EFFECT OF TRAPPED AIR ON HEAT AND MOISTURE RESISTANCE OF MULTI-LAYERED SOFT BODY ARMORS

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CHAPTER I

INTRODUCTION

Thermal comfort is one of the major concerns in the use of protective clothing. Protective garments can offer protection to individuals exposed to extreme environmental conditions, such as temperatures below zero (e.g. space suit, arctic clothing) or very high temperatures (e.g. firefighters ensemble). Besides protection from environmental conditions, protective clothing applications can be found in many fields, especially when occupational hazardous conditions increase the risk of accidents or jeopardize human lives (e.g. chemical protection suits).

One form of protective garment is described as impact protective. This category of protective clothing includes bullet resistant garments or body armor (BA). This type of clothing is used by military personnel and law enforcement officers all over the world. The basic property of these garments, as their name indicates, is to protect the wearer from bullets or projectiles penetrating into the body. The idea for this type of clothing is actually very old. Historical documents of almost all early world civilizations reveal that protective clothing or equipment was used to protect soldiers from injuries. Today, a variety of garments exist offering the modern military and civilian sectors options to choose appropriate body armor based on areas of the body to be protected (e.g. vest, full body armor) and threat level of protection preferred.

One way to categorize modern body armors is based on the type of ballistic material used for construction. The two categories for this classification are hard body armors and soft body armors. Hard body armor typically uses rigid plates as ballistic material (plastic, ceramic or metal plates) while soft body armors use ballistic textile materials such as Kevlar®, Dyneema®, Spectra® and Twaron® (Chen & Chaudhry, 2005). This study focuses on soft body armors.

Soft armor uses multi-layering of the textile material in order to provide the desirable level of threat protection. Multi-layering can significantly increase the garment's thickness. Thickness is positively correlated with thermal insulation (Huck & McCullough, 1985). For that reason the heat resistance of the multi-layer garment is expected to be high. These types of garments are also susceptible to forming air gaps between the layers. Trapped air in a garment increases the thermal insulation (Huck & McCullough, 1985), and decreases the ability to transfer heat from the microenvironment (body – garment) to the external environment.

Ventilation and air permeability also contribute to clothing insulation (Ueda, Inoue, Matsudaira, Araki & Havenith, 2006). Ventilation is established by garment fit and design, while air permeability is a fabric characteristic (Ueda et al., 2006). BA and especially full BA may cover much of the body's surface. This high percent of body surface coverage is an impediment to allowing ventilation to occur between the garment and the skin. Due to the typical high number of layers of soft BA, the air permeability is expected to be very low. By improving a textile's air permeability characteristics, the ventilation of the garment can be improved. However, in ballistic materials air permeability is difficult to alter.

This project proposed to examine two potential methods of improving the thermal and moisture transfer properties of soft ballistic material, namely, using 3D spacer material to increase ventilation and vacuum sealing the ballistic material for removing air trapped between the layers. Results of current research at the Institute for Protective Apparel Research and Technology suggested the potential advantage of inclusion of 3D spacer materials for reducing R_{et} of assembled multi-layered packs of several types of ballistic material using a sweating guarded hot plate. This study advanced this work. Nothing in the literature was found where vacuum sealing has been used with ballistic material to remove enclosed air. This study initiated this approach. Multi-layers of ballistic material are typically enclosed in Ripstop nylon, which could also be a factor in thermal and moisture resistance.

This study had two phases. Phase I investigated and established the optimum level of vacuum sealing. Phase II determined the impact of three independent variables on two dependent variables.

Purpose

In this study, the effect of inclusion of air gaps via 3D spacer material and the elimination of air gaps via vacuum sealing on dry and water-vapor resistance of two multi-layered soft ballistic materials were investigated. The dry and water-vapor resistance of two alternative fabrics to encase the ballistic packs was also investigated.

Objectives

Phase I

1. Establish the most preferred level of pressure during the vacuum sealing procedure to be used in Phase II based on the dry thermal and water-vapor resistance and results.
2. Choose the most promising ballistic material to be used in Phase II

Phase II

1. Identify the impact of vacuum sealing using the preferred pressure level established in Phase I on dry and water-vapor resistance.
2. Identify the effect of incorporating 3D spacer fabric on dry and water-vapor resistance.
3. Identify the difference between two cover materials on dry and water-vapor resistance.

Hypotheses

Phase I

$H1_0$: There is no significant effect on dry thermal resistance by vacuum sealing the ballistic materials at different levels of pressure.

$H2_0$: There is no significant effect on water-vapor resistance by vacuum sealing the ballistic materials at different levels of pressure.

Phase II

$H3_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material is vacuumed sealed or not.

$H4_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material incorporated 3D spacer material or not.

$H5_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material is enclosed in two different cover materials.

$H6_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material is vacuumed sealed or not.

$H7_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material incorporated 3D spacer material or not.

$H8_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material is enclosed in two different cover materials.

Limitations

1. Although there are several types of commercially available ballistic material, only two selected materials were tested. One was a woven fabric with aramid fibers, (Kevlar® KM2®) and currently used almost exclusively by the US military. The second was a two-layered non-woven fabric made from polyethylene fibers (Unidirectional Dyneema®).
2. Due to the high cost of the ballistic materials, fabric samples were used more than once to form different treatments.
3. Only one type of 3D spacer was selected for testing based on results from on-going research being conducted by researchers at the Institute for Protective Apparel Research and Technology (IPART).
4. Two types of cover material were selected to encase the treatments.
5. Although there are multiple types of bags currently used for the vacuum sealing process, only one type was selected for this study.

Definitions

Clothing comfort: “a state of satisfaction indicating physiological, social-psychological and physical balance among a person, his/her clothing and his/her environment.” (Branson & Sweeny, 1991, p.99).

Thermal comfort: “ the condition of mind which expressed satisfaction with the thermal environment” (Fanger, 1981, p.221).

Thermal Resistance: “Temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. The dry heat flux may consist of one or more conductive, convective and radiant components.” (ISO 11092, 1993).

Water-vapour resistance: “Water-vapour pressure difference between the two faces of a material divided by the resultant evaporative heat flux per unit area in the direction of the gradient. The evaporative heat flux may consist of both diffusive and convective components.” (ISO 11092, 1993).

CHAPTER II

REVIEW OF LITERATURE

A brief background of body armor history and production will be provided followed by an introduction of several key concepts in functional design including both comfort and thermoregulation. Finally a review of recent studies related to the research objectives will be presented.

History of Body Armor

The documented history of human kind is full of evidence that soldiers used artificial gear to protect themselves from injuries (Chen & Chaudhry, 2005). Early civilizations tried to protect their soldiers by manufacturing protective equipment or clothing from hard leather, wood and metal. The ancient Greek states and the Romans used similar protective equipment (Byam, 1988). Typical personal protective equipment, during this time, consisted of a metal helmet and shield; a vest made from leather or metal and metal plates on the legs. Roman legionnaires wore an advanced body armor called “lorica segmentata” (Byam, 1988, p. 13). This body armor was a vest that covered the torso and the shoulders with overlapping iron strips. Another type of compact protective clothing, used by Celts and knights was the “chain mail armor” (Byam, 1988 p. 24). This armor was manufactured from cross-linked steel or iron rings. The wearers felt discomfort while wearing this armor and it was also not sufficient against hits from heavy swords and axes.

In the Middle Ages, the knights replaced the chain mail armor with an armor made by metal plates (Chen & Chaudhry, 2005). During the 15th century gunpowder and firearms were introduced in the battlefields, disabling all previous personal defenses that soldiers had used. By the end of the 19th century, the first ballistic vest appeared (Chen & Chaudhry, 2005) made out of silk (soft armor). This silk vest could stop only projectiles with very low velocity.

As the weapon technology advanced over the years, the need for more advanced protective armor increased. Significant improvement in body armor was made during World War I. France, England, Germany and the USA produced a variety of body armors (Chen & Chaudhry, 2005). The majority of the designs used steel plates as the bullet proof material. However, the English developed a small number of soft body armors among their commercial designs. The textile materials that they used were linen, cotton and silk.

During World War II and the Korean War, advanced ballistic materials like ceramic plates and ballistic nylon were developed. The invention and utilization of these new fabrics increased the possibilities for BA and offered alternative options to manufacture BA that was lighter in weight as compared to previous steel armors. In 1965 a novel textile fabric, Kevlar® 16, was introduced by DuPont. The introduction of Kevlar® was ground breaking, since it was the first textile fabric with better ballistic resistant properties than steel.

Today, BA, as already has been discussed in the introduction, can be divided based on the constructed material into two major categories: hard body armors and soft body armors. Because of the focus for this study only soft body armor materials will be further discussed.

Ballistic Materials for Soft Body Armors

According to Chen and Chaudhry (2005) there is a variety of textile products that are either currently used, or fulfill the requirements to be used as bullet proof materials in BAs. Textiles such as Kevlar®, Twaron® and Technora® are manufactured with aramid fibers. Textiles made of polyethylene, such as Spectra® and Dyneema®, are also used for constructing BAs. Other ballistic fabrics use Zylon® (p-phenylene-2-6-benzobisoxazole) and nylon (polyamide). Chen and Chaudhry (2005) highlighted that the aramid fibers are the most commonly used in the production of soft body armors. They also indicate that in the near future a novel ballistic material is expected to be introduced. This new fabric will be manufactured from polypyridobisimidazole fibers.

Comfort

Apparel comfort as a term is complex and vague. It could be said that comfort is the state in which all the signs of discomfort are not present (Rossi, 2005). According to Rossi (2005) there are four kinds of comfort: sensorial comfort, fitting comfort, psychological comfort and thermal comfort. Defining these terms Rossi explains that sensorial comfort is how a person perceives objects that are in contact with the wearer, in our case the clothes (e.g. if they are soft). Fitting comfort includes how well a garment fits a wearer and also if the garment is light or heavy. Psychological comfort is related to the suitability between wearer, garment and the environmental context. In protective clothing, psychological comfort can significantly affect the wearer's psychology (e.g. if the person feels comfortable in the garment in the given settings). Finally, thermal comfort is achieved when the person or the subject expresses satisfaction about the thermal environmental conditions while wearing the garment.

History of Thermal Comfort

Since the 1920s, researchers from various disciplines such as textiles, engineering, physiology and biology, have been investigating the thermal comfort of a person (Branson, 1982). In general, research in the thermal comfort area has followed the needs of society for the last 90 years. During and immediately after World War II the majority of thermal comfort research was conducted with a primary focus on the military and industrial environments. However, during the past forty years, the interest areas have expanded noticeably to other settings, including industrial and office personnel, firefighters, aerospace and athletes.

Theories and Models in Clothing Comfort

Many researchers developed a number of theories and models in their desire to analyze and understand how humans perceive comfort. For the needs of this study only theories and models that are related to clothing comfort will be presented. Clothing comfort is defined as "a state of satisfaction indicating physiological, social psychological and physical balance among a person, his/her clothing, and his/her environment" (Branson & Sweeny, 1991, p.99).

Four theories related to the clothing comfort field are presented chronologically below: Fourt and Hollies' Comfort Triad (1970), Pontrelli's Comfort's Gestalt (1977), Sontag's Comfort Triad (1985-1986) and Branson's and Sweeney's Clothing Comfort

Model (1991). All of these theories have as a common denominator the fact that they investigate clothing comfort by examining: the wearer, the clothing and the environment. These three elements comprise the comfort triad.

Fourt and Hollies (1970) established the triad variables. However Fourt and Hollies (1970) focused more on the functional aspects of the clothing comfort setting aside the attributes of the triad’s components.

Pontrelli's Comfort's Gestalt (1977) presented the variables and demonstrated the existence of interactions among the triad variables. Pontrelli included in the model physical and psycho-physiological factors. As physical variables Pontrelli (1977) identified the environment, transport properties (moisture, heat and air), level of physical activity and garment (fit/stretch, fabric and fiber). On the other hand the variables that were considered for psycho-physiological stimuli were state of being, end-use and occasion of wear, style-fashion, fit and tactile aesthetics. The real innovation in Pontrelli’s model was the incorporation of a filter. This filter consisted of the person’s “stored modifiers” (Pontrelli, 1977) which are past experiences, prejudices, expectations imagery and life style. In that way the psychological and physical units are filtered through the wearer’s mind for determining which of them will contribute in the final perception of the wearer.

Sontag's Comfort Triad (1985-1986) advanced Fourt and Hollies' Comfort Triad (1970) by connecting in a two way relationship the variables of each triad and also by adopting the stored modifiers from Pontrelli’s theory. Sontag's Comfort Triad theory suggests that the attributes of the triad’s components interact with each other and by filtering through the person's stored modifiers establish the person's perception and response to the garment.

Branson and Sweeney (1991) stated that all the attributes of the triad's components have either physical or social-psychological dimensions. In the Branson and Sweeney model in addition to the physical and social-psychological components there is a third component, the physiological/perceptual response which leads the wearer in a comfort judgment. The physiological/perceptual component includes human responses that have been generated from the interaction among the triad's attributes. Thus the physiological/perceptual component in the Branson and Sweeney model follows the physical and social-psychological components. In their theory all the attributes and responses are filtered through a person's selected variables (e.g. previous experience, aesthetic etc) for determining the final perception of the garment.

Thermoregulation

Humans need to maintain a stable body temperature (homoeothermic) to survive. According to Wunderlich and Reeve (1869) the range of the normal temperature interval varies from 36.2 ^{o}C to 37.5 ^{o}C for the auxiliary temperature. Today although there is a debate about what body temperature is considered to be normal, in general the interval given back in 1869 from Wunderlich and Reeve is still considered to be correct (Mackowiak, 1997). Outside of these limits humans start to have signs of illness and when extremes in temperature are present, death can occur.

The human body itself produces heat due to metabolic reactions that take place within the body (Havenith, 2002). This heat production increases with an increase in body activity. The higher the activity, the higher the amount of heat that is produced.

There are several equations that estimate the heat balance of the body (Barker, Kini & Bernard, 1999; Cheuvront & Haymes, 2001). All of them are based on the same principle that heat storage is equal to the metabolic heat produced plus or minus all the factors that contribute to heat loss or gain.

According to Havenith (2002), Barker et al. (1999), and Cheuvront and Haymes (2001), the human body can release heat to the environment through conduction, convection, radiation, evaporation and respiration. Considering these factors the form of the equation is shown below.

$$S = M - W \pm R \pm C - E,$$

where S is the maintained energy of the body, M is the metabolic energy, W is the consumed energy for work, R is radiation energy, C is energy by convection and E is the heat lost by evaporation.

A different but similar version of the equation is given by Holmer (2006).

$$S = M - W - RES - E - R - C - K$$

Holmer (2006) also takes under consideration the "respiratory heat exchange" (RES) as well as the "conductive heat exchange" (K). However, when it comes to the garment level, the factors that can influence the thermal equilibrium between the human body and the environment are reduced to radiation, convection, conduction and evaporation (Holmer, 2006).

Test Instruments

Humans wear clothes almost constantly in their daily life. They wear them to protect themselves from nature's elements, from hazardous conditions in their working environment and because it is illegal to not wear clothes. Garments influence the heat exchange that takes place between the body and the environment. The level of that influence depends on the technical characteristics of the garment system.

For measuring some of the effects caused by clothing on the heat exchange phenomenon, the sweating guarded hot plate, the cylindrical model and the thermal manikin were developed and used for testing.

Sweating Guarded Hot Plate

The hot plate is one of the instruments that measure the thermal insulation of fabrics. There are several versions of hot plates, such as vertical and horizontal hot plates, guarded hot plates and sweating guarded hot plates. The most recent version and the most frequently used today is the sweating guarded hot plate. This latest type can measure the dry thermal resistance and the water-vapor resistance.

The basic concept for the instrument is that the hot plate simulates the human skin. To achieve this, the sweating guarded hot plate has a porous metal plate that is heated to 35^{o}C (ISO 11092, 1993), simulating the human skin temperature. The plate is heated from underneath with a metal block that contains heating elements. This metal block is connected with a heating-power measuring device, providing to the device the amount of energy needed to maintain a constant 35^{o}C temperature. To regulate the temperature of the metal block and the temperature of the plate, the instrument has a temperature sensor and a temperature controller. The plate is also connected with a water-dosing device that is needed only when the instrument is set for measuring the water-vapor resistance. The plate from the sides and the bottom is covered with a thermal guard. The purpose of the thermal guard is to eliminate the plate's heat loss from the sides and the bottom, so the plate will lose heat only from its upper surface. The thermal guard contains a thermal sensor that is connected with a temperature controller to help maintain the temperature of the thermal guard constant.

The ISO standards (11092, 1993) also indicate that the hot plate should be enclosed in an environmental chamber. This way the ambient temperature and humidity can be regulated and maintained during testing.

As already presented, the hot plate measures the thermal and the water-vapor resistance of fabrics. The unit for the thermal resistance is R_{ct} and it stands for square meters times Kelvin divided by Watts (m^2K/W). On the other hand the unit for water-vapor resistance is square meters times Pascal divided by Watts (m^2Pa/W).

Satsumoto, Ishikawa & Takeuchi (1997) have compared the vertical hot plate versus the thermal manikin. They concluded that the vertical hot plate can retrieve more accurate results and is also more helpful when the purpose of the study is to investigate the heat transfer through the garment's fabric. In the same study the authors claim that data from the vertical hot plate can provide better understanding of how fabrics affect the thermal transfer, therefore it is easier to translate the results when the experiment goes into full scale by testing the whole garment.

Cylindrical Model

In an effort to develop new methods that can simulate the body and determine the heat transfer of a garment while worn, cylindrical models have been proposed (e.g. Lotens & Havenith, 1991). As Rossi indicated (2005), cylindrical models are better in simulating the body structure than the hot plates, although, the cylindrical models have lower repeatability in comparison to the hot plates (Rossi, 2005). However Rossi (2005) does not believe that this should be a factor for not using this research instrument. Rossi

(2005) also recommends that cylindrical models should be avoided in studies that investigate the relation between ventilation and heat transfer in garments. As Rossi (2005) stated: “In sweating cylinders used in non-isothermal conditions, the different effects of dry heat loss, moisture driven heat loss, evaporative cooling and moisture transfer are superimposed, and it is therefore difficult to distinguish between the different contributions to total heat loss” (p.245).

Thermal Manikin

Thermal manikins simulate the form of the human body without having the ability to simulate certain reactions occurring daily in the human body (McCullough, 2005). In most cases, combinations of segments are used, forming the shape of the human body. These segments can be controlled separately leaving the researcher with the option to either set the skin temperature the same for all of the segments or to adjust the skin temperature for different body areas (McCullough, 2005). To maintain the skin temperature at the desired level the thermal manikins are heated from the inside (Huang, 2007).

Similar to the hot plate, the thermal manikin should also be placed inside an environmental chamber to control the ambient temperature and humidity, because the environmental conditions should be in steady state for the testing.

Using the thermal manikin, researchers can obtain the thermal insulation (clo) and the water vapor resistance (m^2 Pa/W) of garments. To calculate these values in segmented thermal manikins, two methods are currently available: serial and parallel method (McCullough, 2005). According to McCullough (2005), in the serial method the thermal resistance of every segment is separately obtained before summation for extracting the total value for the garment's resistance. In the parallel method, all obtained data for all of the measured elements from every segment is summed together before extracting the total thermal resistance for the garment.

Thermal manikins enable researchers to explore and study factors related to the thermal resistance phenomenon of garments on a three dimensional form. According to McCullough (2005) factors like fit, fabric coverage percentage, air layer and textile layer distribution, design, body temperature variation, body movement and body position can now be considered and investigated. A thermal manikin is a very convenient instrument to use, however the high cost for purchasing and maintaining this kind of equipment is prohibitive for many scientists (McCullough, 2005).

Fabric Characteristics Influencing Thermal Properties

This study will investigate the inclusion of air gaps via 3D spacer material, the elimination of air gaps via vacuum sealing on dry and water-vapor resistance of two multi-layered soft ballistic materials as they are encased in two different cover materials.

In a review article for testing the guarded hot plate, Huang (2006) identified factors that have an impact on the extracted value of the dry and wet resistance. The presented factors were air speed, air flow direction, turbulence of air flow, leading edge effects, pseudo equilibrium, position of anemometer, air layer, water supply, isothermal and non-isothermal conditions, bubbles/wrinkles and membrane effect. Previously presented, McCullough (2005) identified factors related with the thermal insulation of garments from the angle of construction.

All of these factors are related to thermal characteristics of fabrics or garment systems. However, because of the focus of this study, previous research in the thermal area that investigates thickness, air gaps or air layer, water vapor resistance, ventilation and air permeability are outlined.

Thickness

According to Havenith (1999) the majority of textile fabrics contain enclosed air in their composition. Sometimes the amount of trapped air exceeds the amount of fibers in the material (Havenith, 1999). Havenith (1999) after surveying numerous papers presenting empirical data noted the high correlation between thermal resistance and thickness of the trapped air. He speculated that the enclosed air contributes more than the fibers to thermal resistance.

A study conducted by Huck and McCullough (1985) investigated the thermal insulation between long and short coats and their filling materials. Among their several conclusions they claimed that garment thickness was highly related with thermal insulation. Results from several studies (e.g. Cao, Branson, Peksoz, Nam & Farr, 2006) confirm the conclusion made by Huck and McCullough (1985).

Air Gaps Affecting Insulation of Fire Protective Clothing

In 2002, Kim, Lee, Li, Corner and Paquette studied the impact of air gaps on heat transfer. The sample for their study consisted of five flame protective ensembles used by military personnel. All of the protective ensembles were multi-layered and the number of layers varied from two to eight. The authors used a 3-D whole body digitizer for measuring the dimensions of a naked thermal manikin. Their next step was to dress the thermal manikin measuring this time the dimension of the dressed manikin. The authors estimated the air gap thickness and distribution by subtracting the dimensions of naked thermal manikin and garment’s thickness from the dressed thermal manikin dimensions.

After estimating the amount and the specific locations of the trapped air, the authors compared the obtained air gap distribution with data of burn injury from previous research, searching for similarities. From the obtained data the authors concluded that formed air gaps help to prevent burn injuries and in extension air gap in garments increase thermal insulation.

In a similar experiment, Song (2007) studied the air gap distribution between a single layered garment and a flash fire simulation manikin and also the air gap effect on the thermal transfer. For estimating the amount of air layer between the garment and the manikin, Song (2007) used a 3D body scanner. Based on the results the author claimed that the areas of the body with a thinner air layer received the highest burn injuries due to reduced thermal insulation. This statement is in accordance with the conclusion made by Kim et al. in 2002.

Water Vapor Transportation

In a three part study, Hong, Hollies and Spivak (1988), Kim and Spivak (1994) and Kim (1999) investigated the moisture vapor transfer through textiles in a dynamic state. In the first part (Hong et al., 1988), the authors stated that the investigated phenomenon does not occur in daily life in steady state environmental conditions. They also claimed that information retrieved from a vapor transfer experiment for textiles, when the system is in the equilibrium status, does not provide a good indicator for estimating the comfort level. Thus for these two reasons the authors conducted this experiment under dynamic conditions. The sample of this research consisted of three fabrics: 100% cotton, 100% polyester and 50/50 cotton/polyester blend. The construction properties of these fabrics were identical. The authors concluded that the cotton generated the most comfortable feeling of the three tested fabrics, because it permitted the moisture to be transferred into the environment. To the contrary, polyester was concluded to be the most uncomfortable for the opposite reason. Finally, the obtained data for the 50/50 blended fabric demonstrated that the fabric is less comfortable than cotton but more favorable than polyester.

In the second part, Kim and Spivak (1994) introduced a new testing method for measuring the wet transfer through textile fabrics as well as the surface temperature of garments. This method has many similarities with today's standardized method for measuring water-vapor resistance. Kim and Spivak (1994) used a hot plate to simulate the temperature of the skin. The hot plate was supplied with water in such a way that the water level was maintained at the same level. Also in this testing method (Kim & Spivak, 1994), sensors measuring the temperature and the pressure in both sides of the sample were used. The goal of their study was to identify possible relationships between the type of the fabric and the measured test values. The sample used by the authors was constructed of two layers of fabric and in between a micro porous film was incorporated. The tested types of fabric that formed the samples were 100% cotton knit and 100% spun polyester knit in all possible combinations (cotton/cotton, cotton/polyester, polyester/cotton and polyester/polyester). One of their conclusions was that the cotton/cotton combination was drier and warmer than the polyester/polyester combination, which was considered as being wet and cold. This conclusion derived from the results that showed the cotton/cotton combination prevents fast increase in vapor pressure in the microclimate (skin-fabric) due to cotton's absorption property. This conclusion is in agreement with the conclusion made in the first part of their study.

The third and final part of this investigation Kim (1999) studied the effect of semi permeable films on fabrics. The author used the same testing method that was introduced in the second part of the study. In this third part, Kim (1999) used 100% cotton and 100% polyester fabrics. For the needs of this study a two-layered sample was placed in the testing instrument. Between the two layers of fabrics the author placed three polytetrafluroethylene (PTFE) semi permeable films, all of them with different pore size, and one polyurethane (PU) non permeable film. The total number of treatments for this experiment was sixteen, four with cotton layers, four with one cotton layer beneath the film and one polyester layer on top, four with one polyester layer beneath the film and one cotton layer on top and four with polyester layers. The obtained results for the fabric combination were in agreement with those of the previous parts of the study, highlighting the importance of fabric's fiber composition. Although the film's porosity level was positively related to the level of comfort, film incorporation into a fabric was found to decrease the overall comfort level.

Yoo, Hu and Kim (2000) studied the heat and moisture transfer with a vertical sweating skin model. The considered variables for this experiment were type of fiber, air layer and garment openness. For openness, the authors considered both the porosity of the fabric and the garment openings. The authors used cotton broadcloth and polyester broadcloth for their testing, with similar weights, thickness and fabric count. The findings showed that cotton was more comfortable during the first 10 minutes of the test. However for a longer time period (approximately, after maximum vapor pressure was reached), the order was changed and polyester broadcloth presented better comfort level than the cotton broadcloth. The given explanation from the authors was based on the hydrophilic or hydrophobic properties of the fabric. In hydrophilic fabrics, as in cotton broadcloth, the absorption of water reduced the porosity of the fabric (Wehner, Miller & Rebenfeld, 1987). For the effect of the air layer in heat and moisture transfer Yoo et. al. (2000) found that the thickness of the air layer was negatively correlated with the vapor pressure and as an extension positively correlated with the wearer's comfort. According to the results, vapor pressure decreased significantly when they increased the thickness of the air layer from 6mm to 12mm (Yoo, et al., 2000). The vapor pressure also decreased when the authors increased the thickness from 12mm to 18mm but the difference on pressure was not in the same level as the difference observed between 6 mm and 12 mm. The authors also claimed that vapor pressure decreased while openness increased. As their results indicated, at 60% openness both vapor pressure and time needed for reaching dry state, reduced in approximately half, compared with the 0% openness. Also the authors concluded that at 60% openness the impact caused by the type of fabric is negligible and tends to be equivalent to nude skin as the percentage of openness continues to increase.

Chen, Fan and Zhang (2003) investigated the influence of perspiration on clothing thermal insulation. In their study, Chen et al. used a sweating thermal manikin with two different skin types. One with low water transfer ability and one with high. They repeated both tests (skin with low and high perspiration ability) using twelve clothing ensembles. They concluded that there was a significant difference between the two treatments, referring to a 2 to 8% decrease in the thermal insulation for the highly breathable skin. The given explanation was that heavy sweat rate can decrease the thermal insulation of a garment.

Ventilation and Air Permeability

Konarska, Soltynski, Sudol-Szopinska, Mlozniak and Chojnacka (2006) tried to identify factors that are strongly related with thermal insulation when measured with a thermal manikin. In this study, they used a standing thermal manikin and three clothing ensembles. The thermal insulation value was obtained both with the serial and parallel methods. Among the conclusions they claimed that the air velocity lowered the thermal insulation by 7% (air velocity was increased from 0.3 m/s to 0.7 m/s), due to ventilation phenomenon. They also indicated that the expected thermal insulation of the garment should be the key factor for setting the appropriate environment inside the chamber. The higher the thermal insulation the longer the time period until the steady state was achieved. Another conclusion from their study was that the thermal insulation was not related to the way that the heat was supplied to the manikin.

Ueda, Inoue, Matsudaira, Araki and Havenith (2006) studied the clothing ventilation phenomenon and the impact on humidity. Using thermal manikin and human subjects, the authors measured the ventilation and the humidity level of five work shirts, with similar characteristics, in the back area, the chest area and the upper arm area. According to the obtained results from the thermal manikin testing, the torso area was ventilated better compared with the upper arm area. However, analyzing the results from the human subject testing the authors reported that there are existing indications that air permeability of the fabric is related to the ventilation level of the garment. However this statement was not statistically supported (null hypothesis was accepted). The authors also claimed that different values of ventilation can be obtained while measuring different body areas. Factors such as body movement, type of fabric and formed air layers effect the ventilation of garments (Ueda et al., 2006).

Vacuum Sealing

Vacuum is defined by the American Vacuum Society as “the condition of gaseous environment in which the gas pressure is below atmospheric pressure”. While seal is “a mean to prevent leakage through a joint, but the term seal is used as well to denote the sealed joint itself” (Roth, 1966, p. 11).

A vacuum device, enclosure material and seal are the major components in order to create a vacuum sealed space. For removing gases there are two types of pumps that can be used, positive displacement and momentum transfer (Hoffman, Signh & Thomas III, 1998). While numerous materials can be used as seals based on the composition of the material in which the vacuum is going to be created within, the same material can be used as an enclosure and seal material at the same time.

According to Roth (1966) depending on the criterion used, vacuum sealing methods can be assigned into categories with five different ways, as presented in Table 1.

Table 1. Classifications of vacuum techniques based on purpose, requirements, joined materials, degree of permanency and seal technique used.

Classification criterion	Arrived categories
Purpose	Against gas penetration, transmission of electric current, transmission of motion, material transfer, radiation transmission
Requirements	Vacuum, temperature, rigid or flexible seals, chemical corrosion
Joined Material	Metal to metal, glass to glass, glass to metal, ceramic to glass, ceramic to metal, wax or resin to glass or metal, elastomer to glass or metal
Permanency	Permanent, semi-permanent, de-mountable
Seal technique	Welded and fusion, brazed or soldered, wax and resin, ground and lapped, liquid, gasket

Theoretically a vacuum sealed space should maintain its pressure for an infinite length of time. However, this is impossible in real applications. (Roth, 1966; Hucknall & Morris, 2003). Leaks, outgassing and permeation let gas molecules penetrate either the seal or the barriers and enter the vacuum sealed space. Also for the same reasons it is impossible to completely remove all existing gases from a space through vacuum sealing (Hucknall & Morris, 2003). According to the American Vacuum Society leak, outgassing and permeation are defined respectively as:

“a hole or permeable element through which leakage may occur under the action of a pressure difference”

“The evolution (setting-free, releasing) of gas from a liquid or solid under vacuum”

“The passage of gas through a solid. The process always involves diffusion through the solid and may involve surface phenomena such as sorption, dissociation, migration and desorption”

There are several methods and instruments that help to identify the amount of existing leakage of vacuum sealed spaces that can be assigned into two categories, pressure rise method and test gas methods.

According to Roth (1966) when a gas is under pressure with any given opportunity (such as leaks or permeation) it will try to move to an environment with lower pressure. Most of the gases found in the atmosphere are considered to be ideal gases (Hucknall & Morris, 2003). Thus kinetic theories for gases (such as Maxwell-Boltzmann distribution, Boyle’s law, Charles and ideal gas laws etc) can be applied predicting or estimating their behavior or energy (Hoffman, Signh & Thomas III, 1998; Holland,Steckelmacher and Yarwood, 1974; Hucknall & Morris, 2003).

CHAPTER III

METHODOLOGY

This study investigated the effects of elimination of air gaps via vacuum sealing and the inclusion of air gaps via a 3D spacer material on dry and water-vapor resistance of two multi-layered soft ballistic materials. The effect on dry and water resistance of two alternative fabrics to encase the ballistic packs was also investigated. This chapter presents the materials used, the sampling procedure, the two phases with their experimental designs, testing methods and the statistical analysis. It also presents additional information about the equipment.

Sampling

Two types of commercially available ballistic material were selected and tested, Kevlar® KM2® (KK) and Unidirectional Dyneema® (UD). The number of layers of ballistic material used for soft BA varies. The layering depends on the desired level of protection and on the ballistic material that were used. UD is known to provide the same level of protection compared to KK with a smaller number of layers. In this experiment, 32 layers of KK and 15 layers for UD were used to form the ballistic samples. However in this study, it was not tested if the 32 layers of KK and 15 layers of UD samples had equivalent ballistic protection. The dimensions for all of the layers, both for KK and UD, were 12 inches in length and 12 inches in width. The assignment of the fabric layers into group samples was based on random number tables.

Phases

Phase I Identifying the Vacuuming Level

For the first step of this phase, ten multi-layered treatments with three replications each were created for both KK and UD. The control package contained only the multi-layers of each ballistic material; the second package contained two outer layers (one bottom layer and one top) of the same material as the vacuum sealing bags, with the ballistic material sandwiched between. The remaining eight sets of sample packages had the ballistic material enclosed in nylon/polyethylene bags and vacuum sealed at different levels. The eight tested vacuum sealed treatments levels were vacuumed at 1, 2, 4, 6, 8, 12, 16 and 20 IOM respectively.

Dry thermal resistance and water-vapor resistance of all ten packages for both ballistic fabrics were determined using a sweating guarded hot plate. Two completely randomized treatment combinations were formed, for each one of the ballistic materials, with one independent variable (vacuum sealing) and one dependent variable (either R_{ct} or R_{et}). The obtained data were analyzed using one way ANOVA followed by post hoc LSD analysis, for identifying differences between the vacuum sealing treatments. Furthermore regression analysis was conducted to identify a potential relationship between thickness and dry thermal or water-vapor resistance. The SAS statistical software was used for analyzing the data.

From the results of this phase, the optimum vacuum-sealing level was established. The selection was based on the dry thermal resistance and the water-vapor resistance with respect to the recorded measurements for the treatment characteristics previously presented, as well as a subjective assessment of package flexibility. Considering all these factors, the most preferable level of vacuum sealing was selected and used in Phase II.

Vacuum Sealing Protocol

The main components for the vacuum sealing equipment included a pump that removes the air from the chamber and a hot wire sealing mechanism that helps to seal the bag when the vacuum is completed. The instrument that was used in this study gave the option to the user to regulate the power of the pump and the time of the applied vacuum. Because there was no standardized method for vacuum sealing, a protocol was developed and is described below.

The first step in the procedure was to insert the sample package of ballistic material in the bag (the bags were made of nylon/polyethylene and their dimensions were 14’’ width and 16’’ long). It was critical to insure that there was no material from the ballistic package that extended beyond its edges, even fibers. It was very likely that there would have been a leak in the vacuum sealed sample if some part or fibers of the layered ballistic material were trapped at the sealing seam. In the case that the previously described phenomenon occurred, the vacuum sealed bag was opened and replaced with a new bag. Then the bag was placed inside the chamber of the vacuum sealer according to the manufacturer’s recommendations for positioning and alignment. The next step was to adjust the settings for the pump power and the time that the vacuum lasted, based on the final pressure that the sample was desired to be vacuum sealed. The door of the chamber was closed and the instrument automatically started the vacuum sealing process. First the vacuum sealer removed air from the chamber with the volume that was previously set and for the time period that was also previously set. Afterwards, it automatically started the sealing process. The instrument notified the user that the sealing of the bag was done by making a characteristic noise. At this time the instrument displayed the level of Inches Of Mercury (IOM) that the sample was vacuum sealed. Finally the chamber was depressurized and the sample was ready to be removed.

In order to verify that the samples were sealed in the appropriate vacuum level and without having any major leakage from the seam, the vacuum sealed samples were placed individually inside the vacuum sealer and afterwards vacuum was applied to them. The shape of the vacuum sealed sample remained the same as long as the pressure of the air surrounding (environment inside the vacuum chamber) the vacuum sealed sample was higher compared to the air inside the vacuum pouch. Eventually as the vacuum level inside the chamber continued to increase there was a time that the vacuum level inside the chamber matched the vacuum level of the pouch. From that point on, since the chamber environment had less dense air compared to the environment inside the pouch, the vacuum sealed samples started to change their shape by expanding, addressing with that way the vacuum level of the sample. Although this is an empirical method and not highly accurate, due to lack of access to other apparatus, it was the only way for verifying that the samples were vacuum sealed at the desired level.

Hot Plate Procedures

Both dry thermal resistance and water-vapor resistance experiments were conducted according to the ISO 11092 standard. The standard indicates for both methods that every measurement should be replicated three times. The tested material should cover completely the surface of the plate and should be free from wrinkles. The standard also suggests twenty-four hours as the minimum time of acclimatizing samples thicker than 5mm prior to testing the materials.

Dry Thermal Resistance

For the dry thermal resistance, the settings for the sweating guarded hot plate and the environmental chamber according to the ISO 11092, standard are presented in Table 2.

Table 2. Settings for the sweating guarded hot plate and the ambient environment as indicated from the ISO 11092 for dry thermal resistance.

	Set interval
Temperature of test plate (^oC)	35 ± 0.5
Temperature of guard section (^oC)	35 ± 0.5
Temperature of bottom plate (^oC)	35 ± 0.5
Air temperature (^oC)	20 ± 0.5
Relative humidity (%)	65 ± 3
Air velocity (m/s)	1 ± 0.05

The standard specifies that the dry thermal resistance value of the bare plate should be obtained every time, before testing the material samples. The materials should be placed in the same manner as they are placed into a garment, with the plate surface simulating the skin. If the sample consists of one layer, the side of the fabric that faces the human body should be facing the plate. Similarly when the sample is multi-layered, the fabrics should be layered in the same order as they would appear in a garment and the appropriate side should be facing the plate. Wrinkles, bubbles and air gaps should be eliminated in multi-layered samples.To start recording the measurements, the specimen should reach steady state conditions.

The equation for calculating the dry thermal resistance is

$$R_{ct} = (T_s - T_a)\, A / H_c\ ,$$

where R_{ct} is the dry thermal resistance of the fabric and the air layer ($^{o}C\ m^2$ / W), T_s is the surface temperature of the plate (^{o}C), T_a is the air temperature (^{o}C), A is the surface of the plate (m^2), and H_c is the power input (W). For obtaining the dry thermal resistance of the tested material (R_{ct}), the dry thermal resistance of the bare plate (R_{ct0}) should be subtracted from R_{ct}.

Water Vapor Resistance

For the water-vapor resistance experiment, the settings for the sweating guarded hot plate and the environmental chamber according to the ISO 11092 standard are presented in Table 3.

Table 3. Settings for the sweating guarded hot plate and the ambient environment as indicated from the ISO 11092 for water-vapor resistance.

	Set interval
Temperature of test plate (^oC)	35 ± 0.5
Temperature of guard section (^oC)	35 ± 0.5
Temperature of bottom plate (^oC)	35 ± 0.5
Air temperature (^oC)	35 ± 0.5
Relative humidity (%)	40 ± 3
Air velocity (m/s)	1 ± 0.05

Similar to the method for the dry thermal resistance, the standard specifies that the water-vapor resistance value of the bare plate should be obtained every time, before any attempt to test the material samples. However to obtain this value, distilled water should be provided to the plate. The tested materials should remain dry during the testing, thus a semi-permeable film (permits only water in vapor form to penetrate the film) should be placed on top of the plate as a liquid barrier. The standard specifies that the film should be carefully placed to avoid formation of wrinkles and air bubbles. The instructions for placing the materials on the plate are identical with those for the dry thermal resistance.

As in the dry thermal resistance method, when determining water-vapor resistance, the specimen should reach steady state conditions.

The equation for calculating the water-vapor resistance is

$$R_{et} = (P_s - P_a)\ A / H_c,$$

where R_{et} is the water-vapor resistance of the fabric and the air layer (Pa m^2 / W), P_s is the water pressure the surface of the plate (Pa), P_a is the water pressure in the air (Pa), A is the surface of the plate (m^2), and H_c is the power input (W). For obtaining the water-vapor resistance of the tested material (R_{et}), the water-vapor resistance of the bare plate (R_{et0}) should be subtracted from R_{et}.

Thickness

The thickness measurements for all materials and treatments were conducted according to the ASTM D 1777-96 (2007) standard. Testing option 1 was used for measuring the thickness of UD and KK, while testing options 2 and 5 were used for measuring the thickness of the pouch and all of the samples respectively.

Mass per Unit Area

All weight measurements were made according to ASTM D3776-07 standard option C. The instrument used for obtaining the samples was capable of cutting circle sample pieces of 100 cm^2 total surface area. Since for every material three replications were made, the total surface measured was 300 cm^2.

Phase II Identifying the Impact of the Factors

After the optimum level of vacuum sealing and the favorable ballistic material were determined in Phase I, the experiment proceeded to Phase II. Two separate experimental designs were developed for measuring the two dependent variables, dry thermal resistance and water-vapor resistance. In both cases, a completely random factorial treatment combination with the same three factors was used. The factors were: vacuum sealing (non-vacuum sealed and vacuum sealed), spacer (no spacer and incorporated spacer) and enclosure material (ripstop and mesh). In this stage, all possible combinations of the independent variables were made with three replications for each combination and were tested with the sweating guarded hot plate for dry and evaporative resistance for both ballistic fabrics. The methods of testing vacuum sealing, R_{ct}, R_{et}, thickness (testing option 1 was used for measuring Cordura®, mesh and spacer samples) and mass per unit area were the same as Phase I. Table 4 illustrates all the treatments combinations that were formed.

Table 4. R_{ct} ($^{o}C\ m^2$ / W) and R_{et} (Pa m^2 / W) treatments of Unidirectional Dyneema®.

Ripstop–non-vacuum sealed-without spacer	Ripstop vacuum sealed-without spacer
Ripstop–non-vacuum sealed-with spacer	Ripstop–vacuum sealed-with spacer
Mesh–non-vacuum sealed-without spacer	Mesh-vacuum sealed-without spacer
Mesh–non-vacuum sealed-with spacer	Mesh–vacuum sealed-with spacer

Since the samples were constructed to simulate the layering of soft BAs, one layer of Cordura® nylon was always used as outer layer. Underneath the Cordura® were placed the multiple layers of Unidirectional Dyneema® ballistic fabric, either non-vacuum sealed or vacuum sealed based on the treatment requirements. Below the ballistic material the selected 3D material was placed, depending on the treatment. The sides and bottom were enclosed with either nylon ripstop or nylon mesh was used as enclosure material. Figure 1 presents the layering of the samples.

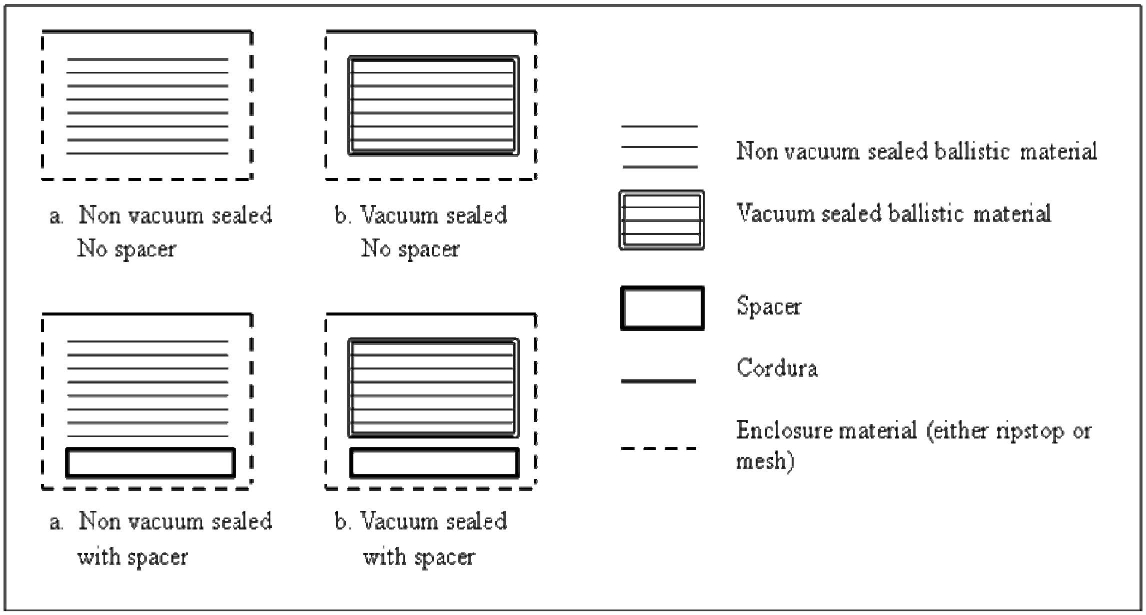

Figure 1. Material layering for constructing Phase II treatments

The obtained data in this Phase were analyzed using factorial ANOVA followed by the post hoc LSD analysis to identify if there were significant differences between the treatments. The SAS statistical software was used for the calculation.

Instruments

Vacuum Sealer manufactured by Multivac (Model number: A300 / 16MC series 1994), was a table-top vacuum packing machine with built in vacuum pump and gas flush. For sealing it used a single seam and a hot wire for cutting off. The dimensions of the machine were 22’’ wide, 20 ½’’ long and 14’’ high, while the dimensions of the chamber were 19.3’’ wide, 14.9’’ long and 5.9’’ deep. The maximum length for the sealing seam was 19.3’’.

The Sweating Guarded Hot Plate manufactured by Measurement Technology (Model number: SGHP-8.2) was housed inside an environmental chamber manufactured by Lunaire Environmental (Model number: CEO910W-4).

The thickness gauge was manufactured by Industrial Laboratory Equipment Company, Inc. (Model: ILE-TG-2-D).

A cutter manufactured by Industrial Laboratory Equipment Company, Inc.(Model: ILE-CFC-100) was used for cutting precisely weighted samples.

The scale used for measuring the weight of the used material was manufactured by Denver Instrument (Model: APX-100).

CHAPTER IV

MANUSCRIPT

Abstract

Body armors can affect significantly the thermoregulation mechanism of the human body by providing high thermal and vapor insulation.

The overall purpose of this study was to investigate the effect of elimination of air gaps via vacuum sealing and inclusion of air layer via use of a 3D spacer material within multi-layered structures of soft body armors on R_{ct} and R_{et}. The objectives of this study were to investigate the impact of vacuum sealing on R_{ct} and R_{et} of multi-layered ballistic samples at different vacuum levels, indentify the vacuum sealing treatment that produced significantly lower R_{ct} values with respect to R_{et}, thickness and rigidness and determine the treatment that presented optimum R_{ct} and R_{et} results among several treatment combinations that were simulating the multi-layered construction of soft body armor.

In this study two ballistic materials, one type of vacuum sealing pouch, one type of 3D spacer material, one type of Cordura® and two types of enclosure material were used. The R_{ct} and R_{et} measurements were obtained using a guarded hotplate, and vacuum sealing was accomplished using a table top vacuum chamber.

It was found that Unidirectional Dyneema® (UD) vacuum sealed samples at 1, 2 and 4 Inches of Mercury (IOM) presented significantly lower R_{ct} values ($p<0.05$) and samples vacuum sealed at 16 and 20 IOM had significantly higher R_{ct} values ($p<0.05$). For Kevlar® KM2® (KK), no treatment was found to significantly decrease R_{ct} compared to the control (non-vacuum sealed ballistic material). Significantly higher R_{ct} compared to all other treatments was obtained by the non-vacuum sealed treatment with one layer of vacuum pouch over and under. All R_{et} measurements for both ballistic materials were out of the instrument's range (R_{et} > 999 Pa m^2/W). From treatments that simulated construction of soft body armor, it was found that the treatment combination presenting lower R_{ct} values was the one that incorporated vacuum sealed ballistic material, enclosed in ripstop without using the 3D spacer material. However, both treatment combinations that incorporated mesh enclosing the 3D spacer material with the ballistic material either vacuum sealed or not, presented significantly lower R_{et} values compared to all other treatments.

It was concluded that UD and KK reacted differently to vacuum sealing applications. The results suggested that UD vacuum sealed at 2 IOM had merit and should be further investigated for use in soft body armors. Incorporating 3D spacer material with UD vacuum sealed at 2 IOM as the ballistic material with all enclosed in mesh, improved the thermal properties of the package.

Introduction

Ballistic protective clothing is used mainly for military and law enforcement personnel all over the world. The ballistic protection is provided either by using multiple layers of textile materials or by using hard plates combined with ballistic textiles. Body armors that use only textile fabrics are often called soft body armors while hard body armors refer to body armors that have incorporated hard plates.

According to the National Institute of Justice (NIJ) standards for ballistic resistance of personal body armor (2008) the highest level of protection that soft armors can achieve is IIIA, which actually can prevent penetration of projectiles fired from almost all types of handguns. A greater level of protection can be achieved using hard plates combined with soft armor.

As with any other garment, body armor acts as a barrier, providing insulation and restraining the natural mechanisms that the human body has for controlling its temperature. The multi-layered construction of body armor combined with its weight can exhaust the human body and under extreme conditions can even lead to death. According to Carter et al. (2005) there are 5,246 recorded incidents between 1980 and 2002 of US soldiers getting medical help for treating heat related illnesses. In the same study it was reported that among those incidents 37 were fatal.

Previous studies have shown that fabric composition and structure (Hong, Hollies & Spivak, 1988; Kim & Spivak, 1994; Kim, 1999) can affect the thermal characteristics of fabrics. Thickness has also been found to be positively correlated with R_{ct} (Huck & McCullough, 1985; Cao, Branson, Peksoz, Nam & Farr, 2006) and R_{et} (Cao, Branson, Peksoz, Nam & Farr, 2006). Havenith (1999) claimed that since air is less heat conductive compared to most fibers, enclosed air within the structure of textile materials can have a greater impact on insulation than the fibers used to compose the materials.

Also Yoo, Hu and Kim (2000) found that the thicker the air layer between the vertical sweating skin model and the textile sample, the lower the vapor pressure. From the same study it was also concluded that the "openness" (openness was defined by the authors as the combination of the material's porosity with the garment's openings) was negatively related with the vapor pressure (Yoo, et al., 2000). Gibson (1993) claimed that air permeable fabrics, taking also into consideration the thickness of the air layer, demonstrated ameliorated R_{ct} and R_{et} measurements especially when there was a space between fabric and the hotplate.

Although the contribution of trapped air to the phenomenon of heat exchange between a wearer and environment through a garment is documented and highly acknowledged, no previous study was found that deliberately eliminated or controlled the existing air within the structure of the textile material or layers in order to investigate the impact of this action on the R_{ct} and R_{et}.

This study investigated the impact of vacuum sealing on R_{ct} and R_{et} measurements of multi-layered ballistic materials. More specifically this study explored if R_{ct} and R_{et} measurements of multi-layered ballistic samples can be manipulated by controlling the amount of air existing among the sample layers through application of vacuum sealing. The vacuum sealing application that presented the most favorable R_{ct} and R_{et} results was determined for two selected ballistic materials. The final objective was to determine the effect of inclusion of a 3D spacer device with a vacuum sealed ballistic material while enclosed with two different encasing fabrics in a structure simulating the structure of body armor, on R_{ct} and R_{et}.

Material and Methods

To explore the multiple goals of this study, two separate experiments were completed. The first series of tests were named Phase I and the second series Phase II.

Two types of ballistic material (KK and UD) and one type of vacuum sealing pouch were used in Phase I. While for Phase II, UD, Cordura®, ripstop, mesh, 3D spacer material and one type of vacuum sealing pouch (same type used in Phase I) were the materials used for constructing the samples. Table 5 presents information about the content and structure of all the materials used in this study.

Table 5. Content and structure of UD, KK, pouch, ripstop, mesh, Cordura® and spacer.

	Unidirectional Dyneema®	Kevlar® KM2®	Pouch	Ripstop	Mesh	Cordura®	Spacer
Content	Polyethylene	Aramid	Nylon/Poly	Nylon	Nylon	Nylon	Polypro-pylene
Structure	non-woven film composite	Woven	Film	Woven coated	Knit	Woven	Weaved spacer

Phase I

In Phase I the goals were first to determine differences by level of vacuum sealing and second, to determine which ballistic material and what vacuum level provided more preferable R_{ct} and R_{et} measurements. For achieving this goal, ballistic samples were vacuum sealed and afterwards tested on a guarded hot plate for determining their R_{ct} and R_{et} values. Thickness measurements were also obtained for all applied treatments in an attempt to relate thickness with R_{ct} and R_{et} measurements and verify findings from previous studies (Huck & McCullough, 1985; Cao, Branson, Peksoz, Nam & Farr, 2006).

Experimental Design

A total of ten treatments were formed for each of the two ballistic materials. Eight treatments used different levels of vacuum sealing and two were not vacuum sealed, one of which was left untreated and used as the control, and the second consisted of one layer of vacuum sealing bag placed over and one under the ballistic sample lay-up. The data were analyzed with the SAS program as completely randomized treatment combination. One way ANOVA was used to determine differences among the applied treatments. Post hoc LSD was used to identify the differences when they were present. Also to investigate if there was a significant relationship between the thickness and thermal results, regression analysis was conducted.

Sampling

Two ballistic materials were used in this phase (Unidirectional Dyneema® (UD) and Kevlar® KM2® (KK)). UD can provide the same level of ballistic protection with fewer layers, compared to KK. Therefore the tested samples for UD were constructed with 15 layers while KK samples were formed with 32 layers. Due to the high cost of the ballistic materials, only 75 and 160 layers of UD and KK respectively were obtained. The test samples were formed daily with the help of a random number table by assigning each fabric layer to new test samples which were subsequently vacuum sealed as described below. Ten samples (five of each ballistic fabric) were constructed and tested per day.

Vacuum Sealing

A table top vacuum sealer with a hot wire incorporated for creating the sealing seam, manufactured from Multivac (model: A300/16MC) was used for the vacuum sealed treatments. To achieve the desirable vacuum level for each of the vacuum sealed treatments the settings on the vacuum sealer for the volume and the operation time of the pump were appropriately adjusted according to the vacuum level that was needed for the treatment.

One type of commercially available vacuum sealing pouch, manufactured by VacMaster Vacuum Packaging was used for all treatments. This pouch was composed of dual layers of nylon and polyethylene. Dimensions were 14’’ wide and 16’’ long.

Dry Thermal and Evaporative Resistance

R_{ct} and R_{et} were measured using a sweating guarded hotplate manufactured by Measurement Technology Northwest (model: SGHP-8.2) which was installed inside an environmental chamber manufactured by Lunaire Environmental (model: CEO 910W-4). The experimental conditions were in accordance with ISO 11092 standard, except the acclimatization procedure was modified. The ISO standard for the hotplate indicates that thick materials (over 5 mm thick) should be acclimatized for twenty four hours prior to testing. However for this study, the ballistic materials were vacuum sealed just before they were tested on the hotplate. Since the vacuum sealer and the hotplate were located in different buildings, it would have been impossible to maintain the acclimatized ballistic material before the thermal insulation tests. Instead the samples were left on a lab bench overnight, vacuum sealed the next morning and then left for at least four hours (according to the acclimatization guidelines of the ASTM F 1868-02 standard) inside the environmental chamber for acclimatization. According to Kamenidis, Branson, Peksoz & Cao (2009) differences in environmental conditions from day to day did not affect the R_{ct} results of vacuum sealed UD and KK samples.

For minimizing any potential effect from seal leakage on the vacuum level of the samples, all R_{ct} and R_{et} measurements of the vacuum sealed samples were made within 16 hours from the moment that they were vacuum sealed.

Thickness

A thickness gage manufactured by Industrial Laboratory Equipment Company, Inc. (Model: ILE-TG-2-D) was used for measuring all of the tested multi-layered samples and the individual materials, according to the ASTM D 1777-96 standard. Testing option 5 (at 0.1 psi pressure) was used for measuring the ballistic samples while option 2 (at 3.4 psi pressure) was used for measuring the vacuum pouch and testing option 1 (at 0.6 psi pressure) was used for mesh.

Mass per Unit Area

The mass per unit area measurements was determined according to the ASTM D3776-07 standard (option C). Three samples from every used material were cut at 100 cm^2 surface area with a metric sample cutter manufactured by Industrial Laboratory Equipment Company (Model: ILE-CFC-100). Afterward, the samples were measured with a high precision (resolution: $1*10^{-4}$ gr) scale manufactured by Denver Instrument (Model: APX-100).

Phase II

Two results from Phase I were used as input for conducting Phase II. The ballistic material with lower R_{ct} and R_{et} values from Phase I was selected while sealed at the optimum vacuum level for Phase II testing. The incorporation of a 3D spacer material and types of enclosure materials on R_{ct} and R_{et} values of multi-layer samples that simulated the construction of body armor were also investigated in Phase II. All materials

(UD, KK, vacuum sealing pouch, spacer, ripstop, mesh and Cordura®) used in this phase were commercially available.

Experimental Design

The independent variables in this stage were spacer (two levels, with and without spacer), enclosure material (two levels, ripstop and mesh) and vacuum sealing (two levels, vacuum sealed and not), while the dependent variables were R_{ct} and R_{et}. A completely randomized treatment combination design was formed for each one of the dependent variables. With the help of SAS, factorial ANOVA (2X2X2) was used for analyzing the R_{ct} and R_{et} data.

Sampling and method used for vacuum sealing, R_{ct} and R_{et}, thickness and mass per unit area measurement for Phase II were the same as the ones described in Phase I.

Results and Discussion

Material Testing Results

All materials used in both Phases were measured for R_{ct}, R_{et}, thickness and mass per unit area (Table 6). Both KK (1 layer) and mesh (1 layer) presented the lowest R_{ct} values ($R_{ct} = 0.0069$) while ripstop was found to have the highest R_{ct} ($R_{ct} = 0.0985$). Mesh and Cordura® demonstrated the lowest R_{et} value measurements (R_{et} =2.5365 and 7.8947 respectively). One layer of UD and one layer of pouch demonstrated the highest R_{et} measurements (R_{et} >999), which were out of the instrument's range. The thinner materials were the pouch (0.13 mm), the spacer was the thickest of the materials used in this study (6.44 mm). 3D spacer (4.1442 gr/m^2) and pouch (0.7025 gr/m^2) presented the highest and lowest mass per unit area measurements respectively.

Table 6. R_{ct}, R_{et}, thickness and density measurements for 1 layer of all materials used in Phases I and II.

Materials	R_{ct} [z] (°C m²/W)		R_{et} [z] (Pa m²/W)		Thickness [z] (mm)		Mass per unit area [z] (gr/m²)	
	Average	Std	Average	Std	Average	std	Average	std
Dyneema®	0.0148	0.0003	999*	-	0.17	0.01	1.2867	0.01
Kevlar®	0.0069	0.0016	17.2482	0.3521	0.34	0.01	2.3356#	0.0237
Pouch	0.0357	0.0117	999*	-	0.13	0.01	0.7025	0.0286
Spacer	0.0666	0.0026	12.7652	1.1969	6.44	0.06	4.1442#	0.0304
Ripstop	0.0985	0.0078	120.1958	11.8668	0.18	0	1.1920	0.009
Mesh	0.0069	0.0020	2.5365	0.0980	0.64	0.01	1.7521	0.0082
Cordura®	0.0299	0.0165	7.8947	1.5886	0.42	0.01	2.0972	0.0209

* All three replications were out of range (R_{et} > 999 Pa m^2 / W)

[#] The instrument used for cutting the samples had difficulties to cut through KK and Spacer thus scissors were used to separate completely the sample pieces.

[z] All measurements of all the replications of the R_{ct}, R_{et}, mass per unit area and thickness for the materials used can be found in Appendices A, B, C, and D respectively.

Phase I

As was stated previously, in this phase ten treatments were applied to both ballistic materials and the R_{ct} and R_{et} values were obtained. Eight of those treatments used vacuum sealing at different levels, one was the control and the final treatment included the vacuum pouch layers over and under the non-vacuum sealed ballistic material. The average R_{ct} and R_{et} measurements (after three replications), thickness measurements (after 10 replications) and information about the volume and operation time of the pump during the vacuum sealing procedure for all treatments and both ballistic materials appears in the Tables 7 and 8. The analytical R_{ct}, R_{et}, thickness and weight results of the three replications for all the treatments can be found in Appendices E and F respectively.

Table 7. R_{ct}, R_{et}, thickness and vacuum chamber settings for all UD treatments.

Treatments	R_{ct} ($^oC\ m^2/W$)	R_{et} ($Pa\ m^2/W$)	Thickness (mm)	Pump Volume (IOM)	Pump operation time (sec)
Control (no vacuum)	0.0762	999*	2.786	N/A	N/A
Control + pouch (no vacuum)	0.1195	999	3.126	N/A	N/A
1 (IOM)	0.0232	999	2.716	0.2	10
2 (IOM)	0.0249	999	2.74	0.62	6
4 (IOM)	0.0389	999	2.818	1.01	1
6 (IOM)	0.0521	999	2.876	2.21	2
8 (IOM)	0.0872	999	2.926	2.90	1
12 (IOM)	0.0943	999	2.956	4	1
16 (IOM)	0.1195	999	2.986	9	1
20 (IOM)	0.1365	999	3.022	11.01	1

* 999 means that all three replication were out of range (R_{et} > 999 Pa m^2 / W)

Table 8. R_{ct}, R_{et}, thickness and vacuum chamber settings for all KK treatments.

Treatments	R_{ct} ($^{o}C\ m^2/W$)	R_{et} ($Pa\ m^2/W$)	Thickness (mm)	Pump Volume (IOM)	Pump operation time (sec)
Control (no vacuum)	0.1031	999*	10.408	N/A	N/A
Control + pouch (no vacuum)	0.1363	999	10.736	N/A	N/A
1 (IOM)	0.1056	999	9.476	0.56	1
2 (IOM)	0.0990	999	9.504	0.98	1
4 (IOM)	0.1007	999	9.564	1.55	1
6 (IOM)	0.1049	999	9.616	2.72	1
8 (IOM)	0.1056	999	9.698	3.50	1
12 (IOM)	0.1096	999	9.796	4.48	1
16 (IOM)	0.1172	999	10.362	9	1
20 (IOM)	0.1250	999	10.464	11.01	1

* 999 means that all three replication were out of range (R_{et} > 999 Pa m^2 / W)

In general for both UD and KK, the greater the amount of air removed through vacuum sealing, the lower the R_{ct} values obtained from the samples. However, the R_{et} measurements for all of the applied treatments were out of the instrument's range, suggesting that all treatments were non water-vapor permeable and if there was an effect from the applied treatments it was impossible to detect and thus no statistical analysis was conducted for the R_{et} measurements.

The ANOVA analysis for R_{ct} showed that there was a significant difference among the vacuum sealed treatments for both Dyneema® ($p<0.0001$) and Kevlar® ($p<0.0001$) as shown in Table 9.

Table 9. ANOVA for R_{ct} for both ballistic materials.

Material	Source	DF	Sum of squares	Mean Square	F-value	Pr>F
UD	Vacuum level	9	0.0412	0.0046	44.39	<0.0001
KK	Vacuum level	9	0.0039	0.0004	10.15	<0.0001

Furthermore the post hoc LSD test for UD (Table 10) revealed that the treatments formed five groups. More specifically, UD samples vacuum sealed at 20 and 16 IOM presented the highest R_{ct} values among the treatments; followed by the vacuum pouch not sealed, vacuum sealed treatments at 12 and 8 IOM. However, the 8 IOM treatment was not significantly higher than the control. The fourth group included the two treatments vacuum sealed at 6 and 4 IOM. Finally the treatments that had significantly lower R_{ct} values compared to the other treatments (besides the treatment vacuum sealed at 4 IOM) were vacuum sealed at 2 and 1 IOM.

Table 10. Significant differences for R_{ct} among the UD treatments for Phase I, based on the post hoc $LSD_{0.05}$

20 (IOM)	16 (IOM)	Control with vacuum pouch not sealed	12 (IOM)	8 (IOM)	Control not sealed	6 (IOM)	4 (IOM)	2 (IOM)	1 (IOM)

Table 11. Significant differences for R_{ct} among the KK treatments for Phase I, based on the post hoc $LSD_{0.05}$

Control with vacuum pouch not sealed	20 (IOM)	16 (IOM)	12 (IOM)	8 (IOM)	1 (IOM)	6 (IOM)	Control not sealed	4 (IOM)	2 (IOM)

For KK (Table 11) the post hoc LSD test showed that the unsealed vacuum pouch treatment presented a significantly higher R_{ct} compared to all other treatments, followed by the vacuum sealed treatments at 20 and 16 IOM. The 16 IOM treatment was also grouped with the treatment vacuum sealed at 12 IOM. Finally the control and the vacuum sealed treatments at 12, 8, 6, 4, 2, and 1 IOM were all grouped together and presented the lowest R_{ct} measurements.

In this Phase it was also found that the thickness of the two tested ballistic materials were affected by the vacuum sealing applications but again UD behaved differently from KK. Figures 2 and 3 show R_{ct} values plotted against thickness for UD and KK respectively.

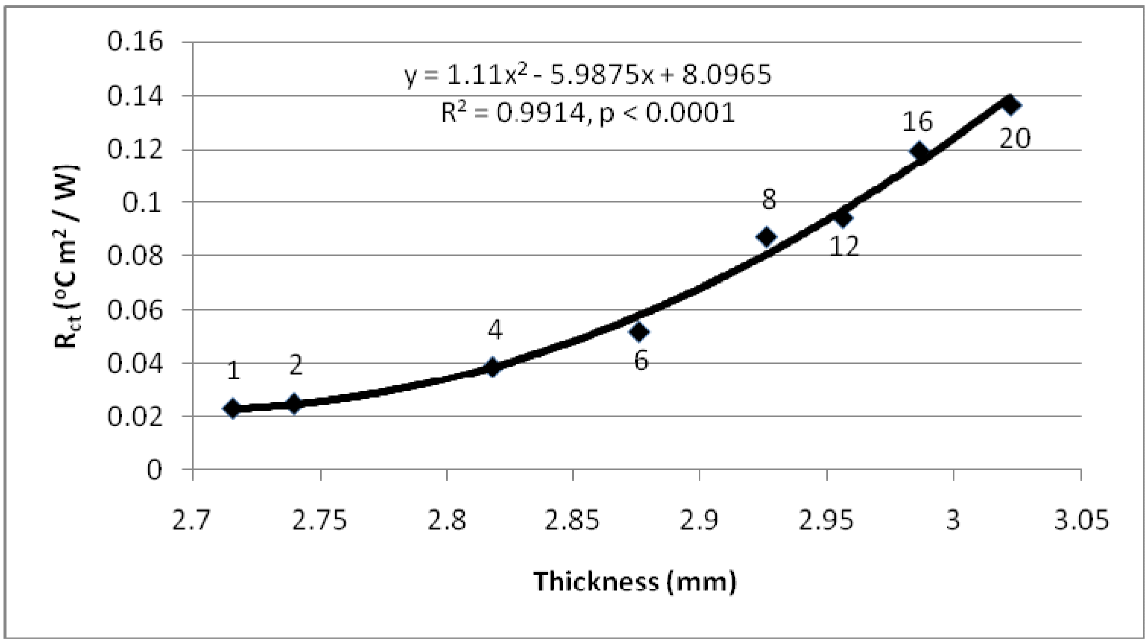

Figure 2. The relationship between thickness and R_{ct} on UD treatments

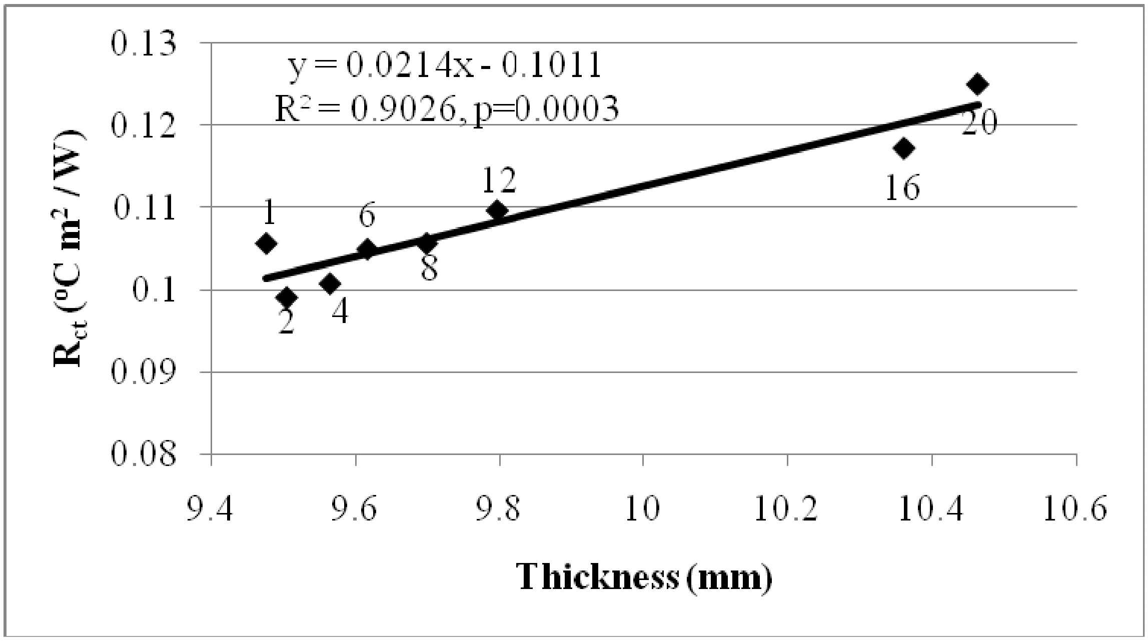

Figure 3. The relationship between thickness and R_{ct} on KK treatments

From the regression analysis for UD, thickness and R_{ct} presented a significant quadratic relationship (R^2=0.9914, p<0.0001). For KK the same attributes were correlated with a linear relationship (R^2=0.9026, p=0.0003).

During the experiment it was noticed that the KK samples fit more snugly into the pouch than the UD samples because they were thicker and the pouches were 14 inches wide (the pouches were not custom made). This may have influenced the measurements since the volume of KK samples was greater compared to UD samples, thus the net amount of air inside the vacuum sealed samples of KK was always larger than the UD samples vacuum sealed at the same vacuum level.

Another interesting observation was that as vacuum sealing was increased the samples for both ballistic materials became more rigid. So for UD and KK the most rigid samples were observed at 1 IOM vacuum sealed while in the low vacuum sealed treatments, such as 16 and 20 IOM, the samples behaved similar to the controls. However for body armors, as long as rigidness does not affect the wearer's mobility but helps to sculpt the ballistic material into the shape of the body, some rigidity can be tolerated.

It is obvious that the two ballistic materials behaved differently with the same vacuum sealing applications. However considering only R_{ct}, R_{et} and thickness observed measurements, it is difficult to make an assumption about the reason that caused the difference. R_{ct} and R_{et} are affected also by material structure and air permeability. By vacuum sealing the samples, the structure of the material remained intact however, it is expected that changes in air permeability occurred. It is known that air is less thermally conductive compared with most textile fabrics and also air permeability helps to decrease the insulation. Since UD is a non-woven film composite textile material, UD was expected to have little or no air. However KK is a woven material and is expected to have a higher air permeability compared to UD. This suggests that UD as a potential air impermeable fabric may trap air between layers causing the insulation value to increase. When the air existing between the layers of KK can escape or circulate helping to improve insulation through convection.

Given the results of the Phase I experiment it was decided that only UD would be used as the ballistic material for Phase II. Since the Phase I results indicated that the 2 IOM treatment produced a low R_{ct} and the UD samples were not very rigid, the vacuum sealing level for the vacuum sealed treatments was set at 2 IOM for Phase II.

Phase II

The purpose of this phase was to identify if vacuum sealing, enclosure material and the use of a spacer material influenced the R_{ct} and R_{et} values of test samples constructed to simulate the structure of body armor. The average R_{et} and R_{ct} values for all of the treatment combinations are presented in Tables 12 and 13 respectively.

Table 12. Mean R_{et} (Pa m^2/W) values of all tested treatment combinations after three replications.

Involved factors		Ripstop	Mesh
Not vacuum sealed	No spacer	Over 999*	Over 999
	Spacer	Over 999	26.0707
Vacuum sealed	No spacer	Over 999	Over 999
	Spacer	Over 999	25.2763

* R_{et} > 999 (Pa m^2/W) out of instrument's range.

Similarly to Phase I R_{et} results, six of the eight treatments were out of range for Phase II, suggesting that these treatments were practically non vapor permeable. Thus, no statistical analysis was conducted. However it was noticed that both treatments that provided in range measurements incorporated mesh and spacer in their construction. This finding is in agreement with the results from Su et al. (2008), which claimed that incorporating spacer material in ballistic samples reduced R_{et}. However the results of this experiment indicated that the material which encloses the spacer should be carefully chosen. Enclosing the spacer and ballistic sample with ripstop did not reduce the R_{et} value of the sample (Table 12). Enclosing the spacer and ballistic sample with mesh decreased R_{et} from out of range (R_{et}>999) to 26.0707 and 25.2763 Pa m^2/W for non-vacuum sealed and vacuum sealed ballistic material, respectively.

The R_{ct} results, which are presented in Table 13, showed that vacuum sealed ballistic samples had lower R_{ct} values compared to the non-vacuum sealed samples. These measurements are in agreement with the results from Phase I where samples vacuum sealed at 1, 2 and 4 IOM presented significantly lower R_{ct} values from the untreated ones. Also the incorporation of a spacer material appears to increase the thermal insulation in the tested samples. This is logical considering that the spacer material actually creates a thick air layer between the hotplate and the ballistic material.

Table 13. Mean R_{ct} ($^oC\ m^2/W$) values of all tested treatment combinations after three replications.

Involved factors		Ripstop	Mesh
Not vacuum sealed	No spacer	0.0654	0.0794
	Spacer	0.1450	0.1106
Vacuum sealed	No spacer	0.0515	0.0581
	Spacer	0.1258	0.1041

For the enclosure materials however no clear conclusion is apparent. When a spacer material is incorporated into the samples, ripstop enclosed samples achieved higher R_{ct} values compared to mesh enclosed samples. When the samples were constructed without a spacer, mesh enclosed samples presented higher R_{ct} values.

From the ANOVA analysis (Table 14) for R_{ct}, significant differences exist for the interaction between enclosure material and spacer ($p<0.0001$), the enclosure materials ($p<0.0276$), vacuum sealing ($p<0.0007$) and spacer ($p<0.0001$).

Table 14. ANOVA analysis for R_{ct}.

	F Value	Pr > F
Enclosure material	5.88	0.0276
Vacuum sealing	17.33	0.0007
Spacer	248.91	<.0001
Enclosure material *Vacuum sealing	0.13	0.7255
Enclosure material *Spacer	27.39	<.0001
Vacuum sealing*Spacer	0.43	0.5200
Enclosure material *Vacuum sealing*Spacer	1.88	0.1888

So without using spacer material, ripstop presented lower R_{ct} compared to mesh, while the opposite outcome arrived when spacer material was incorporated into the samples (Figure 4). This interaction may be caused by the combination of spacer and mesh. Mesh material has large openings in its structure that can potentially increase the heat loss through convection when thick air layers are present (air layers similar to the air layer that the spacer material forms). However air permeability measurements are needed to verify this claim.

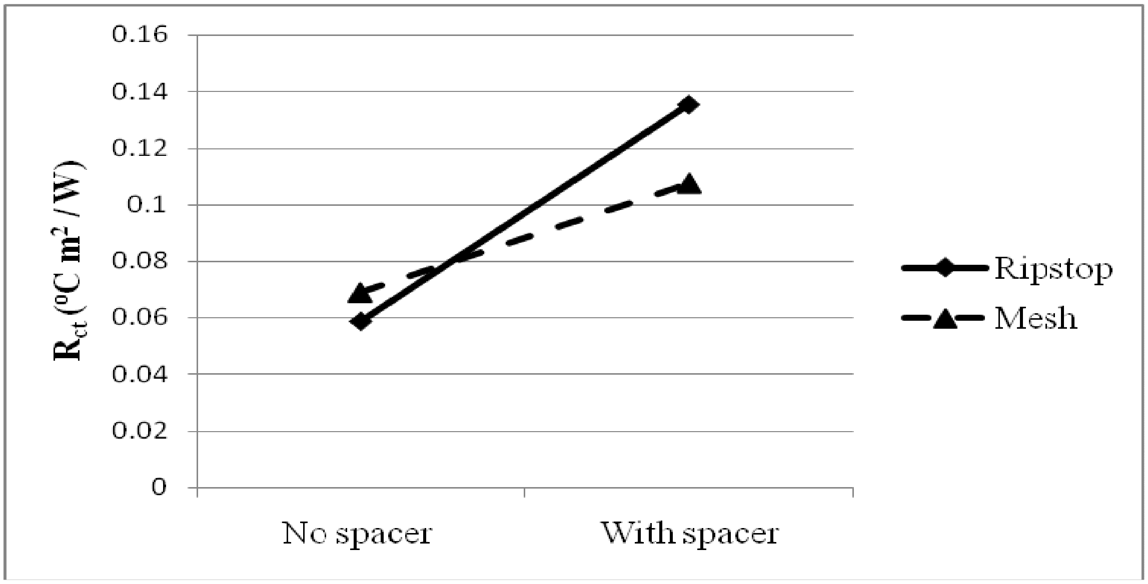

Figure 4. Interaction between type of enclosure and 3D spacer material

Also from the ANOVA analysis (Table 14) for the three independent variables it was found that mesh, vacuum sealed and without spacer present significantly lower R_{ct} values compared to ripstop, non-vacuum sealed and with spacer respectively.

Conclusions

The results from this study suggest that there is a distinction between UD and KK on how they behaved when vacuum sealing is applied to a sample packet. The R_{ct} of UD can be manipulated (within a range) either decreasing or increasing the R_{ct} by applying an intense or moderate level of vacuum sealing respectively, suggesting that the insulation provided by UD samples can be controlled by choosing an appropriate level of vacuum sealing. On the other hand for KK, the vacuum sealing application did not impact R_{ct} drastically. Even with the most intense vacuum sealing application, the obtained R_{ct} values were not significantly different from the control. Furthermore applying treatments with moderate vacuum sealing increased R_{ct} compared with the control but did not exceed the R_{ct} value from the pouch treatment.

It was concluded that removing air gaps and air layers from multiple layers of the two ballistic materials through vacuum sealing achieved a decrease in the dry thermal resistance for UD only.

From the Phase I results, it was suggested that an optimum combination for ballistic material in body armors that need to maintain a low R_{ct} value is to use UD vacuum sealed at 2 IOM. Although vacuum sealing at 1 IOM presents a lower mean in R_{ct}, it was not significantly different and it was found to be more rigid than the selected treatment. The conclusions from Phase I was based only on the R_{ct} measurements and observed rigidness. The R_{et} was not considered since all applied treatments including the control were out of range (>999) and thus no assumptions could be made.

UD demonstrated a strong quadratic relationship between the R_{ct} and thickness measurements from Phase I while KK presented a strong linear relationship between the same factors.

The findings from Phase II also indicate that the optimum construction for body armor (from the tested treatment combinations) incorporates Unidirectional Dyneema® as ballistic material vacuum sealed at 2 IOM with spacer, and mesh as the enclosure material. Although all treatment combinations without spacer incorporated in their structure presented lower R_{ct} values, the R_{et} results showed that spacer (combined with mesh) was the key factor for decreasing vapor transmission.

This study demonstrated that vacuum sealing (as a technique) has merit for decreasing the R_{ct} on multi-layered garments such as soft BAs. However, current vacuum sealing materials that can be used for applying vacuum sealing on textile materials possess other attributes, such as low life time and limited puncture resistance, rendering them problematic for application to body armor. Further research in the vacuum sealing science is needed.

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CHAPTER V

CONCLUSIONS AND IMPLICATIONS

This study introduced vacuum sealing as a tool for achieving a better understanding of how air layers and air gaps affect the thermal characteristics (such as R_{ct} and R_{et}) of ballistic material samples and how the elimination or control of the existing amount of air between the ballistic materials and the hotplate impact R_{ct} and R_{et} measurements on samples simulating the layering of body armors.

Eight null hypotheses were formed and tested, two for Phase I and six for Phase II. For Phase I the first hypothesis stated that:

$H1_0$: There is no significant effect on dry thermal resistance by vacuum sealing the ballistic materials at different levels of pressure.

This hypothesis was rejected for both ballistic materials.

The second hypothesis stated that:

$H2_0$: There is no significant effect on water-vapor resistance by vacuum sealing the ballistic materials at different levels of pressure.

This hypothesis was not tested since all obtained results were out of the instrument's range.

For Phase II the third hypothesis stated that:

$H3_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material is vacuumed sealed or not.

This hypothesis was rejected.

The fourth hypothesis stated that:

$H4_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material incorporated 3D spacer material or not.

This hypothesis was rejected.

The fifth hypothesis stated that:

$H5_0$: There is no significant effect on dry thermal resistance by layering treatment due to whether the ballistic material is enclosed in two different cover materials.

This hypothesis was rejected.

The sixth hypothesis stated that:

$H6_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material is vacuumed sealed or not.

This hypothesis was not tested since most of the obtained results were out of the instrument's range.

The seventh hypothesis stated that:

$H7_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material incorporated 3D spacer material or not.

This hypothesis was not tested since most of the obtained results were out of the instrument's range.

The eighth hypothesis stated that:

$H8_0$: There is no significant effect on water-vapor resistance by layering treatment due to whether the ballistic material is enclosed in two different cover materials.

This hypothesis was not tested since most of the obtained results were out of the instrument's range.

Discussion

It was concluded that by applying either intense or moderate vacuum sealing on UD samples, R_{ct} can be significantly decreased or increased respectively compared to the non-vacuum sealed samples. KK samples were not greatly affected by vacuum sealing applications. Only two vacuum sealed treatments (16 and 20 IOM) presented significantly higher R_{ct} measurements compared to the control, while they were not significantly different from each other. For both UD and KK it was found that thickness is related with the R_{ct} measurements in strong significant quadratic and linear relationship respectively. Considering the R_{ct} and thickness measurements as also the demonstrate rigidness of all treatments tested in this study for both ballistic materials, it was concluded that UD used as ballistic material vacuum sealed at 2 IOM is the most promising treatment for use in body armors. While from the experiment where the samples simulated the layering of body armors it was suggested that the most favorable treatment combination was the treatment that used mesh to enclose spacer material and vacuum sealed ballistic fabric. This conclusion was based on the R_{ct} and R_{et} results.

It was clear from this study that UD and KK reacted differently to vacuum sealing applications. It is believed that this phenomenon maybe caused by differences in construction and air permeability characteristics of the tested textile materials. UD, probably lacking completely a porous surface, may have formed air pockets with trapped air between its layers, increasing over three times the dry thermal resistance (15 layers of UD non-vacuum sealed had a R_{ct} equal to 0.0762 and the same number of layers vacuum sealed at 1 IOM presented a R_{ct} equal to 0.232). Possibly, since KK is a porous material, air is free to move between layers without forming static air within its structure. This observation suggests that possibly textile materials can be divided into categories based on their air permeability into non permeable and permeable, and considering this discrimination predict more accurate the dry thermal resistance of the fabric.

This study's findings suggest that vacuum sealing can decrease dry thermal resistance only in samples with multiple layers of textile materials similar to UD. However, it is considered unlikely that a decrease in R_{ct} can be achieved by vacuum sealing a single layer, since the amount of air inside the structure of a single layer material probably will be insufficient for causing noticeable impact on the R_{ct}.

Although with the right textile ballistic fabric and the appropriate vacuum sealing application, R_{ct} can be manipulated, the same does not confirmed for R_{et}. Furthermore the only conclusion made for R_{et} was that providing space via 3D spacer material, between the samples and hotplate can help to decrease the R_{et}.

During the learning process about vacuum sealing it was found that vacuum sealed material using pouches as a sealing material had a limited life time, mainly because they tended to have leaks on the sealing seams. However, choosing the right pouch or using the right vacuum sealer can help extend the period that the vacuum inside the pouch is maintained. Puncture resistance is another issue that must be addressed in order for vacuum sealed pouches to be viable. In general, the puncture resistance is positively related to pouch thickness.

A potentially beneficial side effect of the vacuum sealing is the observed rigidness that the ballistic samples demonstrated as the vacuum level was increased. It is speculated that this phenomenon may help to increase the ballistic performance of the textile ballistic material, since the projectile will spend more of its energy to bend the ballistic layers before penetrating them.

The same group of researchers currently is conducting a series of experiments trying to correlate air permeability results with R_{ct} and R_{et} values from this experiment and also testing different types of material to compare if the behavior patterns fit those observed for UD and KK. It is expected, that defining the behavioral pattern, may help predict the dry thermal and water vapor resistance of multi-layered garments. For example, probably the air that exists among the multi-layered samples of KK, increases R_{ct} but helps to dissipate an equivalent amount of heat to the environment. This should not be taken into consideration for estimating the dry thermal resistance of garments manufactured from multiple layers of KK. Another need for future study is exploring different instruments, techniques or pouches for vacuum sealing, since in this study only one type of pouch was used with a certain technique using a specific type of vacuum sealer.

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APPENDICES

Appendix A. R_{ct} measurement for all material used in both Phases

Materials	Replications	R_{ct}
1 layer UD	1^{st} replication	0.0151
	2^{nd} replication	0.0148
	3^{rd} replication	0.0145
1 layer KK	1^{st} replication	0.0075
	2^{nd} replication	0.0051
	3^{rd} replication	0.0082
Vacuum pouch	1^{st} replication	0.0415
	2^{nd} replication	0.0223
	3^{rd} replication	0.0434
Spacer	1^{st} replication	0.0656
	2^{nd} replication	0.0695
	3^{rd} replication	0.0647
Ripstop	1^{st} replication	0.0968
	2^{nd} replication	0.1071
	3^{rd} replication	0.0917
Cordura®	1^{st} replication	0.0229
	2^{nd} replication	0.0487
	3^{rd} replication	0.0180
Mesh	1^{st} replication	0.0091
	2^{nd} replication	0.0063
	3^{rd} replication	0.0052

Appendix B. R_{et} measurement for all material used in both Phases

Materials	Replications	R_{ct}
1 layer UD	1st replication	Over 999.0000
	2nd replication	Over 999.0000
	3rd replication	Over 999.0000
1 layer KK	1st replication	16.9537
	2nd replication	17.6382
	3rd replication	17.1527
Vacuum pouch	1st replication	Over 999.0000
	2nd replication	Over 999.0000
	3rd replication	Over 999.0000
Spacer	1st replication	13.1098
	2nd replication	13.7519
	3rd replication	11.4338
Ripstop	1st replication	133.7830
	2nd replication	111.8652
	3rd replication	114.9393
Cordura®	1st replication	6.1026
	2nd replication	8.4521
	3rd replication	9.1295
Mesh	1st replication	2.5011
	2nd replication	2.6473
	3rd replication	2.4611

Appendix C. All thickness measurements for all material used

Replication	1 layer UD	1 layer KK	Mesh	Cordura®	Spacer	Pouch	Ripstop
1st	0.18	0.34	0.64	0.42	6.46	0.12	0.18
2nd	0.18	0.34	0.64	0.40	6.48	0.14	0.18
3rd	0.18	0.34	0.62	0.42	6.40	0.14	0.18
4th	0.16	0.34	0.64	0.42	6.48	0.12	0.18
5th	0.16	0.34	0.64	0.42	6.42	0.14	0.18
6th	0.18	0.34	0.64	0.42	6.50	0.14	0.18
7th	0.16	0.32	0.64	0.44	6.48	0.12	0.18
8th	0.16	0.32	0.64	0.42	6.40	0.14	0.18
9th	0.18	0.34	0.64	0.42	6.30	0.14	0.18
10th	0.18	0.34	0.64	0.42	6.50	0.14	0.18
Average	0.17	0.34	0.64	0.42	6.44	0.13	0.18
Std	0.01	0.01	0.01	0.01	0.06	0.01	0.00

Appendix D. All mass per unit (weight) measurements for all material used

Replication	1 layer UD	1 layer KK	Mesh	Cordura®	Spacer	Pouch	Ripstop
1st	1.2904	2.3086*	1.7586	2.0935	4.1733*	0.7100	1.1997
2nd	1.2753	2.3453*	1.7429	2.0785	4.1127*	0.7266	1.1821
3rd	1.2943	2.3530*	1.7548	2.1197	4.1465*	0.6709	1.1942
Average	1.2867	2.3356	1.7521	2.0972	4.1442	0.7025	1.1920
Std	0.0100	0.0237	0.0082	0.0209	0.0304	0.0286	0.0090

*The instrument used for cutting the samples had difficulties to cut through KK and Spacer thus scissors were used to separate completely the sample pieces.

Appendix E. R_{ct} results for all treatments of Phase I

Treatments	Replications	Unid. Dyneema®	Kevlar® KM2®
Control	1st replication	0.0223	0.1013
	2nd replication	0.0244	0.1107
	3rd replication	0.0228	0.1048
Control + 2 layers vacuum pouch	1st replication	0.0281	0.0897
	2nd replication	0.0223	0.1021
	3rd replication	0.0243	0.1051
Vacuumed at 1 IOM	1st replication	0.0367	0.1033
	2nd replication	0.0341	0.1041
	3rd replication	0.0459	0.0948
Vacuumed at 2 IOM	1st replication	0.0557	0.1046
	2nd replication	0.0472	0.1111
	3rd replication	0.0534	0.0989
Vacuumed at 4 IOM	1st replication	0.0735	0.1085
	2nd replication	0.0848	0.1036
	3rd replication	0.1032	0.1047
Vacuumed at 6 IOM	1st replication	0.0956	0.1157
	2nd replication	0.0888	0.1011
	3rd replication	0.0984	0.1121
Vacuumed at 8 IOM	1st replication	0.1094	0.1254
	2nd replication	0.1291	0.1157
	3rd replication	0.1199	0.1105
Vacuumed at 12 IOM	1st replication	0.1462	0.1265
	2nd replication	0.1484	0.126
	3rd replication	0.1149	0.1224
Vacuumed at 16 IOM	1st replication	0.0823	0.1081
	2nd replication	0.0676	0.1051
	3rd replication	0.0786	0.0962
Vacuumed at 20 IOM	1st replication	0.1019	0.1389
	2nd replication	0.1063	0.1251
	3rd replication	0.0794	0.1449

Appendix F. R_{et} results for all treatments of Phase I

Treatments	Replications	Unid. Dyneema®	Kevlar® KM2®
Control	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Control + 2 layers vacuum pouch	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 1 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 2 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 4 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 6 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 8 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 12 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 16 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000
Vacuumed at 20 IOM	1st replication	Over 999.0000	Over 999.0000
	2nd replication	Over 999.0000	Over 999.0000
	3rd replication	Over 999.0000	Over 999.0000

Appendix G. Thickness measurements for all UD treatments from Phase I

Treatments	1	2	3	4	5	6	7	8	9	10	Average	Std
No Vacuum	2.82	2.8	2.84	2.74	2.78	2.82	2.78	2.72	2.72	2.84	2.786	0.046236
No Vacuum + bag	3.16	3.18	3.06	3.24	3.16	3.2	3.04	3.08	3.04	3.1	3.126	0.071212
1	2.76	2.76	2.7	2.7	2.72	2.66	2.72	2.7	2.68	2.76	2.716	0.035024
2	2.72	2.7	2.76	2.78	2.72	2.74	2.64	2.78	2.76	2.8	2.74	0.04714
4	2.82	2.82	2.82	2.86	2.84	2.76	2.76	2.8	2.86	2.84	2.818	0.035839
6	2.9	2.88	2.84	2.88	2.9	2.8	2.86	2.88	2.94	2.88	2.876	0.037476
8	2.9	2.92	2.96	2.96	2.94	2.96	2.88	2.9	2.96	2.88	2.926	0.034059
12	2.98	3	2.92	2.96	2.98	2.92	2.94	2.96	2.94	2.96	2.956	0.026331
16	2.98	2.96	2.94	2.98	3	3.04	2.96	3	2.96	3.04	2.986	0.034059
20	3.08	2.96	3.02	3.06	3	3	2.98	3.06	3.04	3.02	3.022	0.038239

Appendix H. Thickness measurements for all KK treatments from Phase I

Treatments	1	2	3	4	5	6	7	8	9	10	Average	Std
No Vacuum	10.34	10.56	10.46	10.38	10.4	10.36	10.44	10.44	10.38	10.32	10.408	0.070048
No Vacuum + bag	10.74	10.84	10.56	10.64	10.82	10.7	10.8	10.74	10.8	10.72	10.736	0.08682
1	9.48	9.38	9.4	9.44	9.46	9.52	9.54	9.48	9.54	9.52	9.476	0.056411
2	9.5	9.34	9.46	9.42	9.46	9.64	9.56	9.48	9.62	9.56	9.504	0.09228
4	9.64	9.62	9.52	9.56	9.58	9.5	9.54	9.48	9.56	9.64	9.564	0.056411
6	9.54	9.6	9.58	9.62	9.62	9.66	9.74	9.62	9.52	9.66	9.616	0.063105
8	9.66	9.72	9.64	9.68	9.76	9.7	9.76	9.68	9.66	9.72	9.698	0.04158
12	9.7	9.78	9.74	9.72	9.64	9.82	9.92	9.98	9.76	9.9	9.796	0.107827
16	10.44	10.38	10.34	10.36	10.28	10.26	10.36	10.34	10.38	10.48	10.362	0.065625
20	10.54	10.6	10.4	10.68	10.34	10.44	10.48	10.38	10.38	10.4	10.464	0.110272

Appendix I. R_{ct} measurement for all Phase II treatments

		Replications	Ripstop	Mesh
No vacuum	No spacer	1st	0.0724	0.0711
		2nd	0.0678	0.0783
		3rd	0.0561	0.0889
	Spacer	1st	0.1583	0.1134
		2nd	0.1413	0.1048
		3rd	0.1353	0.1136
Vacuum	No spacer	1st	0.0555	0.0545
		2nd	0.0377	0.0615
		3rd	0.0613	0.0582
	Spacer	1st	0.1155	0.0954
		2nd	0.1350	0.1055
		3rd	0.1269	0.1114

Appendix J. R_{et} measurement for all Phase II treatments

		Replications	Ripstop	Mesh
No vacuum	No spacer	1st	Over 999	Over 999
		2nd	Over 999	Over 999
		3rd	Over 999	Over 999
	Spacer	1st	Over 999	18.9868
		2nd	Over 999	23.6032
		3rd	Over 999	35.6220
Vacuum	No spacer	1st	Over 999	Over 999
		2nd	Over 999	Over 999
		3rd	Over 999	Over 999
	Spacer	1st	Over 999	32.1031
		2nd	Over 999	24.0373
		3rd	Over 999	19.6885

VITA

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Scope and Method of Study: This study investigated the potential for a proof of concept for using vacuum sealing to decrease dry (R_{ct}) and water vapor (R_{et}) resistance of multi-layered ballistic materials used in soft body armors. Phase I: Multiple layers of two ballistic materials were vacuum sealed and tested in a sweating guarded hotplate. Phase II: Test samples simulating soft body armors layering were formed using the most promising ballistic material and tested with the same apparatus and methods. Independent variables were type of enclosure material, and use or non-use of 3D spacer material and vacuum sealing.

Findings and Conclusions: Phase I: Both ballistic materials presented significant differences among the different vacuum sealing applications. R_{ct} for both Kevlar® KM2® (KK) and Unidirectional Dyneema® (UD) can be significantly increased compared to the control by using low vacuum sealing treatments. However, with intense vacuum sealing applications only UD demonstrated significantly lower R_{ct} values from the control. KK and UD presented a strong linear and quadratic relationship respectively, when R_{ct} was plotted against thickness. All R_{et} measurements were out of instrument's range. Phase I results showed that UD vacuum sealed at 2 IOM pressure was the most promising treatment for further testing in Phase II. Phase II used test samples simulated body armor layering. Mesh, no spacer and vacuum sealed UD had a significantly lower R_{ct} compared to ripstop, with spacer and non vacuum sealed UD respectively. Based on the R_{ct} and R_{et} measurements, the results suggest that the most promising configuration for soft body armor includes: vacuum sealed UD with spacer placed as the layer closest to the skin and the package enclosed with mesh. Overall vacuum sealing applications of ballistic materials had merit for incorporation in the construction of soft body armors.

ADVISER'S APPROVAL: Dr. Donna Branson