase in $float_{max}$ lengths reduce the cover allowing for greater airflow through the fabric and that the increase in thickness does not take into account that only the ripstop ribs have become thicker, the remaining 85% of the fabric remained unchanged. This shows that the increase in $float_{max}$ lengths offsets any negative impact that the increase in weight or thickness would have on the breathability of the fabric. However, when the soldier is perspiring a heavier fabric will cling to the body more and take longer to cool the soldier and dry. The BDU fabric is meant to be wind resistant and air permeability must be kept under a certain minimum.

The stiffness of the fabric was almost doubled from the original level exhibited in the baseline fabric. This is due to the stiffer e-yarn. The fact that the fabric is stiffer might combat some of the clinginess of the fabric when it is moist because stiffer fabric does not cling as easily. Although the addition of the conductive network had a negative impact on the fabric tear strength when comparing individual samples, looking at all of the experimental samples compared to the baseline shows a different effect. All samples with longer $floats_{max}$ have higher tear strengths than the baseline sample.

One negative impact to the BDU fabric performance was in the resistance to abrasion. Once the conductive network was added to the fabric with $float_{max}$ lengths of two or five, the copper filaments on the outside of the yarn the fabric resistance to Martindale abrasion decreased significantly. In addition to the negative affect on the durability of the BDU, this causes the network to lose functionality.

CHAPTER 6 CONCLUSION

The three factors of yarn type, $float_{max}$ length and $float_{max}$ location did not have a practical impact on thread density, breaking strength and thermal transmittance.

The fabric properties of stiffness, tear strength, air permeability and abrasion resistance were most significantly affected by the addition of the conductive network through the combination of a change in yarn type, $float_{max}$ length and $float_{max}$ location. The study showed that when the network was added in any configuration, the fabric became 6% to 58% stiffer and this is viewed as a negative impact on the comfort of the BDU fabric. Tear strength was increased with the addition of the network, anywhere from about 6% to 49% and of course this is seen as an improvement to the durability of the fabric. On the other hand, the air permeability increased 13 to 168% with the addition of the conductive network and associated construction changes, potentially reducing the wind resistant properties of the fabric. As with any other fabric where air permeability is controlled by a specification requirement, finishing processes such as fabric drying on the tenter frame and calendaring would need to be controlled to bring the air permeability down to specification limits. An increase in the air permeability of the fabric would be expected to cause body heat to flow more easily through the fabric and away from the body. This is beneficial in a warm environment to cool the body but in a cold environment, the increase in permeability could make it harder for the soldier to retain body heat. However, when thermal resistance was evaluated, a less than 3% decrease in the clo value of the experimental samples was identified as statistically significant but was not considered practically significant to cause any real change in comfort to the soldier.

Once the network was added to the fabric in a configuration where the $float_{max}$ lengths were increased, abrasion resistance was severely impacted. The longer $floats_{max}$ of the e-yarn were not able to withstand abrasion as easily as the nylon/cotton $floats_{max}$. This is a negative impact on the durability of the fabric because when the e-yarn is abraded, the fabric loses its functionality as a conductive network. One remedy to this is to construct the BDU jacket with the $floats_{max}$ on the inside of the jacket to protect the conductive network from normal wear and tear.

The fabric weight was significantly impacted by the addition of the e-yarn while $float_{max}$ length and location did not impact the weight at all. The fabric weight increased about 13% with the addition of the e-yarn in both the warp and fill ripstop ribs making the experimental fabric out of tolerance for the weight requirement in MIL-DTL-44436 and can potentially decrease the comfortability of the fabric. Using a reduced level of e-yarn only in the warp direction to create the conductive network provided a weight increase of less than 7%. Another way to reduce the additional weight of the network is to utilize smaller e-yarns that more closely match the size of the warp and filling nylon/cotton yarns.

Yarn crimp, fabric thickness and elongation at break were all affected by the addition of the e-yarn and the change in $float_{max}$ length however, the change of $float_{max}$ location from both sides to only one side did not impact there fabric properties. Yarn crimp and fabric elongation at break was both increased or decreased depending on the factor and level evaluated and more testing would need to be performed to more clearly understand the changes. Fabric thickness was increased almost 12% by the addition of the e-yarn in both direction but the change in $float_{max}$ length resulted in just over 35% increase in thickness. This increase in thickness seems very significant but it is important to remember that this is limited to only the ripstop rib areas, and the remaining 85% of the fabric area was unchanged in thickness. This is probably why a seemingly large increase in thickness did not produce the changes in other fabric properties that are usually associated with thickness.

Overall, the addition of the conductive network was identified to cause both a positive and negative impact to the durability and comfort properties of the Army BDU fabric, however, it seems that with a few processing changes and careful consideration during final garment construction, the negative effects can be resolved. This evaluation and resulting data regarding the effect of the changes in yarn type and ripstop float length and locations can be applied to many other end items that use ripstop fabric.

CHAPTER 7 SUGGESTIONS FOR FUTURE RESEARCH

7.1 Yarn Construction

As a result of this study, it is clear the construction of the e-yarn has an adverse effect on some of the comfort and durability properties of the BDU fabric as well as its weavability. To minimize the negative effect of the e-yarn, alternative techniques of yarn manufacture should be investigated for their ability to perform more closely to that of the standard nylon/cotton yarn. Utilizing e-yarn that is more closely matched to the nylon/cotton warp and fill yarns in denier may reduce some of the weight and stiffness increases as well as improve the fabrics ability to withstand abrasion. Yarn construction where the "e" components are located within the yarn instead of on the surface should improve weavability and tear properties because the amount of surface friction would be reduced.

7.2 Partial Conductive Network

This study showed that e-yarn in only one direction is likely to result in fabric properties that more closely match the current BDU performance in several areas and it would be worthwhile to study this more closely. However, instead of placing the network only in the warp direction, as was done in this study for convenience, placing the network in the filling direction might offer the additional benefit of improving weavability. The e-yarn that was used in this study was coarse and since the "e" component was mostly placed on the surface of the yarn the repeated shedding motion of the warp sheet cause some yarn breakage and deterioration of the "e" component. Utilizing the e-yarn in only the filling direction would eliminate the yarn on yarn abrasion that was occurring in the shedding area and improve weavability.

Or to consider an entirely different method, perhaps putting the conductive network in every other, or every third set of ripstop ribs instead of every rib. It would be useful to determine if the network conductivity is adequate at this level and allows the stiffness, weight and tensile properties to be improved to a more acceptable level.

7.3 Testing & Evaluation

Many properties can change after the finishing of a fabric and it is important to learn how this conductive fabric will perform in the end item state. It would be advantageous to evaluate the experimental fabric properties after dying, printing and finishing to ensure that the test results more accurately reflect end item performance. Also, this fabric was evaluated without regard for the effect that the interconnects would create. As such, performing an evaluation of the fabric properties after the interconnects are made on the fabric would provide a better understanding of the network's final impact on the garment. Ultra-sonic bonding methods are employed to create the interconnects between the e-yarns and form the electrically conductive network. This process most probably would have an effect on the stiffness, air permeability and abrasion resistance of the fabric. Since this study was very limited in terms of fabric properties that could be measured as well as sample size. In general, additional tests such as such as sweating guarded hot plate, durability to laundering and other types of abrasion testing need to be investigated.

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CHAPTER 9 APPENDICES

9.1 Appendix A

Figure A1 Sample 1, face

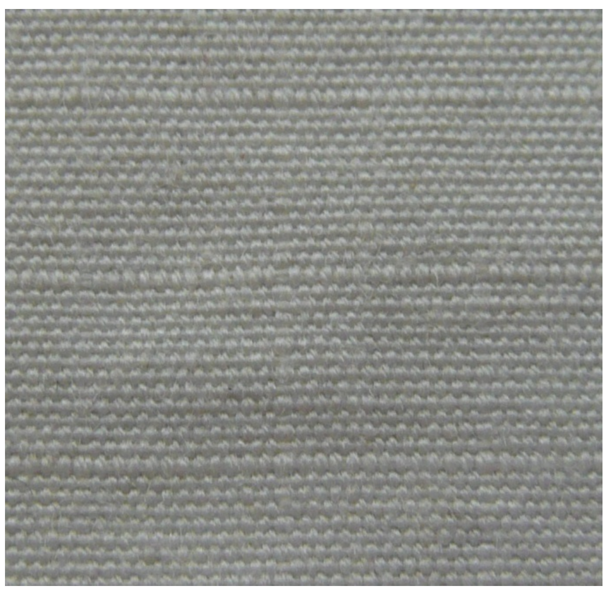

Figure A2 Sample 1, back

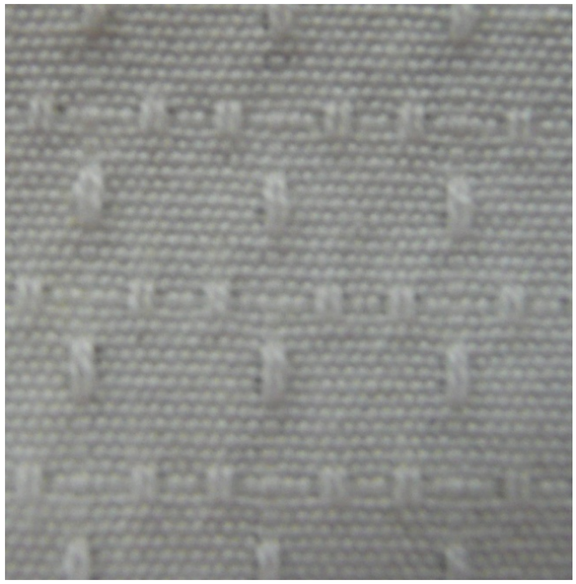

Figure A3 Sample 2, face

Figure A4 Sample 2, back

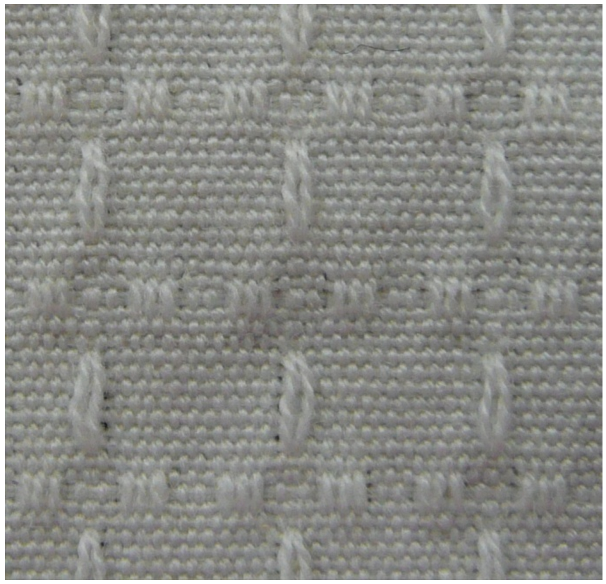

Figure A5, Sample 3, face

Figure A6, Sample 3, back

Figure A7 Sample 4, face

Figure A8 Sample 4, back

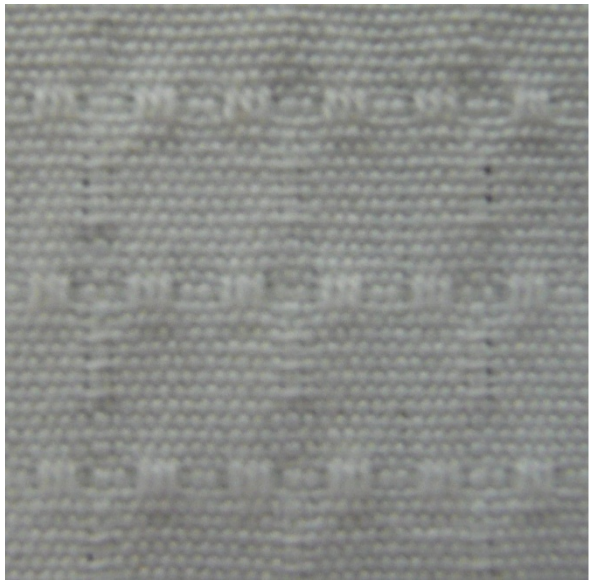

Figure A9 Sample 5, face

Figure A10 Sample 5, back

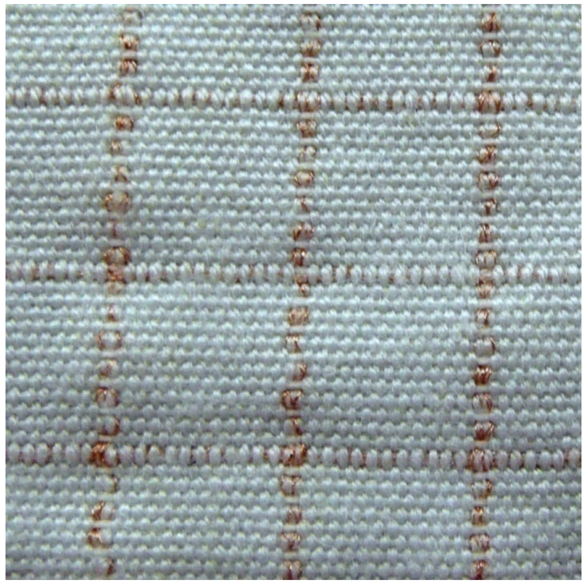

Figure A11 Sample 1E, face

Figure A12 Sample 1E, back

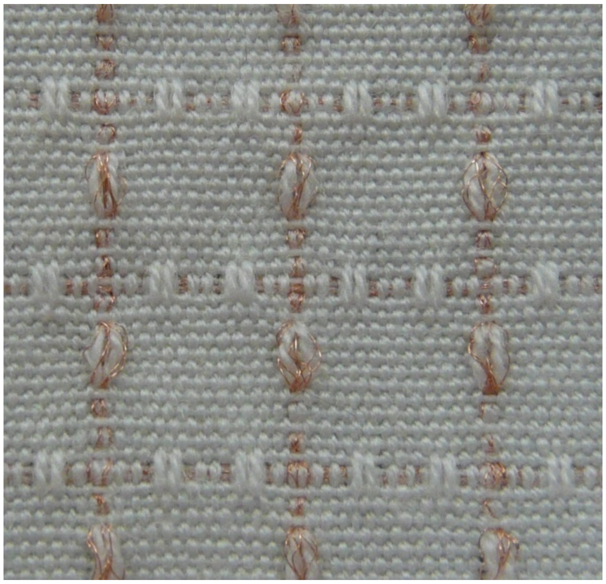

Figure A13 Sample 2E, face

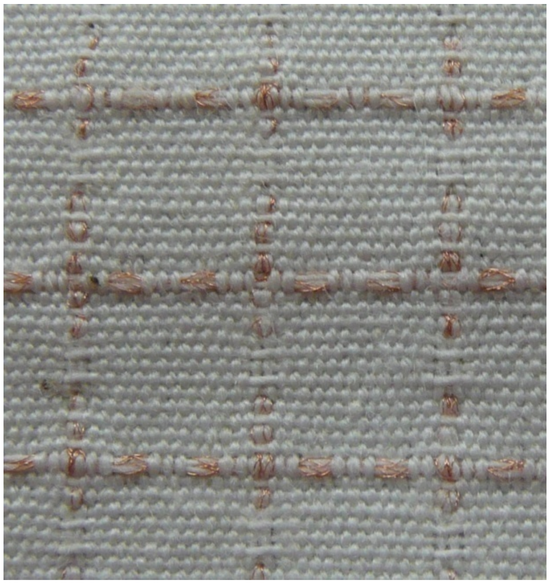

Figure A14 Sample 2E, back

Figure A15 Sample 3E, face

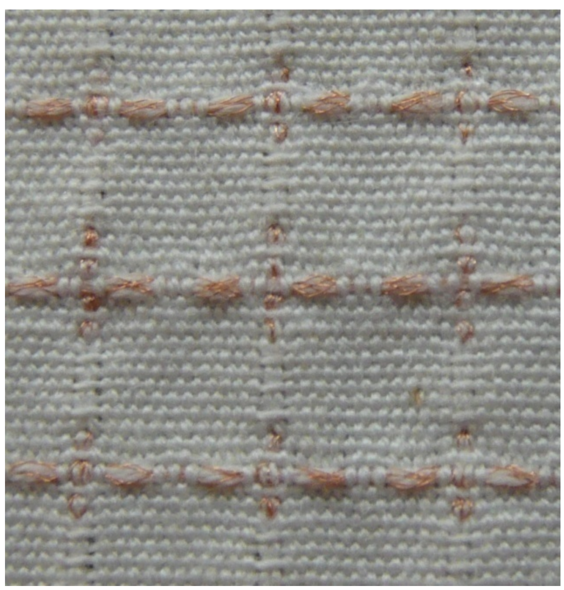

Figure A16 Sample 3E, back

Sample 4E Face

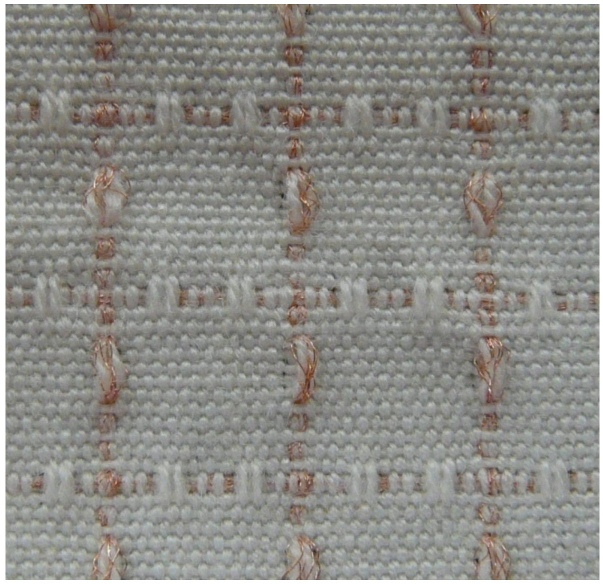

Figure A17 Sample 4E, face

Figure A18 Sample 4E, back

Figure A19 Sample 5E, face

Figure A20, Sample 5E, back

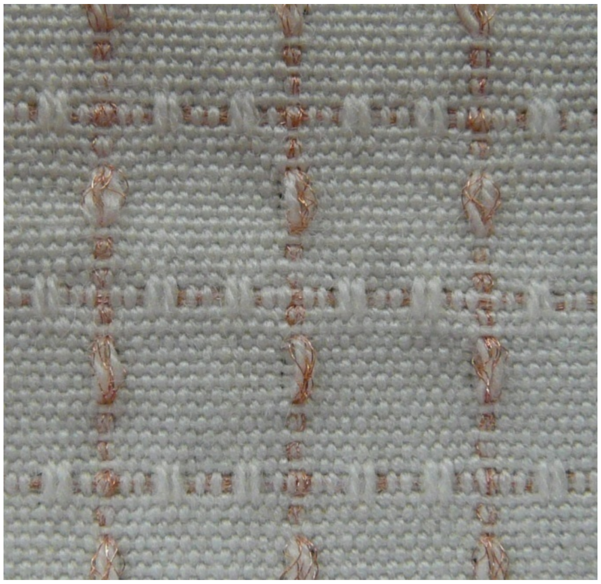

Figure A21 Sample 2ER, face

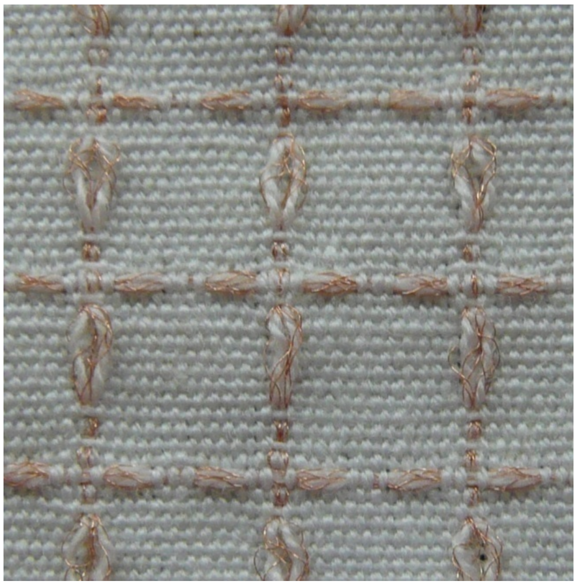

Figure A22, Sample 2ER, back

Figure A23, Sample 5ER, face

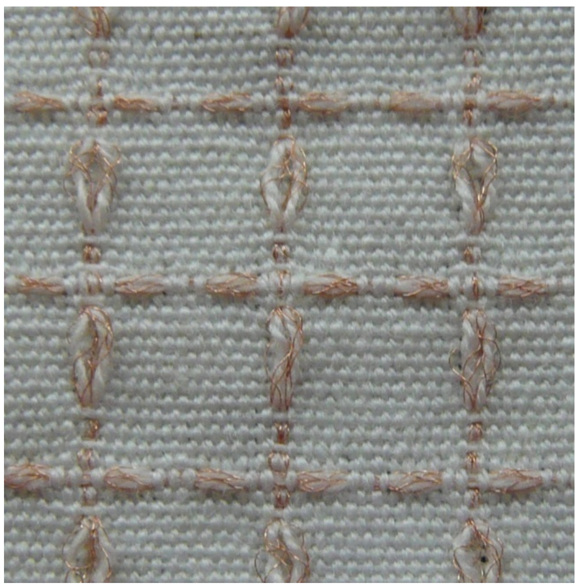

Figure A24, Sample 5ER, back

Figure A25, Sample 5M, face

Figure A26, Sample 5M, back

9.2 Appendix B

Table B1 Nylon/cotton Warp Yarn Properties

Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus (gf/denier)
1	480.2	11.26%	19.53
2	582.3	14.21%	20.58
3	623.3	18.15%	20.85
4	582.5	16.77%	19.46
5	538.7	14.01%	19.36
6	570.3	18.15%	18.53
7	624.5	17.36%	21.2
8	613.4	16.77%	21.18
9	558	13.43%	20.68
10	618.2	17.95%	19.69
11	653.8	17.56%	20.91
12	488.5	12.44%	19.13
13	654.9	17.17%	21.89
14	549.9	13.43%	21.47
15	534	12.64%	20.45
Avg	578.2	15.42%	20.3
Std. dev	54.18	0.024148972	0.98
% CV	9.37%	15.66%	4.83%

Warp Yarn 263.50 measured denier, 42/2 stated cotton count

ASTM D 2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, Option A1

Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table B2 Nylon/cotton Filling Yarn Properties

Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus gf/denier)
1	720.03	17.75%	19.22
2	634.53	13.82%	18.07
3	678.15	17.76%	17.56
4	649.84	14.80%	18.35
5	718.25	16.18%	19.55
6	774.57	22.68%	19.48
7	705.01	14.21%	20.66
8	687.66	13.43%	20.11
9	749.87	23.66%	18.83
10	744.94	19.72%	18.82
11	741.85	16.97%	20.24
12	704.73	15.59%	18.73
13	819.92	19.13%	19.52
14	716.7	18.74%	19.92
15	667.25	17.76%	18.09
16	620.79	16.38%	17.56
17	752.44	20.12%	19.57
18	677.57	14.80%	19.45
19	592.44	11.85%	17.83
20	665.3	15.79%	18.01
21	678.95	20.71%	17.68
Avg	700	17.23%	18.9
Std. dev	54.09	3.06%	0.95
% CV	7.73%	17.75%	5.03%

Filling Yarn 334.24 measured denier, 16/1 stated cotton count

ASTM D 2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, Option A1

Samples were conditioned in accordance with the requirements in
ASTM D 1776 Practice for Conditioning and Testing Textiles

Table B3 e-Yarn Cone A Properties

Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus (gf/denier)
1	674.97	11.66%	14.787
2	644.2	11.65%	14.875
3	684.61	12.64%	15.3543
4	703.9	13.62%	14.3257
5	675.3	14.21%	15.1007
6	739.18	15.00%	15.2628
7	678.7	15.00%	15.3604
8	711.63	14.80%	14.7147
9	742.68	16.57%	14.6244
10	572.76	10.67%	13.819
Avg	682.8	13.58%	14.8
Std. dev	49.19	1.88%	0.49
% CV	7.20%	13.81%	3.30%

e-Yarn Cone A 701.0 measured denier

ASTM D 2256 Standard Test Method for Tensile Properties of
Yarns by the Single-Strand Method, option A1

Samples were conditioned in accordance with the requirements in
ASTM D 1776 Practice for Conditioning and Testing Textiles

Table B4 e-Yarn Cone B Properties

	Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus (gf/denier)
	1	560.98	11.06%	16.18
	2	602.45	12.64%	14.03
	3	611.28	13.82%	13.77
	4	591.02	12.24%	14.9
	5	587.34	12.05%	15.05
	6	579.37	12.05%	15.65
	7	591.87	12.64%	15.05
	8	527.21	9.49%	13.81
	9	628.43	12.64%	15.53
	10	615.41	13.62%	15.29
	11	569.45	11.26%	15.97
	12	582.93	11.26%	15.24
	13	595.6	12.83%	15.6
	14	572.52	10.67%	14.93
	Avg	586.8	12.02%	15.1
	Std. dev	25.28	1.18%	0.75
	% CV	4.31%	9.78%	4.98%

e-Yarn Cone B 681.0 measured denier

ASTM D 2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, option A1

Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table B5 e-Yarn Cone C Properties

Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus (gf/denier)
1	890.62	18.94%	12.94
2	783.93	14.21%	13.03
3	723.72	11.85%	12.56
4	742.24	10.67%	13.78
5	742.05	11.46%	12.45
6	811.52	14.21%	13.58
7	754.49	11.65%	13.1
8	720.12	10.08%	12.66
9	596.95	8.50%	12.56
10	746.73	10.28%	14.17
11	768.04	12.64%	14.09
12	806.47	13.03%	14.54
13	680.5	15.20%	13.39
14	827.05	12.44%	13.1
15	682.5	11.26%	13.55
Avg	751.8	12.43%	13.3
Std. dev	70.03	2.52%	0.64
% CV	9.32%	20.25%	4.84%

e-Yarn Cone C 783.3 measured denier

ASTM D 2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, option A1

Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table B6 e-Yarn Cone D Properties

Specimen	Peak Load (gf)	% Strain at Peak Load (%)	Fiber modulus (gf/denier)
1	589.88	9.10%	11.59
2	782.58	16.18%	12.11
3	744.52	17.16%	11.5
4	776.69	18.34%	12.98
5	762.34	15.20%	11.71
6	639.06	10.67%	11.74
7	725.03	15.78%	12.33
8	647.14	10.27%	12.43
9	661.43	11.46%	11.1
10	713.33	13.82%	12.42
11	596.42	10.67%	12.18
12	708.82	12.24%	11.44
13	748.68	13.42%	13.75
14	733.55	12.83%	12.54
15	697.18	12.44%	12.38
16	633.41	11.26%	12.01
17	652.8	10.47%	12.85
Avg	694.9	13.02%	12.2
Std. dev	61.25	2.69%	0.65
% CV	8.81%	20.66%	5.37%

e-Yarn Cone D 755.40 measured denier

ASTM D 2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, option A1

Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

9.3 Appendix C

Table C1 Results of One-Way ANOVA and Equivalence Tests by Factor Yarn Type

Property	One-Way ANOVA			Levene Test for Equivalence			Welch-ANOVA		
	DF	F-ratio	p-value	DF	F-ratio	p-value	DF	F-ratio	p-value
Warp Density (1/cm)	(1, 58)	17.1924	0.0001	(1, 58)	0.0536	0.8178	(1, 51.5)	17.1333	0.0001
Pick Density (1/cm)	(1, 58)	62.9174	0.0001	(1, 58)	3.1999	0.0001	(1, 45.353)	58.9435	0.0001
Warp Crimp (%)	(1, 118)	88.3972	0.0001	(1, 118)	0.3876	0.3876	(1, 116.17)	94.8886	0.0001
Fill Crimp (%)	(1, 118)	8.6094	0.004	(1, 118)	4.7966	0.0305	(1, 112.87)	10.2358	0.0018
Thickness (mm)	(1, 118)	27.2062	0.0001	(1, 118)	0.8357	0.3625	(1, 103.39)	26.8833	0.0001
Weight (g/m2)	(1, 118)	1869.834	0.0001	(1, 118)	9.1533	0.003	(1, 116.63)	2156.1971	0.0001
Stiffness, (ujoule/cm)	(1, 382)	115.2793	0.0001	(1, 382)	40.4144	0.0001	(1, 266.37)	136.5916	0.0001
Breaking Force, Warp (newtons)	(1, 58)	1.3963	0.2422	(1, 58)	0.1062	0.7457	(1, 53.135)	1.4163	0.2393
Breaking Force Fill (newtons)	(1, 56)	0.0101	0.9203	(1, 56)	3.0117	0.0082	(1, 56)	0.0114	0.9154
Warp Elongation (%)	(1, 57)	55.2563	0.0001	(1, 57)	0.003	0.9567	(1, 48.746)	54.7277	0.0001
Fill Elongation (%)	(1, 56)	3.0203	0.0877	(1, 56)	0.6729	0.4155	(1, 45.288)	2.8809	0.0965
Warp Elmendorf Tear (gf)	(1, 58)	4.5876	0.0364	(1, 58)	2.6637	0.1081	(1, 44.923)	4.2798	0.0444
Fill Elmendorf Tear (gf)	(1, 58)	7.8708	0.0068	(1, 58)	2.2756	0.1369	(1, 44.481)	7.311	0.0097
Air Perm, Face-up ($cm^3/s/cm^2$)	(1, 130)	16.7768	0.0001	(1, 130)	0.8652	0.354	(1, 121.85)	17.2464	0.0001
Air Perm Face-down, ($cm^3/s/cm^2$)	(1, 54)	2.5117	0.1188	(1, 54)	0.0002	0.9902	(1, 41.775)	2.4937	0.1218
Thermal Transmittance Face-up (clo)	(1, 178)	1.0744	0.3013	(1, 178)	0.057	0.8115	(1, 164.87)	1.0956	0.2968
Thermal Transmittance Face Down (clo)	(1, 178)	1.1509	0.2848	(1, 178)	1.2989	0.256	(1, 150.34)	1.1161	0.2925

Table C2 Results of One-Way ANOVA and Equivalence Tests by Factor $Float_{max}$ Length (2, 5 or 7)

Property	One-Way ANOVA			Levene Test for Equivalence			Welch-ANOVA		
	DF	F-ratio	p-value	DF	F-ratio	p-value	DF	F-ratio	p-value
Warp Density (1/cm)	(2, 57)	1.3669	0.2631	(2, 57)	0.6072	0.5484	(2, 24.044)	1.402	0.2655
Pick Density (1/cm)	(2, 57)	2.3491	0.1046	(2, 57)	0.8048	0.4522	(2, 28.281)	2.1704	0.1328
Warp Crimp (%)	(2, 117)	19.4791	0.0001	(2, 117)	2.6411	0.0755	(2, 45.573)	12.4666	0.0001
Fill Crimp (%)	(2, 117)	0.6406	0.5289	(2, 117)	0.7227	0.4876	(2, 64.128)	0.574	0.5661
Thickness (mm)	(2, 117)	91.7253	0.0001	(2, 117)	2.1478	0.1213	(2, 55.197)	147.5979	0.0001
Weight (g/m2)	(2, 117)	0.75	0.4746	(2, 117)	0.1086	0.8972	(2, 53.068)	0.7481	0.4782
Stiffness, (ujoule/cm)	(2, 381)	4.2892	00.0144	(2, 381)	7.0500	0.0010	(2, 191.81)	5.4550	0.0050
Breaking Force, Warp (newtons)	(2, 57)	4.9745	0.0102	(2, 57)	0.6243	0.5393	(2, 25.249)	4.7131	0.0182
Breaking Force Fill (newtons)	(2, 55)	4.9682	0.0104	(2, 55)	3.3816	0.0412	(2, 32)	4.3603	0.0212
Warp Elongation (%)	(2, 56)	5.2723	0.0080	(2, 56)	1.9367	0.1537	(2, 22.577)	3.5050	0.0472
Fill Elongation (%)	(2, 55)	3.2178	0.0477	(2, 55)	0.4987	0.6100	(2, 23.546)	2.5370	0.1005
Warp Elmendorf Tear (gf)	(2, 57)	31.4218	0.0001	(2, 57)	1.0891	0.3434	(2, 26.285)	32.3523	0.0001
Fill Elmendorf Tear (gf)	(2, 57)	24.7456	0.0001	(2, 57)	5.1121	0.0091	(2, 30.957)	34.5722	0.001
Air Perm, Face-up ($cm^3/s/cm^2$)	(2, 129)	497.9384	0.0001	(2, 129)	10.3258	0.0001	(2, 76.155)	792.8794	0.001
Air Perm Face-down, ($cm^3/s/cm^2$)	(2, 53)	427.4640	0.0001	(2, 53)	1.2963	0.2821	(2, 29.427)	642.5217	0.001
Thermal Transmittance Face-up (clo)	(2, 177)	7.7263	0.0006	(2, 177)	1.9700	0.1425	(2, 97.012)	11.4350	0.0001
Thermal Transmittance Face Down (clo)	(2, 177)	6.6492	0.0016	(2, 177)	1.2610	0.2859	(2, 87.89)	8.4231	0.0005

Table C3 Results of One-Way ANOVA and Equivalence Tests by Factor $Float_{max}$ Location (same or both sides)

Property	One-Way ANOVA			Levene Test for Equivalence			Welch-ANOVA		
	DF	F-ratio	p-value	DF	F-ratio	p-value	DF	F-ratio	p-value
Warp Density (1/cm)	(1, 48)	0.4186	0.5207	(1, 48)	3.318	0.0747	(1, 42.655)	0.4186	0.5211
Pick Density (1/cm)	(1, 48)	3.9094	0.0538	(1, 48)	0.2935	0.5905	(1, 47.264)	3.9094	0.0539
Warp Crimp (%)	(1, 98)	0.0139	0.9065	(1, 98)	4.0126	0.0479	(1, 92.986)	0.0139	0.9065
Fill Crimp (%)	(1, 98)	0.0385	0.8448	(1, 98)	0.1693	0.6816	(1, 98.185)	0.0385	0.8448
Thickness (mm)	(1, 98)	0.000	1.000	(1, 98)	11.8433	0.0009	(1, 76.829)	0.0000	1.000
Weight (g/m2)	(1, 98)	0.0909	0.7637	(1, 98)	0.7420	0.3911	(1, 97.507)	0.0909	0.7637
Stiffness, (ujoule/cm)	(1, 318)	0.7045	0.4019	(1, 318)	4.2659	0.0397	(1, 312.17)	0.7045	0.4019
Breaking Force, Warp (newtons)	(1, 48)	6.1851	0.0164	(1, 48)	0.4059	0.5271	(1, 47.71)	6.1851	0.0164
Breaking Force Fill (newtons)	(1, 47)	1.7019	0.1984	(1, 47)	3.5560	0.0655	(1, 44.61)	1.6884	0.2005
Warp Elongation (%)	(1, 47)	1.4201	0.2394	(1, 47)	1.4196	0.2395	(1, 46.555)	1.4331	0.2375
Fill Elongation (%)	(1, 46)	5.2193	0.0270	(1, 46)	0.0156	0.9010	(1, 45.974)	5.2193	0.0270
Warp Elmendorf Tear (gf)	(1, 48)	0.5520	0.4611	(1, 48)	0.0158	0.9004	(1, 47.911)	0.5520	0.4611
Fill Elmendorf Tear (gf)	(1, 48)	2.6306	0.1114	(1, 48)	0.1001	0.7531	(1, 47.878)	2.6306	0.1114
Air Perm, Face-up ($cm^3/s/cm^2$)	(1, 108)	2.2541	0.1362	(1, 108)	2.2541	0.1362	(1, 105.76)	2.2541	0.1362
Air Perm Face-down, ($cm^3/s/cm^2$)	(1, 45)	3.2080	0.0802	(1, 45)	0.1280	0.7222	(1, 44.878)	3.2018	0.0803
Thermal Transmittance Face-up (clo)	(1, 148)	3.5187	0.0626	(1, 148)	0.7439	0.3898	(1, 142.53)	3.5187	0.0627
Thermal Transmittance Face Down (clo)	(1, 148)	9.5180	0.0024	(1, 148)	0.0792	0.7788	(1, 147.46)	9.5180	0.0024

Table C4 Results of One-Way ANOVA and Equivalence Tests by Factor Test Configuration, face-up or face-down

Property	One-Way ANOVA			Levene Test for Equivalence			Welch-ANOVA		
	DF	F-ratio	p-value	DF	F-ratio	p-value	DF	F-ratio	p-value
Air Permeability	(1, 155)	1.6204	0.2049	(1, 155)	0.5612	0.4549	(1, 98.521)	1.8013	0.1826
Thermal Transmittance	(1, 299)	53.5426	0.0001	(1, 299)	1.4781	0.2250	(1, 293.88)	53.4978	0.0001

Table C5 Results of One-Way ANOVA and Equivalence Tests by Factor Regular or Replicate

Property	One-Way ANOVA			Levene Test for Equivalence			Welch-ANOVA		
	DF	F-ratio	p-value	DF	F-ratio	p-value	DF	F-ratio	p-value
Thickness	(1, 38)	6.7980	0.0130	(1, 38)	1.0752	0.3603	(1, 34.7)	6.7980	0.0134
Weight	(1, 38)	8.8867	0.0050	(1, 38)	0.3666	0.5484	(1, 36.74)	8.8867	0.0051
Stiffness	(1, 126)	3.9578	0.0488	(1, 126)	6.2403	0.0138	(1, 116.07)	3.9578	0.0490
Breaking Force (filling)	(1, 17)	5.2550	0.0349	(1, 17)	0.0752	0.7873	(1, 16.859)	5.2669	0.0349
Elmendorf Tear Strength (warp torn/fill direction)	(1, 18)	3.2597	0.0878	(1, 18)	1.0218	0.3255	(1, 14.778)	3.2597	0.0914

9.4 Appendix D

Comparison of Regular Samples (2E, 5E) to Replicates (2ER, 5ER)

Samples 2E and 5E were randomly selected to have replicates woven. These replicates were woven after all the regular samples were complete to determine if the weaving process was consistent. The replicate group included 2ER and 5ER while the regulatr group included 5E and 5E. Averages for all the properties of the two groups are located below in Table D1.

Table D1 Summary of Test Averages by Experimental and Replicates

Property	Experimental	Replicate
Ends per cm	39.4	39.5
Picks per cm	22.9	22.8
Warp Crimp (%)	23.4%	23.8%
Fill Crimp (%)	5.0%	5.4%
Thickness (mm)	0.88	0.93
Weight (g/m2)	261.004	257.064
Stiffness, all directions, (µjoule/meter)	1.236	1.412
Breaking Strength, Grab, Warp direction (newtons)	1135	1148
Breaking Strength Grab Fill Direction (newtons)	645	614
Elongation Grab Warp Direction (%)	53.3%	54.5%
Elongation Grab Fill Direction (%)	25.7%	26.3%
Elmendorf Tear (grams/force) Warp Dir/Fill Yarns	5501	5354
Elmendorf Tear (grams/force) Fill Dir/Warp Yarns	3808	3334
Air Perm, Face-up (cm3/s/cm2)	6.759	7.145
Air Perm Face-down, (cm3/s/cm2)	6.350	6.369
Thermal Transmittance Face-up (clo)	0.472	0.477
Thermal Transmittance Face Down (clo)	0.459	0.457

In all of the testing performed, no differences were found between the experimental and replicate samples in terms of yarn count, % yarn crimp, % elongation, air permeability, and thermal transmittance. Properties of thickness, weight, stiffness, filling break strength and warp torn tear strength were found to have p-values of over 0.10 and were identified a having a statistical difference between the property average of the experimental group and the replicate group. Detailed ANOVA and Equivalence Test results are located in Appendix C, Table C6.

The only differences between the weaving of the experimental and the replicates were day of weaving and the e-yarn used in the filling direction of the fabric. The experimental and replicates were woven two weeks apart. Experimental samples 2E and 5E used e-yarn cones B and C respectively. Replicate Samples 2ER and 5ER used C and D respectively.

Thickness, weight and stiffness were the three fabric properties that were identified as being significantly different in the experimental averages from the replicate averages and are all interrelated. Figures D1, D2 and D3 describe the data from these tests.

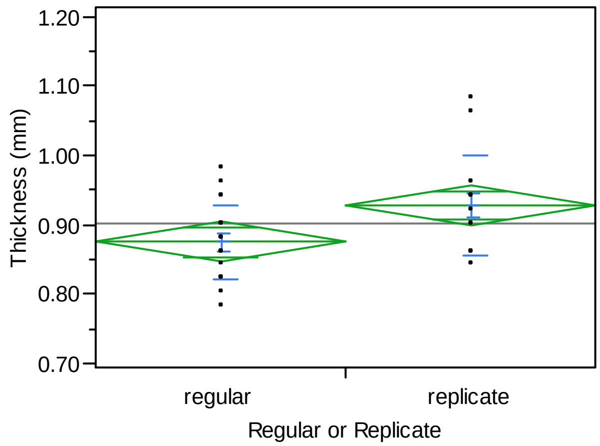

Figure D1 Difference in Thickness

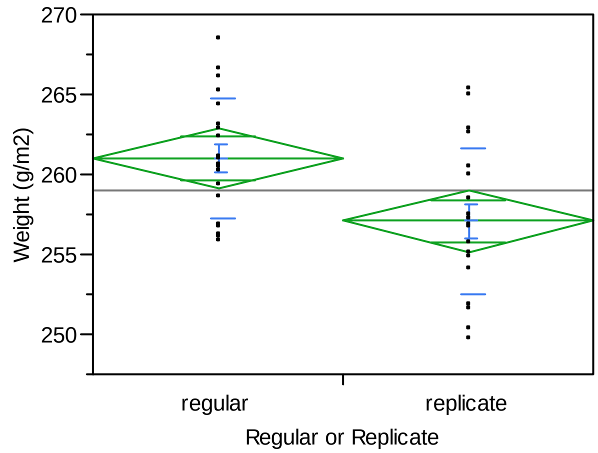

Figure D2 Difference in Weight

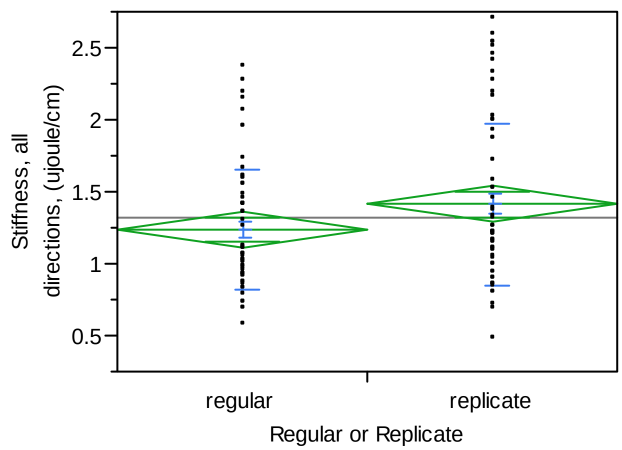

Figure D3 Difference in Stiffness

From the experimental group to the replicate group the thickness and stiffness increased while the weight decreased. This does not follow conventional wisdom of how these three properties behave; one would have expected all three to increase or decrease together. The thickness increased 6.06% and the stiffness increased 14.18% from the regular to the replicate. This change is likely related to the different e-yarn cones used. Although there was a statistical difference noted in the weight of the fabrics, there was only a decrease in 1.5% from the regular samples to the replicates.

The experimental break and tear strength in the fill direction only was greater than the replicate in both tests. This seems very likely to correspond with e-yarn data but it does not as the experimental samples used e-yarn with a lower tensile strength than the replicates. The experimental fill direction break strength was 645 newtons and the replicate break strength was

614 newtons. The experimental tear strength was 3808 gf and the replicate tear strength was 3304 gf. A description of this data is shown below in Figures D4 and D5.

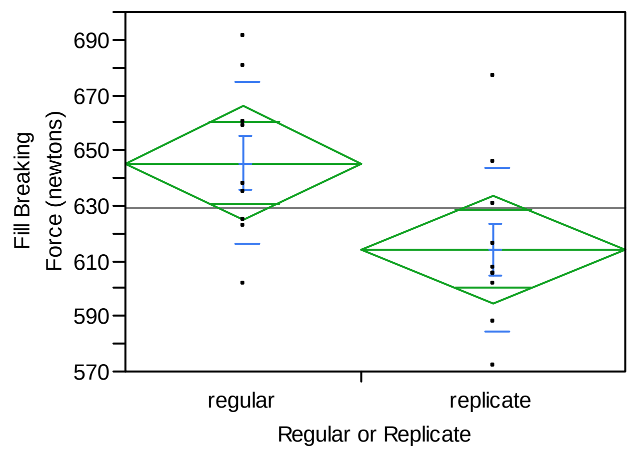

Figure D4 Difference in Filling Break force

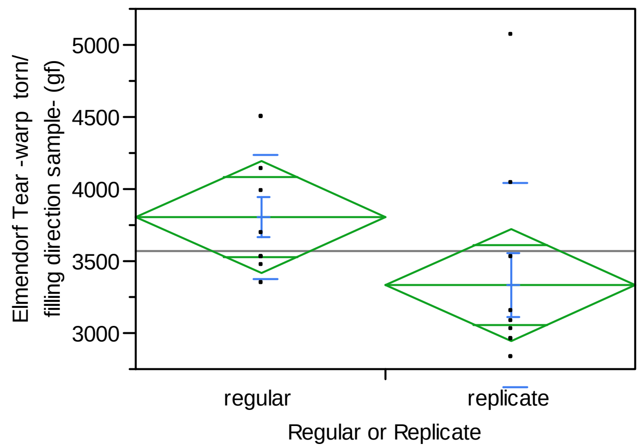

Figure D5 Difference in Warp torn Tear Strength

The change in break and tear strength in the fill direction only is most likely due to the e-yarn cone changes. Looking at the yarn strength data in Table 6, the average yarn strength of Cones C and D (used in the replicates) is less than that of Cones B and C (used in the regular samples). This may account for the decrease in break and tear strength when the replicates were woven.

9.5 Appendix E

Table E1 Thread Density

Warp Density (1/cm)				
sample ID	cm	# of pattern repeats	# of yarns measured	yarns per cm
1	40.7	65	1625	39.9263
2	20.4	33	825	40.4412
3	27	45	1125	41.6667
4	19.2	31	775	40.3646
5	20.4	33	825	40.4412
1E	59.5	95	2375	39.916
2E	40.1	65	1625	40.5237
3E	20.4	33	825	40.4412
4E	50.2	80	2000	39.8406
5E	44.7	72	1800	40.2685
2ER	51.3	83	2075	40.4483
5ER	48.4	78	1950	40.2893
5M	19.8	32	800	40.404

Filling Density (1/cm)				
sample ID	cm	# of pattern repeats	# of yarns measured	yarns per cm
1	26.5	22	616	23.24528
2	26.4	22	616	23.33333
3	20.9	17	476	22.77512
4	26.5	22	616	23.24528
5	23.2	19.5	546	23.53448
1E	41.9	34	952	22.72076
2E	25.2	20.5	574	22.77778
3E	26.2	21.5	602	22.9771
4E	28.4	23	644	22.67606
5E	30	25	700	23.33333
2ER	27	22	616	22.81481
5ER	30.5	25	700	22.95082
5M	25.5	22	616	24.15686

Table E2-A Warp Crimp %

Sample ID	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	26.89%	24.26%	25.90%	26.23%	26.23%	21.31%	23.61%	21.31%	21.97%	22.30%	24.59%	21.31%	23.61%
2	26.89%	24.59%	23.61%	26.23%	24.59%	21.31%	24.26%	21.64%	22.30%	22.30%	24.59%	22.30%	24.59%
3	26.56%	25.25%	23.28%	24.92%	24.59%	25.25%	23.61%	23.93%	24.59%	23.28%	24.59%	22.95%	24.92%
4	26.56%	25.25%	24.92%	24.92%	24.59%	25.90%	23.93%	23.28%	23.93%	23.28%	23.61%	22.95%	24.59%
5	26.56%	24.59%	24.59%	25.25%	25.25%	25.25%	23.93%	22.95%	23.93%	23.28%	24.59%	22.95%	26.23%
6	26.89%	24.59%	24.59%	25.90%	25.25%	26.23%	23.28%	22.30%	23.28%	22.95%	23.93%	23.61%	24.59%
7	26.89%	24.59%	25.25%	25.57%	25.25%	25.25%	23.61%	23.28%	23.28%	23.28%	23.61%	23.93%	24.59%
8	27.21%	24.92%	25.57%	26.23%	25.25%	25.57%	24.59%	22.95%	23.61%	22.95%	24.59%	24.59%	24.92%
9	26.56%	24.92%	24.92%	24.92%	24.59%	25.25%	23.61%	22.62%	23.61%	23.93%	24.59%	24.26%	26.56%
10	26.56%	25.57%	25.25%	26.23%	25.25%	26.23%	23.28%	22.62%	23.93%	23.28%	24.26%	23.93%	26.23%
Average	26.8%	24.9%	24.8%	25.6%	25.1%	24.8%	23.8%	22.7%	23.4%	23.1%	24.3%	23.3%	25.1%
Std. Dev	0.2%	0.4%	0.8%	0.6%	0.5%	1.9%	0.4%	0.8%	0.8%	0.5%	0.4%	1.0%	0.9%
CV	0.85%	1.62%	3.31%	2.32%	2.07%	7.50%	1.74%	3.46%	3.37%	2.13%	1.73%	4.25%	3.76%

Table E2-B Fill Crimp %

Specimen#	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	4.92%	4.92%	3.93%	4.92%	6.23%	6.56%	2.62%	3.28%	1.64%	3.28%	2.95%	2.30%	4.92%
2	6.23%	5.25%	4.26%	5.25%	5.90%	7.21%	2.62%	3.28%	1.64%	3.28%	3.28%	2.62%	4.92%
3	7.21%	5.57%	5.57%	4.92%	6.56%	4.92%	6.23%	6.23%	5.57%	5.25%	6.23%	5.57%	5.57%
4	5.57%	5.57%	6.23%	5.25%	6.56%	5.25%	4.92%	5.90%	5.25%	5.25%	6.23%	5.90%	5.25%
5	5.25%	5.90%	5.90%	6.23%	6.23%	4.92%	5.25%	6.23%	5.57%	5.57%	6.56%	5.57%	5.25%
6	5.25%	5.90%	6.56%	6.56%	7.21%	5.25%	5.90%	5.90%	5.25%	6.56%	8.20%	5.57%	5.25%
7	5.25%	5.57%	6.23%	6.56%	6.56%	5.25%	5.25%	6.23%	4.92%	5.90%	6.56%	6.23%	5.57%
8	4.92%	5.57%	5.57%	5.90%	6.89%	4.92%	4.92%	5.90%	5.90%	5.57%	5.90%	5.25%	5.57%
9	4.92%	5.25%	5.90%	6.23%	6.89%	5.25%	5.25%	5.57%	5.25%	6.23%	5.57%	5.90%	5.57%
10	4.92%	5.57%	6.23%	6.56%	6.23%	4.92%	5.25%	5.57%	5.90%	5.57%	5.90%	5.57%	6.56%
Average	5.4%	5.5%	5.6%	5.8%	6.5%	5.4%	4.8%	5.4%	4.7%	5.2%	5.7%	5.0%	5.4%
Std. Dev	0.7%	0.3%	0.9%	0.7%	0.4%	0.8%	1.2%	1.1%	1.6%	1.1%	1.6%	1.4%	0.5%
CV	13.64%	5.43%	15.49%	11.77%	6.02%	14.50%	25.49%	21.23%	34.88%	21.23%	27.12%	27.57%	8.60%

Notes:

% Crimp was determined using ASTM D 3883 Standard Test Methods for Yarn Crimp and Take-up in woven Fabrics, Option A By Hand. Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E3 Thickness (mm)

Specimen#	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	0.64	0.74	0.82	0.78	0.84	0.76	0.86	0.98	0.88	0.88	0.86	0.86	0.96
2	0.60	0.74	0.90	0.82	0.88	0.64	0.90	0.98	0.88	0.88	0.90	0.94	0.92
3	0.60	0.72	0.80	0.82	0.80	0.70	0.86	0.90	0.84	0.88	0.90	0.96	0.86
4	0.60	0.74	0.90	0.86	0.92	0.72	0.86	0.88	0.86	0.96	0.86	0.84	0.86
5	0.60	0.74	0.90	0.80	0.86	0.66	0.82	0.92	0.82	0.94	1.08	0.86	0.88
6	0.62	0.74	0.84	0.84	0.88	0.74	0.78	0.96	0.82	0.82	0.96	0.94	0.98
7	0.60	0.74	0.88	0.78	0.82	0.66	0.80	1.00	0.88	0.90	1.06	0.92	0.88
8	0.62	0.74	0.86	0.78	0.92	0.70	0.82	0.92	0.84	0.94	0.90	0.94	0.94
9	0.64	0.76	0.90	0.82	0.86	0.70	0.88	0.96	0.88	0.90	0.92	0.84	0.86
10	0.68	0.74	0.82	0.84	0.86	0.72	0.84	0.96	0.82	0.98	1.08	0.94	0.88
Average	0.62	0.74	0.86	0.81	0.86	0.70	0.84	0.95	0.85	0.91	0.95	0.90	0.90
Std. Dev	0.03	0.01	0.04	0.03	0.04	0.04	0.04	0.04	0.03	0.05	0.09	0.05	0.04
CV	4.30%	1.27%	4.57%	3.48%	4.47%	5.39%	4.40%	4.12%	3.17%	5.21%	9.30%	5.30%	4.95%

Notes:
Thickness was determined in accordance with ASTM D 1777 Standard Test Method for Thickness of Textile Material, Testing Option 1. The AMES Gage Logic/Basic 99-0697 was used to conduct this test. SN#043292941, resolution 0.0001", range 1". Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E4 Weight (g/m^2)

Specimen #	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	227.380	235.792	225.277	229.112	230.720	254.225	255.709	257.318	258.802	260.163	265.235	251.751	249.771
2	233.813	225.648	231.833	233.442	230.967	255.462	265.977	259.421	256.575	260.905	259.916	257.318	247.297
3	229.730	224.658	230.473	232.699	232.204	259.544	263.008	252.864	256.081	264.245	256.575	255.586	244.947
4	227.380	229.359	229.483	231.338	232.452	251.503	260.410	258.060	262.514	256.575	256.699	257.070	244.328
5	230.844	230.473	231.710	232.699	229.112	262.637	260.534	258.184	263.627	256.081	249.648	254.967	242.472
6	225.153	232.823	226.885	227.503	231.710	255.215	266.472	259.792	256.328	255.957	257.070	262.761	246.802
7	228.122	229.112	231.710	233.936	230.720	251.503	265.111	260.410	259.792	261.029	254.720	260.410	249.400
8	232.576	231.462	228.493	229.607	234.308	257.194	262.761	257.936	259.297	259.297	250.266	258.431	249.277
9	230.967	228.988	226.390	228.246	234.308	261.153	262.266	259.544	265.235	256.699	253.978	262.514	250.637
10	228.493	228.369	227.380	230.967	227.627	261.895	268.328	260.905	264.245	258.555	251.503	264.864	247.297
Average	229.446	229.668	228.963	230.955	231.413	257.033	263.058	258.443	260.250	258.951	255.561	258.567	247.223
Std. Dev	2.642	3.251	2.430	2.255	2.091	4.125	3.656	2.280	3.445	2.705	4.712	4.060	2.655
CV	1.15%	1.42%	1.06%	0.98%	0.90%	1.60%	1.39%	0.88%	1.32%	1.04%	1.84%	1.57%	1.07%

Notes:
Weight was determined in accordance with ASTM D 3776 Standard Test Method for Mass per Unit Area, Testing Option D

The Mettler Scale PM 480 DeltaRange, Type: PM-480, Serial#L57461 was used to conduct this test.

Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E5 Stiffness (ujoule/cm^2)

specimen	direction	location	1	2	3	4	5
1	fill	LB	0.607	1.020	0.677	1.179	1.471
1	fill	LF	0.755	0.755	0.478	0.800	0.802
1	fill	RB	0.755	0.881	0.478	0.760	1.236
1	fill	RF	0.972	0.838	0.640	0.978	0.761
1	warp	LB	0.302	0.716	0.640	0.349	0.375
1	warp	LF	0.642	0.607	0.605	0.577	0.647
1	warp	RB	0.242	0.642	0.640	0.454	0.761
1	warp	RF	0.925	0.716	0.677	0.886	0.665
2	fill	LB	0.678	1.020	0.753	1.206	1.350
2	fill	LF	1.226	0.679	0.572	0.931	0.761
2	fill	RB	0.642	1.340	0.508	1.407	1.292
2	fill	RF	0.881	0.972	0.346	0.843	0.802
2	warp	LB	0.224	0.607	1.169	0.646	0.545
2	warp	LF	0.678	0.796	0.714	0.683	0.427
2	warp	RB	0.451	0.642	1.223	0.283	0.761
2	warp	RF	0.925	0.796	0.714	0.931	0.375
3	fill	LB	0.925	1.020	1.395	0.978	1.471
3	fill	LF	1.019	0.972	0.640	1.026	0.722
3	fill	RB	0.837	1.399	1.169	0.908	1.236
3	fill	RF	1.172	0.838	0.753	0.720	0.844
3	warp	LB	0.324	0.607	0.605	0.544	0.761
3	warp	LF	0.795	0.881	0.677	0.544	0.722
3	warp	RB	0.347	0.642	0.539	0.483	0.844
3	warp	RF	0.716	0.838	0.677	0.683	0.578
4	fill	LB	1.069	0.926	1.223	1.348	1.236
4	fill	LF	1.226	0.972	0.714	1.026	0.722
4	fill	RB	0.881	0.881	1.518	1.348	1.292
4	fill	RF	1.120	0.838	0.753	1.234	0.612
4	warp	LB	0.224	0.642	0.605	0.611	0.665
4	warp	LF	0.451	0.755	0.794	0.720	0.802
4	warp	RB	0.261	0.796	0.605	0.426	0.684
4	warp	RF	0.755	0.755	0.677	0.760	0.761
		Average	0.720	0.837	0.756	0.821	0.843
		Std. Dev	0.307	0.191	0.279	0.300	0.309
		%CV	0.427	0.228	0.369	0.365	0.366

Table E5 Stiffness (ujoule/m^2), continued

specimen	direction	location	1E	2E	3E	4E	5E	2ER	5ER	5M
1	fill	LB	1.197	1.535	2.350	1.156	0.994	1.135	2.396	1.030
1	fill	LF	1.634	1.343	1.148	1.454	0.897	1.190	1.444	1.106
1	fill	RB	0.845	1.405	1.786	1.329	1.940	1.993	2.579	1.510
1	fill	RF	1.600	1.405	1.575	1.950	1.293	1.365	1.509	0.781
1	warp	LB	1.169	0.821	0.723	0.368	0.945	0.932	0.477	0.957
1	warp	LF	0.986	1.114	0.992	1.519	0.921	0.797	1.148	0.866
1	warp	RB	0.938	0.777	0.683	0.511	0.685	0.841	1.095	1.158
1	warp	RF	1.197	1.061	0.896	1.156	1.044	1.305	1.095	0.911
2	fill	LB	1.254	1.603	2.531	1.873	1.717	2.503	2.532	1.213
2	fill	LF	1.197	1.254	1.094	1.586	0.969	0.886	2.016	0.741
2	fill	RB	0.845	1.405	2.178	1.798	2.141	2.691	2.441	1.641
2	fill	RF	1.566	1.469	1.094	1.329	1.096	0.841	1.509	0.957
2	warp	LB	0.802	1.009	0.850	0.578	1.096	1.135	0.684	0.911
2	warp	LF	1.254	1.114	0.645	0.561	0.921	1.190	1.381	0.957
2	warp	RB	0.938	0.865	0.574	0.511	0.724	0.981	1.148	0.781
2	warp	RF	0.802	1.061	0.943	0.856	1.096	1.247	1.320	1.005
3	fill	LB	0.680	1.603	1.575	1.212	2.355	1.915	1.861	1.158
3	fill	LF	1.776	1.343	1.575	1.725	1.578	1.247	1.861	0.911
3	fill	RB	0.537	1.405	1.937	1.049	2.268	2.154	2.180	1.510
3	fill	RF	1.142	1.405	1.320	1.798	1.578	1.190	1.575	0.911
3	warp	LB	0.986	1.009	0.992	0.296	0.685	0.715	1.204	0.781
3	warp	LF	1.142	0.912	0.850	1.270	0.897	1.030	1.095	0.957
3	warp	RB	0.719	1.061	0.683	0.728	0.994	0.886	1.148	0.781
3	warp	RF	1.088	0.912	0.896	0.856	0.852	1.082	1.204	1.269
4	fill	LB	1.142	1.343	2.263	1.519	2.183	1.993	2.264	0.628
4	fill	LF	0.938	2.051	1.261	1.725	1.646	1.082	1.714	0.741
4	fill	RB	1.142	1.405	1.860	1.212	1.940	2.324	2.532	1.447
4	fill	RF	1.254	1.535	1.203	1.725	1.446	0.841	1.204	0.781
4	warp	LB	1.197	0.865	0.764	0.511	1.019	0.981	1.042	1.005
4	warp	LF	1.634	1.061	0.896	0.879	0.575	1.247	1.204	0.911
4	warp	RB	0.845	0.821	0.896	0.544	0.724	0.797	0.828	0.866
4	warp	RF	1.600	0.960	1.042	0.856	0.969	0.932	1.204	1.005
		Average	1.126	1.217	1.252	1.139	1.256	1.295	1.528	1.006
		Std. Dev	0.309	0.297	0.548	0.500	0.518	0.541	0.577	0.248
		%CV	0.274	0.244	0.438	0.439	0.413	0.418	0.377	0.246

Test Notes:
Stiffness was determined in accordance with ASTM D 1388 Standard Test Method for Stiffness of Fabrics, Option A Cantilever Test. An IDM Industries motorized Cantilever Test Apparatus was used to conduct this test. Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E6 -A Warp Breaking Force (Newtons)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	1149	1171	1176	1170	1095	1140	1102	1139	1160	1092	1132	1143	1082
2	warp	1149	1161	1115	1130	1116	1144	1170	1091	1132	1098	1133	1083	1080
3	warp	1177	1162	1144	1138	1106	1134	1160	1125	1116	1139	1188	1169	1076
4	warp	1226	1118	1128	1119	1151	1136	1136	1096	1114	1177	1173	1136	1106
5	warp	1155	1172	1146	1135	1132	1158	1181	1165	1102	1092	1182	1142	1119
	Average	1171	1157	1142	1138	1120	1142	1150	1123	1125	1120	1162	1134	1092
	Std Dev	32.91	22.38	23.11	19.09	22.11	9.66	31.59	30.52	22.39	37.75	27.04	31.52	19.01
	%CV	2.81%	1.93%	2.02%	1.68%	1.97%	0.85%	2.75%	2.72%	1.99%	3.37%	2.33%	2.78%	1.74%

Table E6 -B Filling Breaking Force (Newtons)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	605	622	634	629	623	645	660	612	696	624	601	645	664
2	warp	626	659	669	603	616	632	658	617	647	637	630	588	635
3	warp	624	625	669	618	636	633	680	618	639	634	605	572	671
4	warp	630	668	657	616	611	609	691	603	661	622	607	615	669
5	warp	672	639	595	644	632	632		592	651	601	676	605	672
	Average	631	643	645	622	623	630	672	608	659	624	624	605	662
	Std Dev	24.64	20.27	31.07	15.17	10.49	13.05	15.90	10.91	22.17	14.22	31.46	27.93	15.42
	%CV	3.90%	3.15%	4.82%	2.44%	1.68%	2.07%	2.37%	1.79%	3.37%	2.28%	5.05%	4.62%	2.33%

Notes:
Breaking Strength was determined in accordance with ASTM D 5034, Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Method) The Q-Test (type E tensile tester) with a 1000 lb load cell was used. The specimen was type G. 1"x3" back jaws and 1"x1" face were used lined with rubber to reduce slippage, jaw pressure was 1600 psi, gage length was 3", test speed was 12"/min Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E7-A Warp Elongation at Break (%)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	59.5	58.1	57.5	57.5	56.1	56.8	52.1	54.1	55.5	48.8	54.1	54.8	51.5
2	warp	58.1	57.5	55.5	56.8	56.1	53.5	54.1	52.1	54.1	49.5	54.1	51.5	50.1
3	warp	59.5	60.1	56.8	56.1	56.1	54.1	56.1	54.1	53.5	54.1	55.5	56.1	50.8
4	warp	63.5	55.5	54.8	56.8	57.5	54.1	54.1	52.8	52.8	55.5	54.8	53.5	52.8
5	warp	59.5	60.1	57.5	56.8	57.5	55.5	56.8	54.1	51.5	52.1	56.1	54.1	52.1
	Average	60	58	56	57	57	55	55	53	53	52	55	54	51
	Std Dev	2.04	1.94	1.22	0.49	0.77	1.34	1.86	0.94	1.49	2.88	0.88	1.70	1.06
	%CV	3.39%	3.32%	2.16%	0.87%	1.35%	2.44%	3.40%	1.75%	2.78%	5.54%	1.60%	3.15%	2.06%

Table E7-B Filling Elongation at Break (%)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	24.1	26.8	27.5	26.1	26.8	25.5	27.5	27.5	27.5	26.1	26.1	26.8	27.5
2	warp	24.8	28.1	29.5	24.8	27.5	24.1	25.5	26.1	26.1	25.5	28.1	26.1	26.1
3	warp	24.8	24.8	28.1	27.5	27.5	26.8	28.1	26.8	24.1	23.5	24.8	24.1	28.1
4	warp	24.1	26.1	28.8	24.8	26.8	23.5	25.5	24.8	26.8	24.1	26.1	27.5	28.1
5	warp	28.8	28.1	25.5	26.1	26.1	24.1	26.8	25.5	24.8	24.1	27.5		26.8
	Average	25	27	28	26	27	25	27	26	26	25	27	26	27
	Std Dev	1.98	1.40	1.53	1.12	0.59	1.34	1.17	1.06	1.40	1.09	1.30	1.47	0.87
	%CV	7.81%	5.24%	5.48%	4.35%	2.17%	5.39%	4.39%	4.05%	5.42%	4.42%	4.90%	5.61%	3.17%

Notes:

Breaking Strength was determined in accordance with ASTM D 5034, Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Method) The Q-Test (type E tensile tester) with a 1000 lb load cell was used. The specimen was type G. 1"x3" back jaws and 1"x1" face were used lined with rubber to reduce slippage, jaw pressure was 1600 psi, gage length was 3", test speed was 12"/min Samples were conditioned in accordance with the requirements in ASTM D

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Table E8-A Tear Strength (filling torn./warp direction)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	4480	5568	6016	6336	6400	4480	5056	5632	5440	6048	5568	5504	6144
2	warp	4416	5888	6400	5952	6400	4288	5440	6016	5824	5888	4800	5792	5760
3	warp	4672	4672	6208	5376	6400	4416	5440	5952	5632	5760	5248	5376	5248
4	warp	5184	5184	6400	5312	6336	4672	5568	6400	5120	6400	5504	5568	5888
5	warp	5440	5440	6336	5760	6400	4864	4928	5888	5216	4480	5312	4864	5760
	Average	4838	5350	6272	5747	6387	4544	5286	5978	5446	5715	5286	5421	5760
	Std Dev	452	456	163	423	29	226	277	277	290	731	302	346	326
	%CV	9.33%	8.53%	2.60%	7.36%	0.45%	4.98%	5.25%	4.64%	5.33%	12.79%	5.72%	6.38%	5.67%

Table E8-B Tear Strength (warp torn./filling direction)

Specimen #	Direction	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	warp	3072	3520	4672	3840	4928	2688	3520	4096	4032	4480	2944	4032	6144
2	warp	2816	3776	4992	3648	4992	2560	3520	3904	4096	3680	2816	3136	5376
3	warp	3328	3648	4352	4160	5184	2496	3968	3840	4000	4128	3008	5056	5312
4	warp	2752	3392	5248	4032	5248	2624	3520	3904	3712	3456	2944	3072	5312
5	warp	3456	3136	4352	3968	4480	2752	4480	3968	3520	3328	2816	3520	5248
	Average	3085	3494	4723	3930	4966	2624	3802	3942	3872	3814	2906	3763	5478
	Std Dev	308	246	396	195	302	101	426	97	246	481	86	818	375
	%CV	9.99%	7.05%	8.37%	4.97%	6.09%	3.86%	11.21%	2.46%	6.35%	12.60%	2.96%	21.73%	6.84%

Notes:
Tear Strength was determined in accordance with ASTM D 1424 Standard Test Method for Tearing
Strength of Fabrics by Falling-Pendulum (Elmendorf) Type Apparatus. The Elmendorf with Cutter was used to conduct this test. Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice
for Conditioning and Testing Textiles

Table E9-A Air Permeability (face-up)

	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	2.733	4.770	6.528	4.816	6.299	3.251	5.659	7.864	5.822	8.291	5.740	8.413	8.595
2	2.621	4.831	7.264	5.126	7.051	3.099	5.822	8.595	6.528	7.864	5.903	8.413	8.352
3	2.697	5.019	6.452	4.608	7.051	3.221	5.740	8.595	5.497	8.413	5.984	8.108	8.230
4	2.332	5.024	6.980	4.714	6.680	3.399	5.415	7.803	4.917	7.864	5.659	7.681	8.656
5	2.357	4.917	6.853	4.714	6.528	3.129	5.740	8.413	5.659	8.169	6.375	7.986	8.473
6	2.474	4.608	6.680	4.816	6.680	3.068	5.822	8.534	5.822	8.047	6.452	8.473	7.620
7	2.398	4.917	7.407	4.816	6.980	2.972	5.334	7.864	5.659	7.620	6.604	8.890	7.549
8	2.586	4.917	6.980	4.714	6.375	3.129	5.659	7.986	5.578	7.478	6.066	8.291	8.534
9	2.697	5.024	7.407	4.816	6.909	3.038	5.659	8.352	5.578	8.230	5.984	7.620	8.534
10	2.474	4.608	7.264	4.714	6.680	3.068	5.334	7.336	5.822	8.230	5.984	8.473	8.230
11	2.398	4.608	6.528	4.714	6.147	3.038	4.816	7.620	5.415	7.478	5.984	8.108	7.925
Average	2.524	4.840	6.940	4.779	6.671	3.128	5.546	8.087	5.663	7.971	6.067	8.223	8.245
Std. Dev	0.148	0.169	0.361	0.133	0.310	0.121	0.301	0.432	0.385	0.333	0.293	0.372	0.387
CV	5.86%	3.49%	5.20%	2.78%	4.65%	3.86%	5.43%	5.34%	6.80%	4.18%	4.83%	4.53%	4.70%

Table E9-B Air Permeability (face-down)

	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
1	2.662	4.917	6.756	4.714	7.193	2.870	5.126	7.336	5.740	7.620	5.334	7.478	6.833
2	2.586	4.714	7.051	4.917	7.122	2.972	5.126	7.122	5.822	7.407	5.497	7.264	7.122
3	2.697	4.917	6.980	4.714	6.833	3.038	5.126	7.803	5.334	7.864	5.334	7.549	7.620
4	2.662	4.298	6.066	5.024	6.756	3.251	5.578	8.169	5.334	7.193	5.334	7.193	7.407
5			6.299			3.038	4.917	7.122	5.334	7.549	5.232	7.478	7.681
Average	2.652	4.712	6.630	4.843	6.976	3.034	5.175	7.510	5.513	7.527	5.346	7.392	7.333
Std. Dev	0.047	0.292	0.431	0.154	0.214	0.140	0.243	0.461	0.247	0.249	0.095	0.154	0.355
CV	1.78%	6.20%	6.50%	3.19%	3.07%	4.60%	4.69%	6.14%	4.47%	3.31%	1.77%	2.09%	4.84%

Notes

Air Permeability was determined in accordance with ASTM D 737 Standard Test Method for air Permeability of Textile Fabrics. The Frazier High Differential Pressure Air Permeability Tester (SN#5179) was used to conduct this test. Samples were conditioned in accordance with the requirements in ASTM D 1776. Practice for Conditioning and Testing Textiles. A 69.85 mm (2.75") diameter test head was used, with 2 & 3 mm orifices as needed to maintain readings between 3 and 13 on the vertical manometer Readings were taken at 0.5" water pressure

Table E10-A Thermal Resistance (face-up)

Group ID	Time (min)	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
A	3	0.445	0.458	0.457	0.446	0.463	0.460	0.457	0.459	0.461	0.468	0.451	0.467	0.495
A	6	0.460	0.465	0.482	0.463	0.491	0.470	0.470	0.473	0.469	0.480	0.514	0.490	0.523
A	9	0.471	0.484	0.476	0.463	0.496	0.475	0.476	0.480	0.476	0.485	0.503	0.497	0.525
A	12	0.473	0.478	0.496	0.465	0.498	0.470	0.470	0.485	0.474	0.488	0.515	0.497	0.525
A	15	0.473	0.478	0.494	0.471	0.500	0.475	0.482	0.479	0.482	0.490	0.515	0.500	0.520
B	3	0.435	0.451	0.453	0.465	0.454	0.449	0.437	0.419	0.432	0.465	0.439	0.465	0.457
B	6	0.448	0.470	0.482	0.482	0.484	0.471	0.458	0.444	0.455	0.469	0.460	0.479	0.484
B	9	0.456	0.473	0.487	0.487	0.492	0.476	0.468	0.446	0.461	0.467	0.465	0.491	0.491
B	12	0.457	0.477	0.488	0.492	0.492	0.473	0.473	0.454	0.466	0.474	0.467	0.492	0.496
B	15	0.454	0.477	0.487	0.499	0.492	0.473	0.470	0.455	0.476	0.479	0.471	0.488	0.495
C	3	0.452	0.470	0.439	0.442	0.459	0.445	0.440	0.457	0.443	0.460	0.442	0.452	0.466
C	6	0.464	0.491	0.461	0.465	0.474	0.461	0.465	0.457	0.458	0.482	0.449	0.467	0.504
C	9	0.465	0.499	0.471	0.472	0.479	0.471	0.469	0.477	0.464	0.488	0.456	0.478	0.512
C	12	0.465	0.499	0.470	0.474	0.481	0.466	0.473	0.479	0.466	0.496	0.460	0.483	0.512
C	15	0.469	0.500	0.471	0.471	0.485	0.471	0.475	0.479	0.470	0.498	0.463	0.489	0.513
	Average	0.459	0.478	0.474	0.470	0.483	0.467	0.466	0.463	0.464	0.479	0.471	0.482	0.501
	Std. Dev	0.011	0.015	0.016	0.015	0.014	0.009	0.013	0.018	0.013	0.012	0.027	0.014	0.021
	CV	2.41%	3.08%	3.43%	3.27%	2.99%	2.02%	2.73%	3.94%	2.81%	2.45%	5.69%	2.91%	4.14%

Table E10-B Thermal Resistance, face-down (clo)

Group ID	Time (min)	1	2	3	4	5	1E	2E	3E	4E	5E	2ER	5ER	5M
A	3	0.426	0.458	0.439	0.424	0.436	0.428	0.434	0.438	0.434	0.426	0.436	0.426	0.443
A	6	0.442	0.480	0.471	0.441	0.458	0.447	0.454	0.468	0.455	0.463	0.465	0.453	0.468
A	9	0.443	0.485	0.473	0.450	0.466	0.447	0.467	0.474	0.456	0.467	0.472	0.456	0.475
A	12	0.449	0.479	0.473	0.445	0.464	0.454	0.472	0.471	0.460	0.470	0.469	0.460	0.476
A	15	0.450	0.482	0.480	0.447	0.466	0.452	0.473	0.473	0.460	0.470	0.466	0.463	0.475
B	3	0.434	0.422	0.446	0.432	0.440	0.430	0.428	0.436	0.442	0.431	0.435	0.433	0.451
B	6	0.451	0.457	0.474	0.455	0.463	0.460	0.450	0.465	0.458	0.452	0.460	0.455	0.480
B	9	0.453	0.470	0.476	0.466	0.468	0.453	0.462	0.476	0.463	0.458	0.469	0.464	0.482
B	12	0.457	0.467	0.479	0.468	0.473	0.452	0.463	0.476	0.465	0.463	0.472	0.465	0.485
B	15	0.460	0.466	0.479	0.464	0.476	0.453	0.468	0.478	0.467	0.461	0.469	0.469	0.485
C	3	0.440	0.452	0.439	0.429	0.431	0.427	0.438	0.431	0.420	0.452	0.428	0.434	0.429
C	6	0.459	0.473	0.463	0.452	0.457	0.451	0.461	0.465	0.438	0.473	0.450	0.457	0.475
C	9	0.468	0.479	0.465	0.455	0.474	0.459	0.466	0.466	0.449	0.472	0.463	0.465	0.479
C	12	0.468	0.485	0.469	0.452	0.469	0.461	0.465	0.471	0.452	0.476	0.457	0.468	0.480
C	15	0.468	0.479	0.472	0.459	0.466	0.463	0.468	0.474	0.456	0.472	0.460	0.479	0.485
	Average	0.451	0.469	0.467	0.449	0.460	0.449	0.458	0.464	0.452	0.460	0.458	0.456	0.471
	Std. Dev	0.013	0.017	0.014	0.013	0.014	0.012	0.014	0.016	0.013	0.015	0.014	0.015	0.017
	CV	2.80%	3.55%	2.99%	2.95%	3.03%	2.62%	3.10%	3.37%	2.88%	3.24%	3.13%	3.24%	3.57%

Notes:
Thermal Transmittance was tested using a modified version of ASTM D 1518 Standard Test Method for Thermal Transmittance of Textile Materials
Modifications: 5" test specimen, 15 min test length. Samples were conditioned in accordance with the requirements in ASTM D 1776 Practice for Conditioning and Testing Textiles

Table E11A Abrasion Resistance to Martindale, Sample 1

FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11B Abrasion Resistance to Martindale, Sample 2

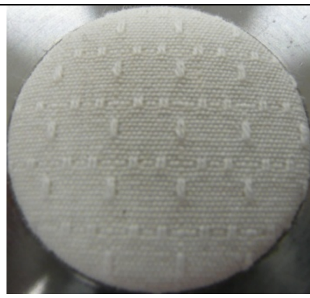
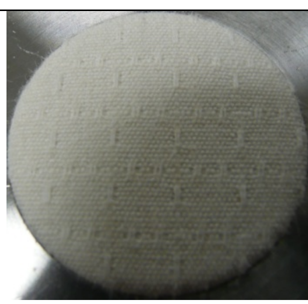
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11C Abrasion Resistance to Martindale, Sample 3

FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11D Abrasion Resistance to Martindale, Sample 4

FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11E Abrasion Resistance to Martindale, Sample 5

FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11F Abrasion Resistance to Martindale, Sample 1E

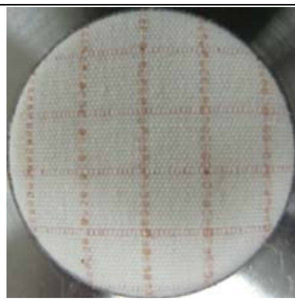
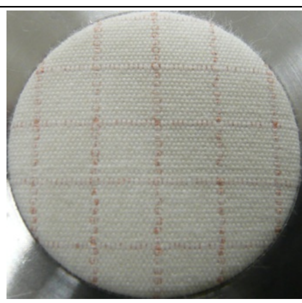
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11G Abrasion Resistance to Martindale, Sample 2E

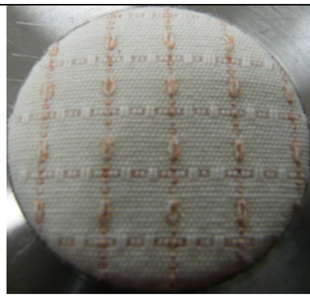
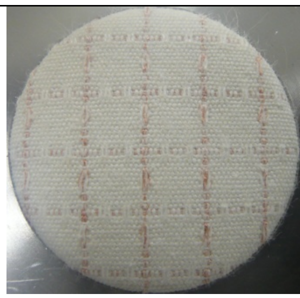
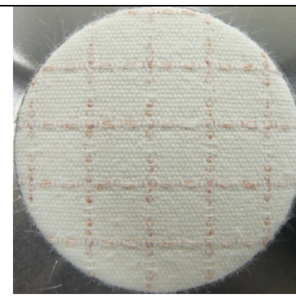
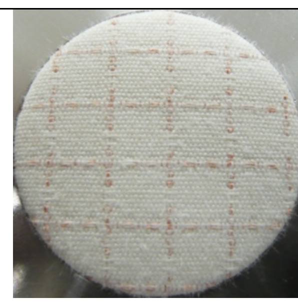
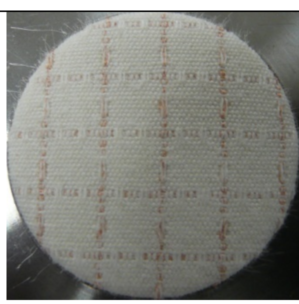
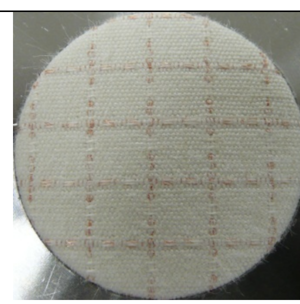
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11H Abrasion Resistance to Martindale, Sample 3E

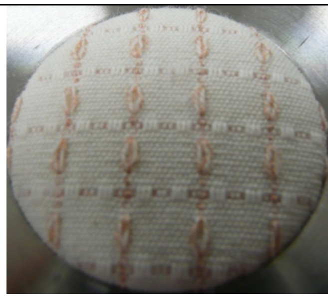
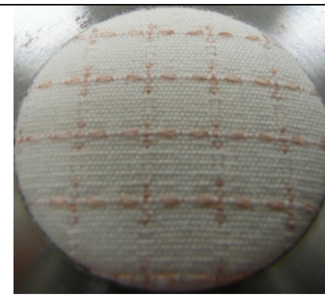
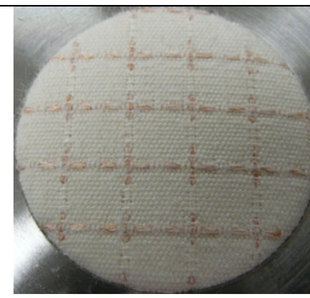
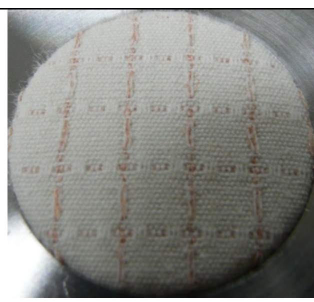
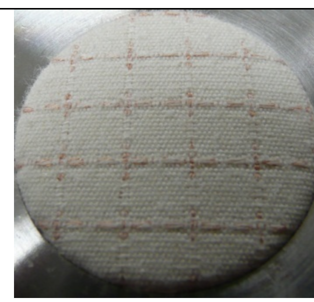
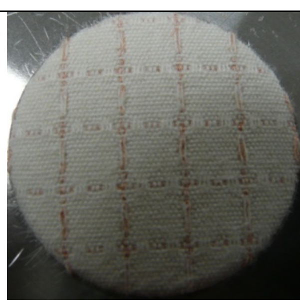
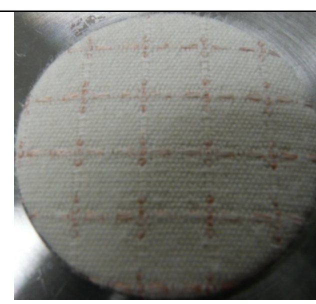
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11I Abrasion Resistance to Martindale, Sample 4E

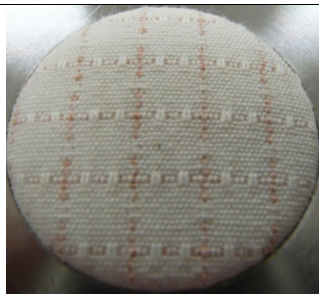
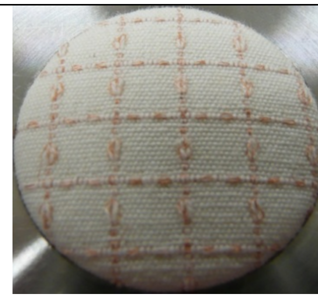
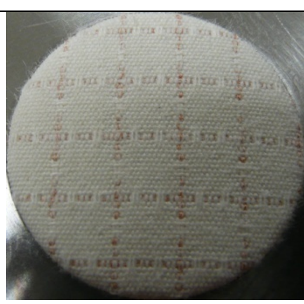
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11J Abrasion Resistance to Martindale, Sample 5E

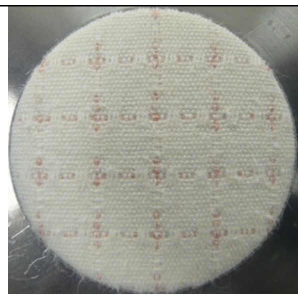
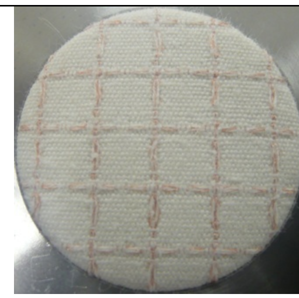
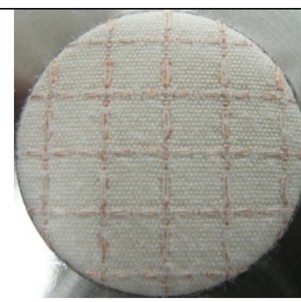
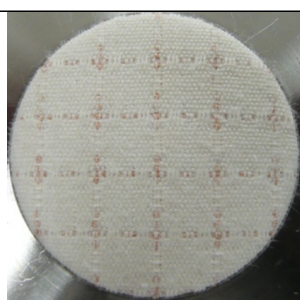
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11K Abrasion Resistance to Martindale, Sample 2ER

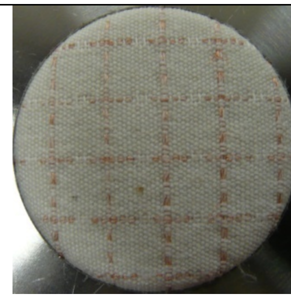
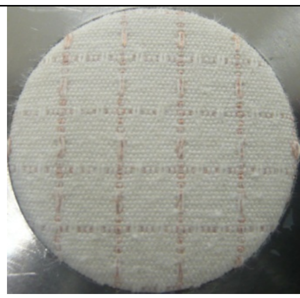
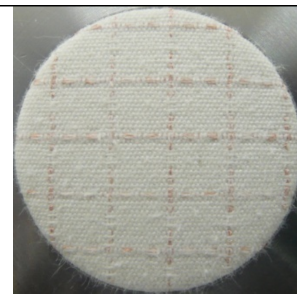
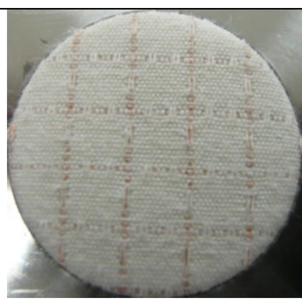
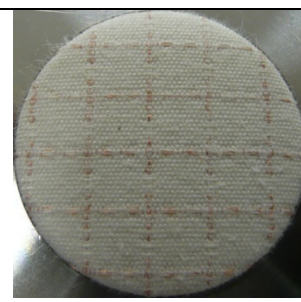
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11L Abrasion Resistance to Martindale, Sample 5ER

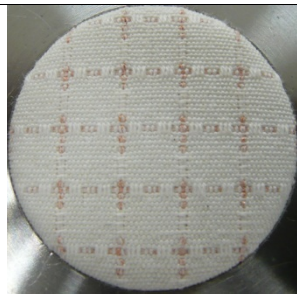
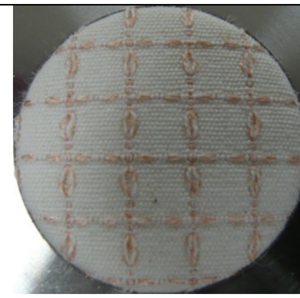
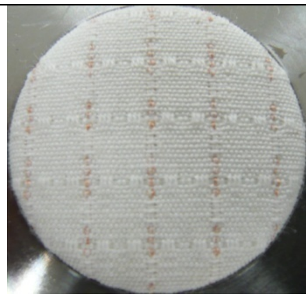
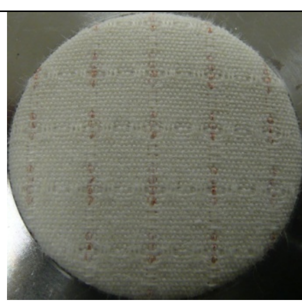
FACE		BACK
	Original	
	10K	
	20K	
	30K	

Table E11N Abrasion Resistance to Martindale, Sample 5M

FACE		BACK
	Original	
	10K	
	20K	
	30K