Evaluating the thermophysiological comfort properties of wet fabrics in winter clothing

by

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ABSTRACT

When physical activity and sweating cease in cold environments, it is imperative that the fabrics near the skin return to a dry state as quickly as possible in order to maintain comfort and avoid excessive heat loss. A variety of moisture management fabrics developed for underwear and jacket linings were studied to understand how their finishing treatments, fibre additives, or fibre morphology influenced the thermal properties of winter jackets. Dry and wet underwear fabrics were tested alone and in combination with three-layer jacket systems (i.e. lining, insulation, & shell) on an advanced sweating guarded hot plate in cold ambient conditions (6°C). The wet insulation values and drying behaviour of the fabrics and fabric systems were measured and compared. Fibre content, finishing treatment, and use of hydrophobic linings had a significant effect on wet insulation values. A significant interaction effect between the underwear and lining fabrics was noted on the drying time of cold weather fabric systems and liquid moisture management properties of two-layer composites (i.e. underwear and lining). The air permeability of the lining fabric had a significant effect on the drying time of the cold weather fabric systems.

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An egoist boasts about having learned a lot;
a wise man is saddened for not having learned more.
~ Aristotle (384 – 322 BC)

Life is like riding a bicycle. To keep your balance, you must keep moving.
~ Albert Einstein (1879 – 1955)

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CHAPTER 1: INTRODUCTION

The emergence of new fibres and innovative fabrics has led to an increased demand for highly functional clothing that offers users the ability to maintain thermophysiological comfort in even the most extreme conditions (Chan & Muran, 2010). Thermophysiological comfort relates to the thermal and wetness sensations experienced by an individual as heat and moisture are transported through their clothing to the environment (Li, 2001, p.2). Maintaining thermophysiological comfort becomes increasingly difficult to accomplish as environments deviate from normal climatic conditions. Thus, designing comfortable clothing for cold weather environments poses a number of challenges for fabric and garment manufacturers. Resting in cold weather requires clothing to reduce the transfer of heat from the body to the environment in order to maintain a comfortable body temperature. However, during physical activity, a large quantity of heat must be dissipated through the clothing to prevent excessive heat storage within the body. The human body uses perspiration to dissipate heat. To achieve optimal comfort in cold environments, clothing must provide resistance to heat loss while allowing perspiration to escape. The properties of the clothing an individual is wearing will greatly influence the transfer of heat and moisture generated during physical activity (Das & Alagirusamy, 2010). Problems occur when exercising in the cold because body temperatures rise with increasing metabolic rates, triggering a human thermoregulatory response to increase perspiration rates in order to return to normal body temperatures. Perspiration accumulates within the clothing system during the period of physical activity, reducing the thermal insulation of the clothing, and causing increased rates of heat loss (Nielsen, 1994). The increased heat loss may be desirable during the period of physical activity to cool the body, but is problematic once activity ceases. Moisture significantly increases the thermal conductivity of fabrics so that energy is lost to the environment more rapidly when clothing is damp or wet (Schneider, Hoschke, & Goldsmid, 1992). Thus, the presence of moisture within clothing causes rapid heat loss when activity ceases in cold environments. Increased rates of heat loss can cause discomfort, may lead to hypothermia, and reduces the duration of time that can be spent in a cold environment. The risk is further increased when materials with poor moisture transport properties are directly against the skin. A study conducted by Nielsen (1994) at 10°C demonstrated that more energy was required by a thermal manikin to maintain a normal body temperature (35°C) as water accumulated in fabric layers closest to the manikin surface. While hypothermia is rare in occupational settings, it should be noted that general discomfort has been closely associated with an increased risk of accidents and injuries (Makinen & Hassi, 2009). This is because cold exposure can reduce cognitive performance, increase physical demands, and impair psychomotor skills (Makinen & Hassi, 2009). Improving the comfort of cold weather clothing is an important issue to address since many Canadians are required to work outdoors all year round and are vulnerable to the risks of freezing tissue and hypothermia during winter months. Although standards for predicting cold stress continue to be developed, the current methods of describing heat and moisture transfer through cold weather clothing systems in cold environments are still inadequate (Makinen, 2009). Research is needed to provide a greater understanding of the interaction between clothing layers and their influence on the movement of heat and moisture (perspiration) through clothing in cold weather.

Statement of Problem and Justification

Many recent clothing developments have focused on optimizing moisture management as a means of improving thermophysiological comfort. Moisture management is a term the textile industry has adopted to describe the inherent or engineered transport of water vapour or aqueous liquids through textiles (AATCC & ASTM, 2008). Designing moisture management clothing requires consideration of the environment in which it will be worn and the quantity of perspiration to be expected. Variability in sweating rates among individuals can be attributed to differences in physiology, acclimatization, fitness, types of clothing worn, evaporative efficiency of the clothing system and environmental conditions (Candas, Libert & Vogt, 1979; Guyton & Hall, 1996; Havenith et al., 2008). A normal person can release sweat at a rate anywhere from one to three litres per hour (Guyton & Hall, 1996). The largest proportion of this sweat is generated by the torso and forehead (Smith & Havenith, 2011). Since the torso is of higher surface area, the focus of many moisture management garments is on the effective transport of high quantities of moisture away from the upper body to dissipate excess heat and maintain comfort. With a sweating rate of one litre per hour, liquid and vapour sweat move into the void spaces of fabrics via wetting, wicking, and diffusion mechanisms (Das, Das, Kothari, Fanguerio & Araujo, 2007; Hsieh, 1995; Kissa, 1996). Eventually fabrics reach a point when no further liquid can be absorbed and all void space in the fabric is filled with liquid; whereby the fabric is said to be saturated (Ghali, Jones, & Tracy, 1994). Note that some fabrics (i.e. mesh) cannot reach complete saturation because the spaces between fibres or yarns are too large to retain moisture. When a fabric is saturated, liquid transport through fabrics via wicking can no longer occur due to the loss in capillary pressure (Das et al., 2007; Ghali et al., 1994; Hsieh, 1995). Thus, moisture must evaporate from void spaces within the fabric before liquid moisture transport can resume. As the rate of moisture vapour transmission through air is much greater than the rate of vapour transport into and out of fibres, keeping void spaces within a fabric free of liquid water is critical for maintaining high rates of moisture transport via evaporation

(Adler & Walsh, 1984). When physical activity and sweating cease, it is imperative that the fabrics near the skin return to a dry state as quickly as possible to maintain comfort and avoid excessive heat loss. If wet fabric remains on the skin, the excessive heat loss causes discomfort and people experience a thermal sensation referred to as "post exercise chill" (Bakkevig & Nielsen, 1995). Thus, the moisture management properties of fabric layers worn in close proximity to the skin (i.e. undergarments and jacket lining) should be important for transferring and keeping moisture away from the body when perspiring. A variety of moisture management fabrics developed for underwear and jacket linings were investigated to determine their ability to maintain a dry layer of fabric next to the skin in cold conditions.

Objectives

The objectives of the study were to:

1. Determine the thermal insulation of selected underwear fabrics with varying moisture management properties when tested dry and after wetting with water;
2. Determine the effect of wet underwear fabric on the thermal insulation of four cold weather fabric systems;
3. Determine the time for wet underwear fabric to return to a dry state when tested as single layers of fabric and when tested under four cold weather fabric systems;
4. Determine the drying rate of wet underwear fabrics when tested as single layers of fabric and when tested under four cold weather fabric systems;
5. Determine the liquid moisture transport properties of underwear and lining fabrics when tested as two-layer composites.

Null Hypotheses

To meet objectives 1 to 5, the following null hypotheses were tested:

1. There is no significant difference in the thermal resistance of selected underwear fabrics with varying moisture management properties when tested as:
    a. single fabric layers
        i. dry
        ii. wet
    b. first fabric layers in cold weather fabric systems
        i. dry
        ii. wet

2. There is no significant difference in the drying time and drying rate of selected underwear fabrics with varying moisture management properties when tested as:
    a. single fabric layers
    b. first fabric layers in cold weather fabric systems
3. There is no significant difference in the liquid moisture transport properties of underwear and lining fabrics when tested as two-layer composites.

Limitations and Delimitations

The limitations and delimitations of this research include:

1. The fabric systems chosen for this research were limited to four fabric layers which included underwear, lining, insulation, and shell fabric.
2. Effects of garment design were not considered, as full-scale testing on garments was not included in this study.
3. Bench scale testing was used to predict performance during actual wear.
4. The ambient temperature for testing was set to 6° C.
5. The quantity of moisture applied to each underwear fabric was the same for each test and was not based on absorbed values of liquid sweat in use.
6. The relative humidity of the cold environment could not be controlled due to the limitations of the environmental chamber. Relative humidity varied, but was recorded during testing.

CHAPTER 1: INTRODUCTION

Definitions

Activated carbon polyester: polyester fibres that contain activated carbon particles which are incorporated during the extrusion process (Splendore, Dotti, Cravello, & Ferri, 2010).

Air permeability: “the number of cubic centimetres of air passing through one square centimetre of fabric per second when the differential between the air pressures on opposite sides of the fabric is equal to 12.7 mm of water” (CGSB, 1997, p. 1).

Cold environment: climatic conditions under which the body heat exchange is just equal to or too great for heat balance. It is generally defined as environments with ambient temperatures below 10°C (ISO 11079, 2007, p. 12).

Cold weather fabric system: a combination of fabrics providing insulation against heat loss in cold environments. For this research, the system is defined by four fabric layers consisting of underwear, lining, insulation, and shell.

Cold stress: the total amount of cooling power an environment exerts on the human body (Holmér, 1994).

Comfort: “a pleasant state of physiological, psychological, neurophysiological, and physical harmony between a human being and the environment” (Slater, 1985, p.4).

Drying time: “the time it takes for a specified amount of liquid to evaporate from a textile under controlled testing conditions” (AATCC, 2012, p. 401).

Drying rate: the average change in mass per unit area per unit time as liquid evaporates from a textile.

Enthalpy of vaporization: the amount of energy required to change a substance from a liquid to a gas; expressed in kilojoules per kilogram of the substance (kJ/kg) (ASHRAE, 2005).

Heat flux: thermal intensity indicated by the amount of energy transmitted per unit area, which may consist of one or more conductive, convective, and radiant components. It is typically expressed in watts per meter squared (ASTM D123, 2009 & ISO 11092, 1993).

Heat transfer: the exchange of thermal energy between two bodies where a temperature difference exists (Cornwell, 1977).

Moisture management: the inherent or engineered transport of water vapour or aqueous liquids through textiles (AATCC & ASTM, 2008).

Moisture regain: “the amount of moisture in a material determined under prescribed conditions and expressed as a percentage of the mass of the moisture-free material” (ASTM, 2009, p. 33).

Porosity: “the ratio of the volume of air or void contained within the boundaries of a material to the total volume (solid matter plus air or void) expressed as a percentage” (ASTM, 2009, p. 37).

Saturated: the point when no further liquid can be absorbed and all void space in the fabric is filled with liquid; it can also be referred to as complete or 100% saturation (Ghali et al., 1994)

Saturation: the fraction of the void space within a fabric that is filled with liquid and is often expressed as a percentage (Ghali et al., 1994).

Sorption: the process of taking up or holding moisture by means of adsorption, absorption, or both (ASTM, 2009).

Absorption: a process in which moisture is taken up or bonds with the internal structure of fibres (ASTM, 2009).

Adsorption: the process in which moisture is taken up or held on the surface of fibres (ASTM, 2009).

Desorption: the process in which moisture is released from a material (ASTM, 2009).

Thermal resistance: a measure of the dry heat flux across a given area in response to a steady applied temperature gradient and is expressed in square metres degrees Celsius per watt (m^2C/W) (ISO, 1993). It is used to provide a measure of the thermal insulation a fabric or fabric system can offer.

Thermophysiological comfort : when a person experiences a comfortable state of thermal and wetness sensations as a result of the heat and moisture that is exchanged between an individual and their environment (Li, 2001, p.2). It can also be referred to as thermal comfort.

Wetting: the initial spreading and adhesion of liquid into the air-fibre spaces of a fabric (Das et al., 2007).

Wicking: the process of liquid transport through a porous system by capillary pressure (Kissa, 1996).

Wet heat flux: the average amount of energy transmitted per unit area when a fabric is wet with liquid moisture. For the purpose of this research, this refers to the average heat flux when a fabric is wet with 25 grams of moisture.

CHAPTER 2: REVIEW OF LITERATURE

Exposure to cold weather is inevitable for most Canadians. While avoiding prolonged cold exposure is possible, many outdoor occupations and activities in Canada require humans to be exposed to the risks and hazards of cold weather for long periods of time. Construction workers, hydro and telecommunication linemen, police officers, fire fighters, emergency response workers, military personnel, transportation workers, food storage workers, fishermen, and outdoor enthusiasts are all examples of people who are vulnerable to the risks of cold weather in Canada (CCOHS, 2011). Assessing the stress caused by cold weather is therefore critical to managing the risks relevant to many Canadian occupations and activities.

The following literature review provides an overview of research relevant to designing effective clothing systems to humans in cold environments. Physiological responses and pathways for heat loss from the human body to cold environments are first examined to understand the risks and hazards of being in cold weather. Research relating to human comfort is then reviewed to understand what factors affect the satisfaction people have with their clothing. Mechanisms of heat transfer and the influence of clothing properties are then reviewed in a section entitled thermal insulation in cold weather. Following this section, mechanisms of moisture transport and the influence of clothing properties are reviewed to understand how to effectively manage moisture in cold weather.

Cold weather hazards

Cold weather has been defined as conditions in which larger than normal heat losses can be expected (Holmér, 2005). It is common for people to use ambient temperature to predict the level of protection they will require to prevent heat loss in cold weather. In fact, CCOHS (Canadian Centre for Occupational Health and Safety) states that some Canadian occupational health and safety regulations specify a minimum temperature for indoor work environments, but no such limits exist for outdoor work in cold weather (CCOHS, 2011). Ambient temperature is a poor predictor of the amount of protection required as there are many additional factors that can amplify or reduce heat loss from the human body to the environment. Air temperature, air velocity, relative humidity, radiant heat, metabolic rate and clothing are all important factors that must be analyzed when determining the magnitude of cold stress one must endure (Holmér, 1993). Cold stress can therefore be defined as the total cooling power that an environment exerts on the human body (Holmér, 1994). The impact of cold stress on the human body is highly dependent on the type of cooling an individual encounters. The types of cooling can be classified into two main categories; whole body cooling and local cooling.

Whole body cooling

Heat loss from the core or torso of the human body is referred to as whole body cooling (Makinen, 2007). There are two main ways the human thermoregulatory system reacts in order to prevent whole body cooling. The first is vasoconstriction which involves the constriction or reduced diameter of blood vessels as a means to decrease blood flow to the skin and conductive pathways for heat loss (Stocks, Taylor, Tipton, & Greenleaf, 2004). Blood flow in the extremities is reduced by vasoconstriction in order to delay the cooling of the body core at the expense of cooling the extremities (Holmér, 1993). The second human thermoregulatory reaction is shivering which is a form of involuntary muscle contraction that generates heat in an attempt to maintain thermal balance (Stocks et al., 2004). Research has found shivering can be initiated by local cooling, but it is significantly more pronounced and vigorous when core temperature decreases (Stocks et al., 2004).

In a worst-case scenario of whole body cooling, a person enters a state of hypothermia. This occurs when cold stress is severe enough to drop the core temperature of the human body below 35°C (Stocks et al., 2004). Core temperatures of 33°C – 35°C are associated with symptoms of confusion, disorientation, amnesia, and violent shivering; and gradually a person will enter a state of exhaustion, fatigue, neuromuscular incapacity, unconsciousness, slow respiration, and reduced circulation as core temperatures further decline (Holmér, 1993; Stocks et al., 2004). While hypothermia is rare in occupational settings, it should be noted that sub-clinical hypothermia (36°C core temperature) and general discomfort have been associated with an increased risk of accidents and injuries (Makinen, 2009). Cold exposure can contribute to an increased risk of accidents and injuries by reducing cognitive performance, increasing physical demands, and impairing psychomotor skills (Makinen & Hassi, 2009). Research by Hoffman (2001) has demonstrated that cold stress can significantly influence cognitive ability in terms of memory, concentration, response time, and general intelligence. For occupational or leisure activities requiring acute cognitive abilities, it is essential that precautionary measures are taken to maintain psychological performance in order to reduce the risk of accidents or injuries.

Local cooling

Local cooling can refer to extremity cooling, skin cooling by wind, skin cooling by contact, and airway cooling (Holmér, 2009). Common injuries due to local cooling include frostbite and numbness.

Frostbite refers to the formation of ice crystals within the skin causing tissue to freeze, while numbness refers to neurovascular damage without the freezing of tissue (Stocks et al., 2004).

Extremities are particularly vulnerable to heat loss because of their high surface area to mass ratio (Kulane, 2009). In particular, extremities such as hands and feet have very low metabolic heat production and rely on warm blood from the core to be circulated to maintain thermal balance (Kulane, 2009). This means inhibiting cooling of extremities requires both a prevention of skin cooling and the maintenance of a steady core temperature in order to avoid injury. For these reasons, injuries such as frostbite or numbness are more likely to occur on extremities (Dolez & Vu-khanh, 2009).

Skin cooling by wind is often assessed by using the Wind Chill Index (WCI) as a guide to determine the risk of freezing tissue of bare skin exposed to wind (Osczevski & Bluestein, 2005). The WCI is often communicated through weather forecasts to provide guidance to the general public on the risks of cold weather. The cooling power of wind can pose significant danger to people in cold weather environments as seen in the wind chill chart presented in Table 1.

Table 1. Wind Chill Chart (CCOHS, 2011).

***WIND CHILL CHART**										
Wind Speed		Ambient Temperature (°C)								
(km/h)	(mph)	4	-1	-7	-12	-18	-23	-29	-34	-40
		Equivalent Wind Chill Temperature (°C)								
0	0	4	-1	-7	-12	-18	-23	-29	-34	-40
8	5	3	-3	-9	-14	-21	-26	-32	-38	-44
16	10	-2	-9	-16	-23	-30	-35	-43	-50	-57
24	15	-6	-13	-20	-28	-36	-43	-50	-58	-65
32	20	-8	-16	-23	-32	-39	-47	-55	-63	-71
40	25	-9	-18	-26	-34	-42	-51	-59	-67	-76
48	30	-16	-19	-22	-36	-44	-53	-62	-70	-78
56	35	-11	-20	-29	-37	-46	-55	-63	-72	-81
64	40	-12	-21	-29	-38	-47	-56	-65	-73	-82
Comments:		**Little danger** in less than one hour of exposure of dry skin			**Danger** – exposed flesh freezes within one minute			**Great danger** – flesh may freeze within 30 seconds		

*data provided to CCOHS by ACGIH (American Conference of Industrial Hygienists)

Skin cooling by contact describes the touching of cold surfaces with bare skin which can cause high rates of heat loss leading to cold injuries (Holmér, 1993). Contact cooling typically occurs in the hands and is known to reduce tactile sensitivity and manual dexterity. This significantly influences the ability of workers to perform manual tasks in a safe and efficient manner (Heus, Hein, and Havenith, 1995). Prevention of contact cooling is necessary to maintain worker performance and reduce risk of injury in cold environments.

Cooling of the respiratory tract can cause intense respiratory distress when large volumes of cold air is inhaled (Holmér, 2009). Airway cooling can account for a loss of 15-20% of the total amount of heat produced by the body (Holmér, 2005). Covering the nose and mouth with an insulating material (i.e. balaclava) can reduce the intensity of airway cooling by warming the cold environmental air before it is inhaled (Holmér, 2009). Covering airways and avoiding intense physical activity are preventative strategies that can be used to avoid excessive heat loss and respiratory distress in cold environments.

Human comfort

Comfort is a challenging concept to define and measure because it is dependent on individual's perceptions of their experiences. Slater (1985) has defined comfort as, "a pleasant state of physiological, psychological, neurophysiological, and physical harmony between a human being and the environment" (p.4). Thus, clothing comfort can be described as human satisfaction with their clothing under any particular condition. Fourt and Hollies (1970) note that under critical or extreme conditions, it may be impossible to achieve any sense of "comfort" and clothing may be assessed only in terms of "tolerance time" (Fourt & Hollies, 1970, p.5). Aspects of clothing comfort can be divided into sensorial, body movement, and thermophysiological comfort. Each aspect is important to consider as they all contribute to the overall perception of human comfort.

Sensorial comfort

Sensorial comfort refers to the neural process that occurs when textiles come into contact with the skin (Li, 2001). Sensory receptors on the skin surface react to external stimuli, which translate into an individual's perception of comfort. Sensorial comfort is largely determined by tactile sensations, which are derived from the texture and feel of fabrics. Tactile sensations can be influenced by a number of factors including the nature of the fibres, the pressure exerted by clothing, a materials affinity for moisture, and its thermal properties.

Wang, Zhang, Postle, & Phillips (2003) found tactile sensations are significantly influenced by fabric properties such as prickliness, roughness, scratchiness, and hairiness. Their research investigated the comfort and tactile sensations of shirts that varied in fibre content through use of wear trials and forearm tests at high and low activity levels. Fabrics containing wool were considered less comfortable than silk, polyester, cotton, and cotton blend fabrics at both levels of activity. The prickliness of wool fibres was identified as the main property causing discomfort. Thus, comfort was negatively correlated with feelings of prickliness and roughness, as participants preferred fabrics with smoother surface properties or softer fibres. The authors further noted that sweating caused a decrease in comfort for all fabrics, but wool and wool blend fabrics were still identified as being the most uncomfortable (Wang et al., 2003). However, the reasons for discomfort varied between fibre types. As previously stated, discomfort in wool samples was attributed to the prickliness, where greater prickliness was felt as the fibre diameter and quantity of sweat increased. Using very fine wool fibres, applying finishing treatments (i.e. chlorination or silicone), or engineering fabric so wool fibres are not in direct contact with the skin are strategies that have been developed to reduce prickliness and improve comfort of wool clothing (Laing, 2009). For polyester, the decrease in comfort was a result of the fabric sticking to the skin and increasing friction between fabric and skin. This finding is in good agreement with a number of authors who note increased friction between the skin and fabric negatively influences comfort (Derler, Schrade, & Gerhardt, 2007; Kenins, 1994; Rossi, 2009; Wang et al., 2003). Additionally, decreasing friction between the skin and fabric is essential for reducing skin injuries such as irritations, abrasions, and blisters which occur due to increased shear forces and cyclic mechanical loads (Derler et al., 2007). The prevalence of such skin injuries will negatively influence perceptions of comfort. Kenins (1994) measured differences in skin-to-fabric friction between various fabrics at different levels of skin wetness. Fabrics varied in fibre content, yarn diameter, hairiness, weight, and treatment (i.e. silicone) in an effort to understand which material properties significantly influence skin-to-fabric friction. Results demonstrated that keeping the skin dry was the most effective strategy for preventing an increase in fabric-to-skin friction, regardless of differences in fabric properties. However, Kenins (1994) also noted that increased hairiness, low fabric weight, and use of hygroscopic fibres provided minor decreases in fabric-to-skin friction under wet conditions. An increase in friction was attributed to a thin film of water developing on the surface of the skin which increased the surface tension between the fabric and skin (Kenins, 1994; Wolfram, 1983). Derler et al. (2007) conducted similar experiments as Kenins (1994) to examine skin-to-fabric friction, except the quantity of moisture applied to the fabric was controlled rather than controlling moisture on the skin. They found friction increased with moisture content and became constant once the fabric was saturated. The authors did not provide any further details on why friction increased with increasing moisture content. It is possible the increase in water content increased the weight and adhesion of moisture between the skin and fabric, leading to greater frictional force. However, Derler et al. (1994) did not state this conclusion. It is worth noting that fabric treatments and constructions have specifically been developed to provide one-way moisture transport properties that remove liquid perspiration from the skin and transport it to the outermost surface of a fabric (Lee, 2002; Li, Yeung, Kwok, & Xu, 2004; Rearick & Anderson, 2006; Stockton & Ware, 2010; Yeh, 2002). These inventions have become widespread in the textile industry and claim to provide a dry inner surface which results in reduced cling and dampness sensations. While no research or literature could be located to provide evidence that these moisture management technologies reduce friction between the skin and fabric, it is highly likely they would provide a reduction in fabric cling (i.e sticking to the skin).

Thermal sensations are another important aspect of sensorial comfort. Thermal sensations refer to the warmth or coolness experienced through contact with a material (Li, 2001). People often use the initial touch of a material to determine whether or not the garment is suitable for their intended end use. As intermittent contact between the fabric and skin during wear can have an effect on thermal flow, the initial touch of fabric can explain thermal comfort to some extent (Fourt & Hollies, 1970, p.46). However, research has demonstrated that touching fabrics with the hand does not account for all aspects of wear comfort and is not a reliable measure of wear comfort (Kenins, 1994). Despite contradictory evidence, initial touch of fabrics is often used by consumers to predict how comfortable a garment will be during actual use. Since initial touch influences consumer purchasing decisions, significant research contributions have been made to understand what material properties influence these thermal sensations (Pac, Bueno, Renner, & Kasmi, 2001; Schneider & Holcombe, 1991; Yoneda & Kawabata, 1983). Notably, all of the research identifies heat transfer via conduction as being the most important variable for determining warmth and coolness sensations. Conduction refers to the transfer of heat between objects that come in contact and are nonhomogeneous in temperature (Cornwell, 1977). Energy in the form of heat will flow from high temperature objects to low temperature objects until thermal equilibrium has been reached. Yoneda & Kawabata (1983) developed an apparatus called the “Thermolabo” to measure warm or cool sensations experienced when fabrics first touch the skin. The device proved to be successful in providing an objective measurement of thermal sensations by recording transient heat flow. The device consists of a small guarded hot plate that measures power loss within the first 0.2 – 0.8 seconds when the fabric comes in contact with the plate; simulating the initial touch of fabric experienced by humans. Yoneda & Kawabata’s (1983) research and apparatus provided the basis for subsequent experiments that measured thermal sensations. Schneider & Holcombe (1991) and Pac et al. (2001) both built equipment based on Yoneda and Kawabata's (1983) experiments to examine fabric properties that contribute to sensations of warmth or coolness. Both studies confirmed that surface hairiness had the greatest contribution to thermal sensations, where brushed fabrics and hairy yarns provided the greatest warmth sensation. The warmer sensations were attributed to trapped air between emergent fibres on the rough fabric surface. This results in a higher proportion of air in contact with the skin in comparison to smooth fabrics (Pac et al., 2001). The thermal conductivity of air is very low in comparison to fibres, thus less heat is transferred between the skin and fabric which results in warmer sensations. Comparatively, smooth yarns provided the greatest cooling sensation. Schneider & Holcombe (1991) did not acknowledge the influence of fibre type in their analysis, even though many of their fabrics were composed of different fibres. Pac et al. (2001) acknowledges differences between fibres, but was limited to the two different types of cotton used in their study. Pima cotton was found to be cooler than Kaba cotton due to the longer and smoother fibres that provided greater contact area. Lastly, two-ply yarns in Pac et al.'s (2001) study produced a smoother fabric surface and resulted in greater cooling sensations than single yarns. Research demonstrates that the characteristics of the surface in contact with the skin significantly affect thermal sensations.

Body movement comfort

Body movement comfort refers to the ability of a textile to allow freedom of movement, reduce physical burdens, and allow body shaping (Li, 2001). Clothing worn in cold weather is significantly heavier and bulkier than clothing worn in warm weather. The increased bulkiness and additional layers of clothing lead to increased energy expenditure (Rintämaki, 2007). A state of fatigue can be reached more quickly as the energy required to maintain physical performance in cold weather is more demanding than in warm weather clothing (Rintämaki, 2007). Lowering friction between layers is essential for improving body movement comfort and should be considered for cold weather garments (Rintämaki, 2007). The fit of garments and use of stretch fabrics are other considerations that play an important role in body movement comfort in terms of reducing the amount of pressure at the skin surface (Li, 2001).

Thermophysiological comfort

Thermophysiological comfort, often termed thermal comfort, refers to the attainment of comfort in terms of thermal and wetness sensations experienced by an individual (Li, 2001, p. 2). The exchange of heat and moisture between the human body and the environment through clothing is what determines thermophysiological comfort. As environments become more extreme (i.e. high velocity winds, subzero temperatures, rain, snow, etc.), it becomes increasingly difficult to achieve thermophysiological comfort. Skin and core temperature must be kept within narrow limits in order for a person to feel comfortable. Many physiological studies suggest core temperature should be 37 ± 0.5°C and skin should be within the limits of 32 to 35.5°C to maintain thermophysiological comfort (Fan, 2009). However, scientists have noted there is a large variation in sensitivity of human skin as different parts of the body respond differently to cold, making it difficult to validate such generalizations about local skin temperatures (Hyun, 1989; Li, Wang, Zhang, & Barker, 2005). Li et al. (2005) conducted a wear trial with a uniquely constructed garment that allowed the researchers to randomly expose specific body parts to the ambient environment (20.5 ± 0.5°C and 50 ± 10% relative humidity). Skin temperatures and an assessment of comfort were recorded when each body part was exposed. The study concluded that the various body parts responded differently in terms of psychological sensitivity and local skin temperature changes. The torso was found to be the most sensitive to cold, then the thighs, upper limbs, and calves. The closer the body part was to the torso, the more sensitive it was to cold stimulation. Thus, people can feel comfortable even if there is a large variation in skin temperature among their body parts under the clothing. This understanding emphasizes the complexity of thermal comfort and makes it difficult to pinpoint objective parameters for measuring comfort.

Achieving thermal comfort is also complicated by physical activity, where a large quantity of heat must be dissipated through the clothing to prevent excessive heat storage within the body. Problems occur when exercising in the cold because as the body temperature increases, moisture from perspiration accumulates within clothing, causing an increased rate of heat loss (Nielsen, 1994). Moisture significantly increases the thermal conductivity of fabrics so that body heat is lost to the environment more rapidly when clothing is damp or wet (Schneider, Hoschke, & Goldsmid, 1992). Wet clothing causes considerable discomfort and reduces the duration of time that can be spent in cold environments due to increased rates of heat loss. Heat loss is further amplified when materials with poor moisture transport properties are directly against the skin. A study conducted by Nielsen (1994) at 10°C demonstrated this when more energy was required by a thermal manikin to maintain a normal body temperature as water accumulated next to the manikin surface. Nielsen (1994) also noted that wet fibres and fabric had a tendency to collapse and cling to neighbouring surfaces, which reduced their ability to insulate. Holmér (1985) conducted a wear trial at 8°C that supports the idea that thermal insulation is reduced when clothing becomes wet. He noted that thermal insulation dropped by approximately 15% when comparing dry and wet clothing. Keeping the skin dry is very important for maintaining thermal insulation, but also for the psychological aspect of thermal comfort. Skin wetness has been identified in research as a common indicator of discomfort, where sensations of dampness are strongly correlated with high humidity levels (Gagge, Stolwijk, & Hardy, 1969; Ha, Yamashita, & Tokura, 1995; Li, 2001; Nielsen & Endrusick, 1990). It has been suggested that people experience discomfort when more than 50-65% of the body surface is wet (Gagge, Stolwijk, & Hardy, 1969). As such, a variety of material factors thought to influence skin wetness and comfort during physical activity has been explored by researchers (Ha, Yamashita, & Tokura, 1995; Ha, Tokura, Yanai, Moriyama, & Tsuchiya, 1999; Nielsen & Endrusick, 1990). Ha, Yamashita, & Tokura (1995) demonstrated that fibre type can have a significant influence on sensations of wetness and perceptions of comfort. They conducted a wear trial where participants engaged in intermittent exercise at 24°C while wearing identically constructed cotton and polyester garments of equal thermal resistance. Initially there were no significant differences in perceptions of wetness or comfort. However, when physical activity was great enough to cause sweating, the microclimate temperature and sensation of wetness was higher in polyester garments. Cotton's moisture absorbing properties were found to delay the on-set of sweating and sensations of wetness. Cotton garments also caused significantly lower rectal temperatures and pulse rates in comparison to the polyester garments. This was attributed to the higher quantity of moisture absorbed by the cotton garments, which accelerated dry heat loss during the experiment and kept core temperatures lower. Moisture is known to increase the thermal conductivity of fabrics with increasing moisture content (Schneider, Hoschke, & Goldsmid, 1992). Thus, cotton's significantly higher moisture regain (≈7%) compared to polyester (≈0.4%) resulted in greater heat loss to the environment when the fabrics became wet with perspiration (ASTM, 2004). Subsequently, both garments were considered uncomfortable by the end of the experiment for different reasons. Participants felt wetter and warmer in the polyester garments, whereas they felt slightly drier, but colder in cotton garments. Ha, Tokura, Yanai, Moriyama, & Tsuchiya (1999) further explored the influence of fibre type in combination with fabric air permeability on comfort during intermittent exercise at 27°C. Three different fabrics were used to construct long sleeve tops and trousers for the wear trial. A cotton fabric with high air permeability ($108 cm^3 cm^{-2} s^{-1}$), a polyester fabric with low air permeability ($4.1 cm^3 cm^{-2} s^{-1}$), and a polyester fabric with high air permeability ($120 cm^3 cm^{-2} s^{-1}$) were investigated. The wear trial demonstrated that microclimate humidity was significantly lower for the polyester and cotton fabrics with high air permeability. When comparing the cotton and polyester fabrics of similar air permeability, the cotton fabric was found to be more effective in reducing microclimate humidity. As it is understood that a component of thermophysiological comfort is related to the level of skin wetness, participants felt more comfortable in the cotton garments that resulted in lower microclimate humidity. Thus, fibre type and air permeability play an important role in perceptions of comfort by reducing microclimate humidity and sensations of wetness. Further details of material factors that contribute to thermophysiological comfort are discussed in the following sections entitled “Thermal insulation in cold weather” and “Managing moisture in cold weather.”

Thermal insulation in cold weather

Modes of Heat Transfer

Thermal insulation is required to achieve thermophysiological comfort in cold weather by providing resistance to heat loss from the human body to the environment. To develop clothing that protects people in cold environments, it is important to establish the ways in which heat is lost from the human body to the environment. Heat loss from the human body can occur by convection, conduction, radiation, and evaporation. Convective heat transfer refers to the transfer of heat through air movement and is a result of the changing density of the air as it gains or loses heat. As air absorbs heat, it becomes less dense and rises, causing a chimney effect on a surface called natural convection (Holmér, 2005). High wind speeds and large differences in temperature between a surface and air will increase the rate of heat exchange via convection. The direct transfer of heat through gases, liquids, or solids in contact with one another is known as conduction (Hopkins, 1950). Conduction is influenced by temperature differences, states of matter, and the total amount of surface area in contact with one another. Radiation refers to the transfer of heat through space or electromagnetic waves (Holmér, 2005). Unlike conduction, radiation does not require direct contact with another medium and is influenced by an objects ability to reflect and absorb heat (Hopkins, 1950). Evaporation is a mechanism the human body utilizes to dissipate excessive heat and cool the body (Holmér, 2005). Heat is removed from skin or clothing when moisture undergoes a phase change from liquid to vapour (Hopkins, 1950). Moisture significantly complicates the heat transfer process and will be discussed in subsequent sections.

Influence of fibre properties

Conduction has been identified as being the main mode of heat transfer through fabrics (Farnsworth, 1970; Rossi, 2009; Varshney, Kothari, & Dhamija, 2010; Woo, Shalev, & Barker, 1994). As the conductivity of air is approximately eight times lower than that of fibres, one of the main strategies for reducing heat transfer in clothing is to increase the total quantity of trapped or still air within a textile (Varshney, Kothari, & Dhamija, 2010). It has generally been accepted that differences in the air trapped by fibres rather than chemical differences in fibres determines the thermal insulation of textile materials (Rossi, 2009; Ukponmwan, 1994). Yet, it is important to note that if high wind speeds are present, convective air currents can remove the insulating still air and the thermal resistance of the material will be dramatically reduced (Ukponmwan, 1994). Examining fibres in terms of morphology and fineness will provide insight into the factors that influence the overall thermal resistance of materials.

Fibre morphology can significantly impact the amount of dead air held within a material. Hollow fibres are commonly used to provide increased thermal resistance and decreased weight in comparison to solid fibres of equivalent denier (Cooper & Rankosky, 1980). The hollow void traps an appreciable amount of still air in comparison to solid fibres, resulting in an increased resistance to heat transfer due to a reduction in the total volume of fibre in a material. A positive correlation exists between the total volume of fibre and the rate of conductivity (Woo, Shalev, & Barker, 1994). Additionally, the type of hollow void will significantly impact the thermal properties of the material under dynamic conditions. This can be understood in terms of a material's resistance to compression due to the type of hollow void. A recent study showed that triangular hollow fibres are more stable and resistant to deformation in comparison to round hollow fibres (Xue, Cheng, & Gao, 2010). A round hollow fibre has a low resistance to compression and can flatten more easily, pushing trapped air out of hollow void and reducing its ability to insulate. Insulating materials undergo considerable amounts of compression in actual use or when sewn into garments. The use of fibres with triangular voids is a construction consideration that can be used to maintain thermal insulation in areas that are expected to experience compression.

There are many ways manufacturers can change the cross-section of fibres to impact the overall thermal properties of a material. The majority of these modifications that are effective (such as trilobal or tetrakelion shapes), increase the thickness and lower the bulk density of fabric due to their fibre arrangement when packed together (Varshney, Kothari, & Dhamija, 2010). The impact of thickness and bulk density on thermal insulation are discussed in the following section regarding the influence of yarn and fabric properties.

Research has consistently shown that fibre fineness or denier contributes to the total amount of thermal resistance a material is able to provide (Woo, Shalev, & Barker, 1994; Cooper & Rankosky, 1980; Varshney, Kothari, & Dhamija, 2010). The use of finer fibres in fabrics can influence how they pack into yarns and contribute to an increase of air within the fabric (Varshney, Kothari, & Dhamija, 2010). This is best explained by the boundary air layer theory, where a thin layer of still air is formed when air comes in contact with a surface (Song, 2009). Fibres with small diameters increase the total amount of surface area the boundary air layer can adhere to, resulting in a rise in air volume and decrease in conductivity. Radiant heat transfer only accounts for about 6% to 8% of the total heat transfer within a fabric, yet reducing the diameter of fibres can also have a large influence on the amount of radiant heat transfer from the body to environment. Reducing fibre diameters increases the fibre volume and density of a fabric to provide a more effective barrier against radiant heat loss (Ukponmwan, 1994).

Fibres therefore have two main functions with regards to thermal insulation; they prevent air movement and shield against radiant heat losses (Ukponmwan, 1994). Considering the fibre properties just discussed can improve a material's ability to perform these two functions.

Influence of yarn & fabric properties

There are many yarn properties that determine the thermal resistance of knitted or woven fabrics. The amount of protruding fibres or hairiness of yarns can contribute to the thermal properties of materials by reducing the amount of air movement on the surface of a fabric by maintaining a thick film of still air (Hopkins, 1950; Ozdil, Marmaral, & Kretzschmar, 2007). This is also the basis behind napping or brushing the inner surface of fabrics, where fibres are orientated perpendicular to the flow of heat to trap large volumes of still air and provide a higher resistance to heat transfer than the original fabrics (Woo, Shalev, & Barker, 1994).

The thermal properties of knit fabrics when yarn twist was manipulated have also been investigated. It was found that an increase in yarn twist caused a decrease in thermal resistance (Ozdil, Marmaral, & Kretzschmar, 2007). Yarns became finer with more twisting, which increased yarn density and reduced the volume of static air within the yarns and fabric.

Numerous researchers have concluded that the single most important factor determining the thermal insulation of a material is governed by thickness (Morris, 1955; Ukponmwan, 1994; Woo, Shalev, & Barker, 1994). Thicker materials provide more space for air to become entrapped and effectively reduce the rate of heat transfer through a material. Yet simply using thickness measurements is insufficient in determining the total thermal insulation provided by a material. Factors such as bulk density, porosity, and air permeability will also influence the thermal insulation of a fabric.

Bulk density is a measurement of the number, sizes, and distribution of spaces within a fabric (Song, 2009). Materials with low bulk density provide increased thermal resistance due to high volumes of air within the structure and are typically constructed using non-woven manufacturing techniques

(Woo, Shalev, & Barker, 1994). However, low density materials are vulnerable to radiant heat loss because radiant heat can easily pass through the gaps between fibres (Ukponmwan, 1994). Compiling fabric layers capable of protecting low density materials from excessive radiant heat loss should be considered when designing clothing for cold weather.

Porosity of fabrics will influence the velocity of air that can penetrate into a fabric or garment system (Varshney, Kothari, & Dhamija, 2010). When fabrics with high porosity are exposed to wind, the motionless still air insulating a wearer is removed and the total thermal insulation of a material is reduced (Ukponmwan, 1994). Low density fabrics will be vulnerable to heat loss from air permeating the structure if they are not protected by a barrier with low air permeability.

Layering

Layering can significantly impact the transfer of heat between the human body and the environment. The most obvious way in which layering influences heat transfer is an increase in thickness as more fabric layers are added to a garment system. The more layers added to the garment system, the greater the thermal resistance provided due to an increase in thickness and volume of air in spaces between fabric layers (Morris, 1955). Gaps between layers of fabrics provide additional insulation as long as the air remains motionless.

Layering fabrics also reduces the air permeability of a multilayer garment by increasing the tortuosity of the path through which the air must flow (Epps, 1988). Reducing the air permeability is especially important in order to maintain trapped air within a garment system. A strategy often employed by garment manufacturers is to use a membrane or high density material on the outermost layer of the garment system to prevent air from penetrating the clothing. The use of a wind resistant outer layer prevents convective heat transfer from removing still air from the low density battings (Holmér, 2005).

Managing Moisture in Cold Weather

Modes of Moisture Transport

The management of moisture in clothing can be described in terms of liquid and water vapour transport mechanisms. Liquid and water vapour transport can occur simultaneously, depending on the level of physical activity or the environment a person is exposed to. In cold ambient conditions, the rate of moisture transport in liquid or vapour form is reduced as these mechanisms are temperature dependent (ASHRAE, 2005; Rossi, Gross, and May, 2004).

Water vapour transport is governed by differences in water vapour concentrations as it moves from regions of higher concentration to lower concentrations (Li & Zhu, 2003). The mechanisms of water vapour transport in textile structures have been identified as vapour diffusion through air voids; absorption, transmission, and desorption by fibres; adsorption and migration along fibres surfaces; and transmission by forced convection (Das et al., 2007).

Liquid water transport is predominantly determined by the fibre and liquid molecular attraction, which is affected by surface tension (or surface energies) and distribution of capillary pores and pathways (Li & Zhu, 2003). Wetting and wicking are described as the two processes that occur in the transport of liquid moisture through a fibrous medium (Das et al., 2007; Hsieh, 1995; Kissa, 1996). Wetting is the first stage of liquid transport and describes the initial spreading and adhesion of liquid into the air-fibre spaces of a fabric (Das et al, 2007). Wetting is required before wicking can occur because wetting introduces capillary pressure required for liquid transport (Hsieh, 1995). Without capillary pressure, wicking cannot occur because wicking is the process of liquid transport through a porous system caused by capillary forces (Kissa, 1996).

Influence of fibre properties

Differences in the chemical composition and structure of fibre types can significantly influence a fabric’s response to moisture (Li & Zhu, 2003). Natural fibres such as wool and cotton are hygroscopic and contain many bonding sites for water molecules (Rengasamy, 2011). These hygroscopic materials transport water vapour through absorption, transmission, and desorption which reduce the amount of humidity built-up in the microclimate by enhancing the effective vapour gradient (Das et al., 2007). Yet the hygroscopicity of fibres can impede the transport of water when high volumes of moisture are present (Wehner, Miller, & Rebenfeld, 1987). As moisture is absorbed into hygroscopic fibres, micro-fibrils are pushed apart by the water molecules causing fibres to swell (Das et al., 2007; Kissa, 1996). Fibre swelling increases the total fibre volume and reduces the diameter of the pores available for liquid and water vapour to flow (Das et al., 2007; Hsieh, 1995; Wehner et al., 1987). Hydrophobic fibres such as polyester are not as affected by swelling because they absorb minimal or no moisture into their molecular structure. This enables good moisture transport and release properties in hydrophobic materials, as moisture can readily evaporate when it is adsorbed and migrates along the surface of fibres

(Adler & Walsh, 1984). However, hydrophobic fibres have lower moisture regain which often results in shorter times for hydrophobic materials to become saturated in comparison to hygroscopic fabrics (Adler & Walsh, 1984). Thus, there are advantages and disadvantages when comparing the ability of hydrophobic and hygroscopic fibres to manage perspiration.

The size or diameter of fibres is significantly related to moisture transport. Reducing the diameter of fibres is often used to improve the liquid transport properties of materials. The use of micro-denier fibres increases the quantity of capillary pores available for transport and the total volume of liquid moisture a material can hold before reaching complete saturation (Das et al., 2007). Complete saturation can be described as the point when no further liquid can be absorbed and all void space in the fabric is filled with liquid (Ghali et al., 1994). In order to maintain liquid transport, it is imperative that materials do not become saturated, because capillary pressure ceases and prevents wicking from occurring (Das et al., 2007; Ghali et al., 1994; Hsieh, 1995). Before a fabric is saturated, the use of micro-denier fibres will amplify the capillary force available for liquid transport, as the formation of smaller pores increase capillary pressure (Ghali et al., 1994; Hsieh, 1995; Varshney, Kothari, & Dhamija, 2010). The distance and speed of liquid spread is therefore enhanced by small, uniformly distributed, and interconnected pores (Hsieh, 1995). While microfibres have a positive impact on liquid transport, they have a negative impact on water vapour transport. The use of fine fibres increases the amount of trapped air, providing greater thermal insulation, but significantly reducing the amount of free air spaces available for water vapour to flow with ease (Varshney, Kothari, & Dhamija, 2010). Thus, the tortuosity of pathways for water vapour to flow is increased, leading to reduced water vapour transmission rates.

The flow of moisture through a material can also be influenced by the shape or geometry of fibres. Modification of the fibre geometry leads to changes in the total surface area and the channels through which moisture can flow. Varshney, Kothari, & Dhamija (2010) found that the presence of surface channels on tetrakelion and scalloped oval polyester fibres allowed liquid moisture to flow more easily and quickly when compared to circular polyester fibres. This was attributed to the increased surface area and additional quantity of capillaries (Varshney, Kothari, & Dhamija, 2010). An increase in total surface area creates more space for adsorption and migration of liquid moisture along the fibres to occur.

Activated carbon particles have been incorporated into fibres during the extrusion process to provide a material with increased adsorptive and thermal properties (Splendore, Dotti, Cravello, & Ferri, 2010). The overall increase in surface area of the fibres due to the activated carbon particles provides a means to remove more sweat per unit of area and provide the user with a sensation of dryness during physical activity (Splendore et al., 2010). The incorporation of activated carbon particles has also been noted to decrease the amount of energy required for evaporation to occur, thus the rate of evaporation is increased (Haggquist, Cohen, Cogdill, Skoff, Sarkar, & Vora, 2009). However, it is important to note that there is contradictory scientific evidence about the evaporation rates, as Splendore et al. (2009) found that evaporation times for polyester with activated carbon had lower evaporation times than regular polyester. Splendore et al. (2010) hypothesized that the strong intermolecular bonds between activated carbon and water and the smaller mass-transfer per unit area slowed the supply of moisture to the surface of the fibre, causing a decrease in the evaporation rate. On the other hand, Haggquist et al. (2009) found that activated carbon acts as an efficient heat collection agent which retains more heat and subsequently facilitates the evaporation of moisture from a surface due to increases in temperature (Haggquist et al., 2009). Yet Splendore et al. (2010) found that conventional polyester had greater thermal properties than polyester with activated carbon. It is important to note that the properties imparted by the activated carbon heavily rely on the type of precursor or raw materials used to manufacture the activated carbon (Mesik & Cerny, 1970). This could be a possible explanation for the differences in performance. Another mechanism that was not considered in both studies is the phenomenon known as heat of wetting. Heat of wetting refers to the process where an exothermic reaction occurs and heat is released as the solid-gas interface of a material is replaced by a solid-liquid interface (Mesik & Cerny, 1970). As the heat of wetting increases with the amount of surface area on a solid, the extremely high surface area of activated carbon may promote significant heat release (Mesik & Cerny, 1970). Thus, improved evaporation rates may be found in materials under dynamic conditions where heat and moisture transport are occurring simultaneously. Upon review of these contradictory studies, it is apparent that further research is need to understand the heat and mass transfer mechanisms in textile fibres with activated carbon.

Influence of yarn & fabric properties

While yarn properties are predominately dependent on the fibres they consist of, there are ways in which yarn can assist the moisture transport properties of a material. For example, fibres come closer to each other and introduce a greater number of capillaries when the packing coefficient of the yarn is increased (Nyoni & Brook, 2006). The way fibres pack into yarns influences the uniformity, shape, and size of pores. Uniform interconnected pores are essential for moisture transport as irregularities in the channels of moisture flows will decrease the movement of water (Hsieh, 1995). Yarns spun with natural or coarse fibres have very irregular capillaries which interrupt the flow of moisture because of discontinuous capillaries (Das et al., 2007). Textured or hairy yarns will also reduce wicking. The variability of the pores can also be influenced by yarn twist. Generally, as the amount of yarn twist increases, the rate of liquid moisture transport decreases (Nyoni & Brook, 2006). However, at very high twist levels, a phenomenon known as spiral wicking occurs where moisture travels along the helical path of less tension (Nyoni & Brook, 2006).

The way yarns and fibres are woven or knitted into fabric can significantly change the function of a material. The thickness and porosity of materials can influence the moisture transport properties of materials by changing the tortuosity and length of the pathways moisture must flow (Das et al., 2007). The porosity of a material is affected by the tightness of a weave or knit. Open or looser constructions promote the flow of water vapour due to increased air circulation, but fail to effectively transport liquid moisture due to a low distribution of capillary pathways for wicking to occur (Bakkevig, 1995; Hsieh, 1995). Porosity is also related to thickness. Increased thickness reduces the porosity of a material and lowers water vapour diffusion rates (Li, Zhu, & Yeung, 2002). This is due to a reduction in the amount of free air spaces between fibres and yarns for water vapour to flow. Additionally, the total volume of liquid a material can hold is positively correlated with its thickness (Crow & Osczevski, 1998). Thicker materials have more trapped air spaces for liquid moisture to be held within the fabric structure (Crow & Osczevski, 1998). As such, evaporation rates are significantly impacted by the thickness of materials, where thinner materials are capable of drying much more rapidly due to lower volumes of water present in the material (Crow & Osczevski, 1998). However, moisture management finishes have been developed to improve the transport moisture through fabrics to the environment (Rearick & Anderson, 2006; Sampath, Aruputharaj, Senthilkumar, & Nalankilli, 2012). Rearick & Anderson (2006) have developed a one-way moisture management finish that introduces hydrophobic regions to the inside of a fabric surface through a screen printing process. This provides additional capillary pressure required to transport liquid moisture to the outer surface of a fabric. Such effects may have a positive influence on the thermal comfort of winter clothing by keeping moisture away from the skin. Sampath et al. (2012) investigated the effects of moisture management finishes on the thermal and moisture transport properties of fabrics with various yarn types. Micro-denier polyester, spun polyester, polyester and cotton blend, filament polyester, and staple cotton were examined in the experiment. All yarns were of equal fineness (i.e. denier) and knitted into single jersey constructions. The water vapour permeability of all fabrics was improved with the moisture management treatment in comparison to their untreated versions. Micro-denier and filament polyester yarns also demonstrated higher vapour permeability.

Results from this research suggest moisture management finishes may improve the comfort of fabrics by facilitating the transport of moisture to the environment.

Distribution of condensation in cold weather *clothing*

As the presence of moisture is known to increase the thermal conductivity and heat capacity of fabrics, high moisture content in close proximity to the skin can significantly accelerate heat loss and increase the risk of hypothermia in cold weather (Nielsen, 1994). Researchers have demonstrated that the location of condensation in cold weather clothing (i.e. multi-layered) is highly dependent upon the order in which hydrophilic materials are arranged (Bakkevig et al., 1995; Keiser et al., 2008). Further analysis of this research reveals additional factors that influence the location of moisture in cold weather clothing. Bakkevig & Nielsen (1995) compared moisture accumulation of human participants wearing three-layer ensembles in a climatic chamber at 10°C. The impact of changing polypropylene and wool undergarments under a wool fleece and jacket (65% cotton, 35% polyester) was examined. A greater quantity of moisture was found to accumulate in the wool undergarments in comparison to the polypropylene undergarments. When polypropylene was worn, the greatest quantity of moisture accumulated in the wool mid-layer. It was stated that wool created a moisture gradient that flowed towards the mid-layer due to its greater affinity for water molecules. The hydrophobic polypropylene provided a means of transporting moisture into the wool mid-layer resulting in higher levels of condensation. Wool next to the skin held high quantities of moisture and was unable to effectively transport moisture to the neighbouring layer. It was concluded that the location of condensation within the multilayer system was highly dependent upon the fibre-type of the underwear (Bakkevig & Nielsen, 1995). Thus, the location of hydrophilic fabric layers influenced the direction of moisture flow and provided evidence of a relationship between neighbouring layers in a multi-fabric system. Research conducted by Keisier, Becker, & Rossi (2008) provides further insight into this synergistic relationship that exists between moisture absorption and wicking properties of neighbouring layers. Keiser, Becker, and Rossi (2008) analyzed the distribution of moisture in firefighter protective clothing layers through the use of a sweating guarded torso in standard conditions (20°C & 65% RH). Cotton and aramid underwear were investigated with two different firefighter jackets and three different station uniforms (cotton, hydrophobic treated aramid/viscose, & aramid). A comparison of all combinations revealed that more moisture accumulated in samples with cotton underwear than the aramid underwear. This confirms the premise that hydrophilic materials such as cotton, will store greater quantities of moisture than hydrophobic materials like aramids. However, it is important to understand how these materials interact within a cold weather system to transport moisture to the environment. The author notes that, "the amount of moisture stored in the underwear strongly depended on the type of neighbouring station uniform layer" (Keiser, Becker, & Rossi, 2008, pp. 608). Layers that were unable to absorb a sufficient amount of moisture to transport water to the next layer acted as a water barrier (Keiser, Becker, & Rossi, 2008,). Evidence that moisture will flow towards hydrophilic layers when materials are combined is provided. The research presented by Keiser, Becker, & Rossi (2008) and Bakkevig (1995) support the idea that the order of hydrophilic materials significantly influences the transport of moisture out of the garment. As these experiments were carried out in environmental conditions above zero, it is important to note that the accumulation of moisture is further amplified by temperature decreases (Rossi, Gross, & May, 2004). Thus, the issue of condensation is of greater magnitude when predicting thermal protection in colder environments. Further research is required to understand the movement of moisture through cold weather garments in sub-zero environments.

CHAPTER 3: METHODS

Experimental design

This study was designed to investigate how the moisture management properties of selected underwear and lining fabrics used in cold weather ensembles influence the transport of heat and moisture. The goal was to identify clothing technologies and physical fabric properties that contribute to the maintenance of a dry layer of fabric next to the skin and improve thermal comfort. The independent variables for this research experiment were the underwear and lining fabrics. The dependent variables calculated were thermal resistance, wet heat flux, drying time, drying rate, and overall moisture management capability (OMMC).

Materials

The seven underwear fabrics examined in this research are all manufactured in similar constructions. All underwear fabrics are single jersey knits, except for fabric Y which is a double knit. Fabric Y contains yarns made of micro-denier polyester fibres with activated carbon on the back of the fabric and yarns composed of cotton fibres on the face of the fabric. It was included because it represents a typical construction employed in the apparel industry to achieve one-way moisture transport. Fabrics A and C are from the same fabric roll and are composed of 95% cotton and 5% spandex. They contain no differences other than the one-way moisture management finishing treatment applied to fabric C. Fabrics B and D are also from the same fabric roll and are composed of 95% polyester and 5% spandex. They contain no differences other than the one-way moisture management treatment applied to fabric D. Comparisons among fabrics A, B, C, and D will allow for a direct measure of the effects of the moisture management treatment and fibre type. Fabric E is made entirely of polyester fibres doped with activated carbon granules, which have previously demonstrate an increased sorption capacity and evaporation rate in comparison to regular polyester (Haggquist et al. 2009; Splendore et al., 2010). Lastly, Fabric G contains fibres with trilobal and hollow morphologies. The trilobal fibres spread moisture and increase the amount of surface area for evaporation. The hollow fibres provide additional insulation. All of the polyester underwear fabrics were composed of texturized filament yarns (fabrics B, D, E, G, & Y).

The four lining fabrics in this research are all constructed in a plain weave. Fabrics H, I, and X were constructed on the same weaving machine and use polyester yarns of equal denier. Fabric H has a wicking finish applied to it. Fabric I has a wicking finish and contains polyester fibres with activated carbon granules. Fabric X has a wicking finish and also contains activated carbon powder in the dye used to colour this fabric. Fabric J is 100% nylon without any special treatment or finish. Thus, Fabric J is the only lining fabric that is hydrophobic. The lining fabrics were composed of filament polyester yarns.

The insulation and shell fabric were standardized across all experiments. The insulation is composed of 100% thermally bonded polyester. The manufacturer provided a mass per unit area of 70 grams per metre squared. The shell fabric is 100% polyester woven in a two by two twill construction and has a polyurethane microporous membrane laminated to its inner surface.

Procedures

A variety of standard and modified test methods were used to determine the physical, thermal, and moisture related properties of single layer fabrics and cold weather fabric systems examined in this research study. All fabrics were conditioned at 20°C and 65% R.H. in accordance with CAN/CGSB 4.2, No.2-M88 for a minimum of eight hours prior to any measurements or experimentation. No two specimens contained the same wales or courses, nor warp or filling yarns.

Measurement of physical properties of single layer fabrics

Fabric count, mass, thickness, and air permeability of the single layer materials selected for this research study was measured. Knitted fabric count was measured using a modified version of CAN/CGSB-4.2 No. 7-M88 Knitted fabric count – Wales and courses per centimetre (CGSB, 2001). A straight rigid scale placed under a microscope was used to determine the count of the conditioned specimens. Six measurements over four centimetres in each direction were taken for each fabric and the mean recorded. Woven fabric count was measured following CAN/CGSB-4.2 No. 6-M89 (CGSB, 1989). The mean number of warp and filling yarns per centimetre were determined following method C using a traversing thread counter with low power magnification. Fabric thickness was measured following CAN/CGSB 4.2, No.37 – 2002 using a 28.7mm diameter presser foot and a pressure of 1.0kPa. Dial readings (with an accuracy of 0.025mm) were taken from the conditioned fabrics at ten different locations and the mean thickness was calculated. Mass per unit area was measured following CAN/CGSB 4.2, No. 5.1-M90 where ten die-cut specimens with a diameter of 50mm were measured and the mean mass per unit area was determined. Mass per unit area was calculated in g/m^2 using Equation 1:

$$Mass\ per\ unit\ area\ (g/m^2) = \frac{mass\ of\ specimen\ (g)}{Area\ of\ specimen\ (m^2)} \tag{1}$$

(CGSB, 2004)

Air permeability measurements were carried out in accordance with CAN/CGSB 4.2 No. 36-M89 where ten specimens with dimensions of 150mm by 150mm were cut from each sample. Air permeability was measured in terms of the number of cubic centimetres of air passing through one square centimetre of fabric per second ($cm^3/cm^2/s$) when the differential between the air pressures on opposite sides of the fabric equal 12.7mm of water. After ten readings were taken from representative areas of the conditioned fabrics, the mean air permeability was calculated in $cm^3/cm^2/s$.

Measurement of thermal properties of single layer fabrics

Thermal resistance measurements were carried out in accordance with ISO 11092: Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady state conditions (sweating guarded-hotplate test), with one modification (ISO, 1993). The relative humidity of the environmental chamber was not controlled, but was recorded throughout the entire test period. As per ISO 11092, thermal resistance (R_{ct}) provides a measure of the dry heat flux across a given area in response to a steady applied temperature gradient and is expressed in square metres degrees Celsius per watt (m^2C/W) (ISO, 1993). It is calculated using Equation 2, where T_m is the steady-state temperature of the measuring unit (hotplate) (°C), T_a is the controlled air temperature in the test chamber (°C), A is the area of the measuring unit (m^2), H is the heating power supplied to the measuring unit to maintain the steady-state temperature of the plate (W), ΔH_c is the correction term for heating power (W), and R_{ct0} is the apparatus constant; also known as the bare plate measurement (m^2C/W). R_{ct0} is a thermal resistance measurement of the boundary air layer that would be present on the outer surface of the fabric.

$$R_{ct} = \frac{A(T_m - T_a)}{(H - \Delta H_c)} - R_{cto} \tag{2}$$

(ISO, 1993)

Testing was performed using a custom-built advanced sweating guarded hotplate (ASGHP) manufactured by Measurement Technology Northwest (Figure 1). The ASGHP was housed in an environmental chamber (Tenney Environmental Test Chamber, Model No. T20RC-3, Serial No. 31154) where ambient temperature, hotplate surface temperature, and wind speed were controlled to maintain steady-state conditions. The conditions for measuring thermal resistance of the single layer materials are outlined in Table 2. Specimens measuring 318mm by 318mm were cut and conditioned prior to testing.

Figure 1. Advanced sweating guarded hotplate (ASGHP)

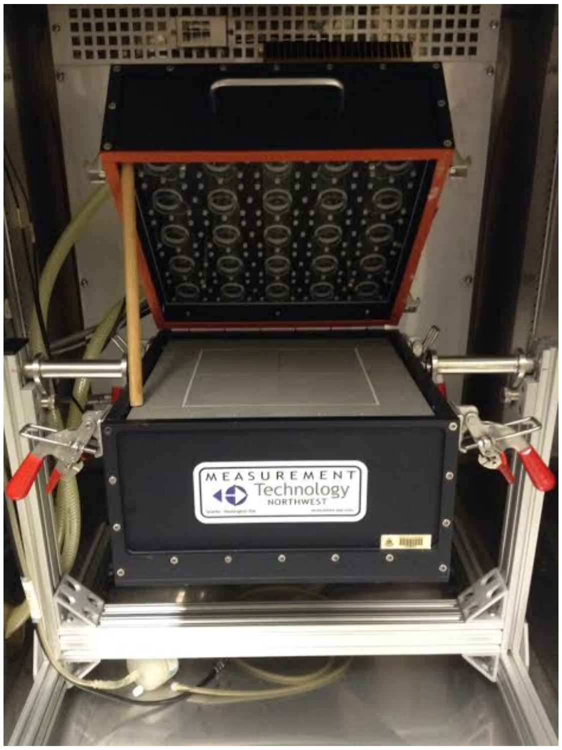


Table 2. Environmental conditions for measurements on ASGHP

Parameter	Symbol	Value
Ambient temperature (°C)	T_a	6 ± 0.1
Temperature of hotplate surface (°C)	T_m	35 ± 0.1
Relative humidity (%)	R.H.	29 – 98
Air velocity (m/s)	V_a	10

Measurement of liquid moisture management properties of single layer fabrics

As per AATCC 195, liquid moisture management properties were measured using a Moisture Management Tester (MMT) in order to characterize the movement of liquid moisture through single layer fabrics (American Association of Textile Chemists and Colorist [AATCC], 2009). Ten 80mm by 80mm specimens were cut from each sample. The fabric specimen is placed between two sets of horizontally laid electrical sensors and a predetermined amount of test solution is dropped onto the center of the test specimen surface (AATCC, 2009). The top side of the fabric is to be considered the side of the fabric that would be worn next to the skin in actual use, while the bottom side is considered the outer surface or fabric face. The MMT uses a data acquisition system that automatically determines accumulative one-way transport capacity (OWTC), spreading speed of top and bottom surfaces (SS_t and SS_b), maximum wetted radius of top and bottom surfaces (MWR_t and MWR_b), and overall moisture management capability (OMMC) (AATCC, 2009). OWTC is an index that calculates the difference of the accumulative moisture content between the two surfaces of the fabric. It provides a good indication of the distribution of liquid moisture within a fabric, where higher values indicate more moisture on the bottom (outside) of the fabric and lower values indicate more moisture on the top (skin-side) of the fabric. Water content (U) is automatically calculated as a percentage by the MMT by supplying a known quantity of liquid to the fabric and simultaneously measuring the electrical conductivity of each side of the fabric. However, AATCC 195 notes that these values should be correctly termed “total surface water content”, as moisture trapped in the interior of the fibre will not be included with a specimen’s detected water content (AATCC, 195). Thus, caution should be taken when interpreting the accuracy of water content (U) and any other parameters that rely on this value for their own calculations (i.e. OWTC & OMMC). Liquid droplets can also slip through the fabric, unabsorbed. This can generate incorrect water content (U) data and associated calculations. To avoid incorrect interpretation of data, previous authors have suggested checking the bottom sensors for liquid moisture that may have passed through the fabrics after every test (McQueen, Batcheller, Mah, & Hooper, 2013). Additionally, observations were recorded when a liquid droplet formed on top of a specimen. OWTC is calculated by the equipment using Equation 3, where U_{bottom} is total water content (%) of the bottom side and U_{top} is total water content (%) of the top side.

$$OWTC = \frac{Area_{Ubottom} - Area_{Utop}}{Time}$$

(3)

(AATCC, 2009)

Spreading speed of the top (SS_t) and bottom (SS_b) provides an indication of the speed of surface wetting from the centre of the specimen to the maximum wetted radius in millimetres per second (mm/sec). Higher spreading speed values imply that fabrics quickly spread moisture across the specimen making it easier for moisture to evaporate or more accessible for transport to adjacent fabrics in multi-layer assemblies. Max wetted radius of the top (MWR_t) and bottom surfaces (MWR_b) provides a measure of the distance moisture spreads across the test specimen (mm), as indicated by the circular laid rings of electrical sensors. Max wetted radius values are given in increments of five millimetres up to a maximum of 30 millimetres, as there are a total of five concentric rings of pins positioned around a centre point spaced five millimetres apart. AATCC 195 notes that the apparatus computes the max wetted radius (MWR) as the farthest circular ring that detects the presence of moisture. Caution should be taken when interpreting this value as some specimens will not exhibit a perfectly circular spread of moisture (AATCC 195). To account for materials that spread moisture in non-circular, elliptical, or amoeboid patterns, visual observations of the shape of the wetted area and direction of greatest spreading were recorded for each sample. Overall moisture management capacity (OMMC) is an index used to describe the overall capability of the fabric to transport liquid moisture by combining the bottom surface absorption rate (AR_b), one way liquid transport capacity (OWTC), and the maximum spreading speed of the bottom surface (SS_b) to complete the calculation; as seen in Equation 4 (AATCC, 2009).

$$OMMC = (0.25 * AR_b) + (0.5 * OWTC) + (0.25 * SS_b)$$

(4)

(AATCC, 2009)

Absorption rate of the bottom surface (AR_b) describes the average speed of liquid moisture absorption of the bottom surface during the initial change in water content and is expressed as the percentage of moisture absorbed per second (%/sec) (AATCC, 2009). Calculations for OWTC and SS_b have previously been described. These three performance attributes are selected by the standard test method AATCC 195 as the most important properties that contribute to a functional moisture management fabric.

Measurement of liquid absorption capacity of single layer fabrics

Liquid absorption capacity (LAC) was measured following Section 5 of ISO 9073-6 Textiles – Test methods for nonwovens – Part 6: Absorption (ISO, 2003). This test measures the amount of liquid retained by a fabric after specified periods of immersion and drainage. Only underwear and lining fabrics were tested for LAC because the insulation and shell fabrics remained constant throughout all experiments. Five specimens measuring 80mm x 80mm were tested for each fabric. Conditioned specimens were placed in a pre-weighed weighing glass and the dry mass determined. Specimens were then fastened to stainless steel gauze and submerged in a pan of distilled water for 60 seconds. Specimens were removed from the frame and hung vertically to drain for 120 seconds before being placed back in the weighing glass and reweighed. The mean LAC in percent was calculated using Equation 5, where m_k is the mass of the dry specimen in grams and m_n is the mass of the specimen and absorbed liquid in grams:

$$LAC\ (\%) = \frac{m_n - m_k}{m_k} \times 100 \tag{5}$$

(ISO, 2003)

Measurement of wet heat flux, drying time, and drying rate of single layer fabrics

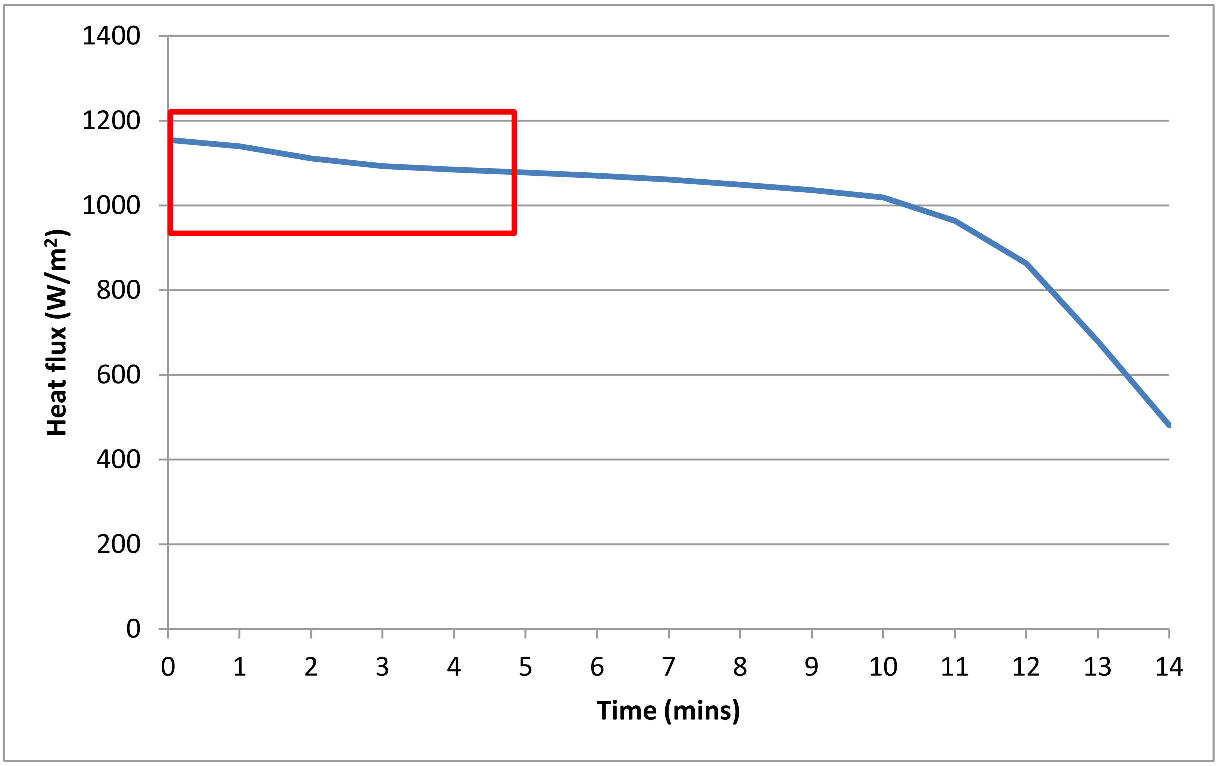
As the focus of this research is maintaining a dry layer of fabric next to the skin, wet heat flux, drying time, and drying rate were measured for all the underwear fabrics. Wet heat flux, drying time, and drying rate were measured under the conditions outlined in Table 2 because previous research conducted by Rossi, Gross, & May (2004) demonstrated that evaporative resistance and condensation rates show greater differences at lower ambient temperatures in comparison to standard climatic conditions (20°C and 65% R.H.). The authors found that the amount of condensation is negligible under standard conditions, but increases exponentially at lower temperatures. As the focus of this research is on materials intended for cold weather, colder air temperatures and higher wind speeds were used to provide greater representation of material performance in their intended environment.

A methodology for wetting fabrics and placing them in the chamber was required to measure the wet heat flux, drying time, and drying rate of single layer fabrics. This procedure was developed to simulate the point when underwear fabric worn against the skin becomes saturated (or nearly saturated) with liquid perspiration. A piece of glass with measurements equal to the size of the sweating guarded hot plate specimens (318mm by 318mm) was placed onto a Mettler Toledo PJ3000 balance (supplied by Mettler-Toledo, New Zealand, capacity 3100g, readability 0.01g). This ensured moisture being applied to the fabric would completely absorb into the specimen or be recorded as residual moisture after application. The fabric was placed face down on the scale and its dry weight recorded. While wearing rubber gloves, distilled water was evenly sprayed onto the inner side of the underwear fabric until it gained 25 ± 0.5g of mass. A rolling pin weighing 257.5g was gently rolled over the fabric to simulate light pressure typically encountered when fabric rubs against skin. If necessary, the application of moisture and rolling procedure was repeated to reach the target mass. This mass was recorded as the initial wet weight. The fabric was then placed on the hot plate in the environmental chamber which had reached the steady state conditions outlined in Table 2. The plate depth was fixed at 1mm below the top of the thermal guard for all samples. While placing the fabric in the chamber, the door was left open for a set time of 3.5 minutes since the duration of time it was open affected the environmental conditions within the chamber. Fixing the amount of time the chamber door was open ensured that fabrics were properly fitted to the hot plate and exposed to identical environmental conditions. However, it should be noted that the relative humidity and temperature of the laboratory were not controlled. Thus, the accuracy of this procedure is limited to the variance of the laboratory conditions, but assumes the laboratory is of equal variance during all data collection periods. Since the power measuring instrument was limited to an accuracy of 2%, data was recorded until the fabric returned to 2% above its dry heat flux value derived from data collected during thermal resistance measurements. Once these requirements were met, the fabric was removed from the chamber. As some of the specimens were re-used, all specimens were exposed to the experimental procedures, air dried, and re-conditioned in accordance with CAN/CGSB 4.2, No.2-M88 prior to data collection in order to avoid any effects caused by their moisture history. Each time a specimen needed to be re-used, it was air dried and re-conditioned in accordance with CAN/CGSB 4.2, No.2-M88 for a minimum of 8hrs prior to testing. Data was collected using these procedures on 3 specimens per fabric.

Wet heat flux, drying time, and drying rate were calculated using the data collected from the wetting and placement of the fabric in the environmental chamber. As previous research has demonstrated maximum heat flux indicates the initial point of contact between a fabric and a hot plate (or skin), the time of maximum heat flux was used as the starting point for data collection (Kawabata & Akagi, 1977).

Wet heat flux was calculated in watts per metre squared (W/m^2) as the average of the first 5 data points of the heat flux plot (as highlighted in Figure 2). This measurement provides an indication of the energy being drawn from the plate when the fabric is saturated (or nearly saturated) with liquid moisture. Kawabata & Akagi (1977) have previously conducted research that found strong correlations between heat flux measurements from hot plates and thermal sensations from human sensory tests. The authors concluded that higher heat flux values indicated greater sensations of cooling, while lower heat flux values provided warmer sensations (Kawabata & Akagi, 1977). As such, wet heat flux was thought to be related to maximum quantity of energy being drawn from the skin in contact with a saturated fabric and could be related to the thermal sensation experienced by individuals wearing the fabric.

Figure 2. Wet heat flux measurement of single layer fabrics



Drying time provides a measurement of the time for a specified amount of liquid to evaporate from a textile under controlled test conditions (AATCC, 2012). Drying time was calculated using criteria for the start and end time of the data collection periods. Using Equation 6, drying time was calculated in minutes (mins) and is equal to the End time subtracted by the Start time of the test. Start time begins at the initial point of data collection, which is indicated by the maximum heat flux value. End time is determined by the point in time when the fabric returned to 2% above its dry heat flux value derived from data collected during thermal resistance measurements.

$$Drying\ time = End\ time - Start\ time \tag{6}$$

Drying rate provides a measurement of the average change in mass per unit area per unit time a liquid evaporates from a textile. It is important to note that drying rates are non-linear over the test period in this research. This measurement provides an average drying rate throughout the entire test period. Drying rate is calculated using Equation 7, where R is the drying rate in grams per square metre per minute ($g/m^2{\cdot}min$), M is the mass of water applied to the fabric in grams (g), A is the area of the specimen (m^2), and drying time is calculated in accordance with Equation 4 in minutes (mins).

$$R = \frac{M}{A * Drying\ time} \tag{7}$$

Measurement of cold weather fabric system properties

A variety of standard and proposed test methods were used to measure the thermal and moisture related properties of the cold weather fabric systems. Fabric combinations are identified by a two letter code, where the first letter identifies the underwear and the second letter identifies the lining fabric selected (Appendix A). Liquid moisture management through two-layer composites (underwear and lining) were measured under standard environmental conditions (20°C and 65%RH). Thermal resistance, wet heat flux, drying time, and drying rate of the cold weather fabric systems were measured using the arrangement in Figure 3 and environmental conditions outlined in Table 2.

Figure 3. Arrangement of layers in cold weather fabric systems

Layer 4	**SHELL**
Layer 3	**INSULATION**
Layer 2	**LINING**
Layer 1	**UNDERWEAR**
	HOT PLATE

Measurement of thermal properties of cold weather fabric systems

Thermal resistance measurements were carried out in accordance with ISO 11092: Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady state conditions (sweating guarded-hotplate test), with two modifications (ISO, 1993). The relative humidity of the environmental chamber was not controlled, but was recorded throughout the entire test period. The second modification is that plate depth was standardized at 5mm from the top of the thermal guard to ensure consistency of measurements among the wet and dry testing. All of the cold weather fabric systems were of similar thickness, so the depth was selected by leveling the thermal guard to their average thickness. Five specimens were tested for each cold weather fabric system.

Measurement of liquid moisture management properties of two-layer composites

Combinations of fabrics used for underwear and jacket linings in this research study were tested as a two-layer composite in order to characterize their ability to transport liquid moisture through multiple layers. Two-layer composites can be understood by their identification (ID) codes, where the first letter indicates the underwear and the second letter the lining fabric tested (i.e. fabric AX means underwear fabric A was tested in combination with lining fabric X). It was hypothesized that the MMT apparatus would provide data to determine the direction and ability of two-layer composites to transport liquid moisture. Overall moisture management capability (OMMC), accumulative one-way transport capacity (OWTC), spreading speed of top and bottom surfaces (SS_t and SS_b), and maximum wetted radius of top and bottom surfaces (MWR_t and MWR_b) were collected for each two-layer composite. Data collected on the top surface properties indicates the speed and distance the underwear fabric spreads moisture, whereas data collected on the bottom surface indicates the speed and distance the lining fabric spreads moisture. Accumulative one-way transport capacity (OWTC) provides information on the ability of the two fabric layers to interact and transport moisture towards the outermost fabric layer. OMMC provides a measure of the overall moisture management capability of the fabrics combined. Ten specimens for each two-layer composite were tested. It is possible for unabsorbed moisture to slip through the two layer composites to the bottom sensors. This would lead to incorrect OMMC and OWTC values. In order to identify such errors, observations were recorded when the bottom sensors were wet.

Measurement of wet heat flux, drying time, and drying rate of cold weather fabric systems

The same procedures and apparatus described in "Measurement of wet heat flux, drying time, and drying rate of single layer fabrics" were used to measure the wet heat flux, drying time, and drying rate of cold weather fabric systems, with a few minor differences. In this case, each layer of the fabric system was individually placed face down on the scale and its dry weight recorded. While wearing rubber gloves, distilled water was sprayed onto the inner side of the underwear fabric until it gained 25 ± 1g of mass. This mass was recorded as the initial wet weight. The fabric system was then placed in the appropriate order (underwear 1st, lining 2nd, insulation 3rd, and shell 4th) on the hot plate in the environmental chamber which had reached the steady state conditions outlined in Table 2. The plate depth was fixed at 5mm below the top of the thermal guard for all samples. As previously described, while placing fabrics in the chamber, the door was left open for a set time of 3.5 minutes as the duration of time the chamber door was open affected the environmental conditions within the chamber. Since the power measuring instrument was limited to an accuracy of two percent, data was recorded until the fabric returned to two percent above its dry heat flux value derived from data collected during thermal resistance measurements. Once these requirements were met, the fabric system was removed from the chamber. Data was collected using these procedures on 3 specimens per cold weather fabric system.

Wet heat flux, drying time, and drying rate for the fabric systems were determined using similar procedures outlined in the section entitled "Determination of wet heat flux, drying time, and drying rate." The only difference was that wet heat flux was calculated in watts per metre squared (W/m^2) as the average heat flux between 5 and 15 minutes of the total test period. In comparison to the single layer measurements, multiple fabric layers caused greater evaporative resistance and longer periods of steady heat flux when the underwear was wet. Thus, taking the average of more data points during this time period provides a better representation of the energy being drawn from the hot plate when the underwear fabric was wet.

Statistical analysis

Descriptive statistics were calculated for all measurements taken from single layer fabrics, two-layer composites and cold weather systems. Significant differences in mass, thickness, air permeability, liquid absorption capacity (LAC), overall moisture management capacity (OMMC), thermal resistance, wet heat flux, drying time, and drying rate between all single layer fabrics were established by analysis of variance (ANOVA]. ANOVAs were also conducted to determine significant differences in thermal resistance, overall moisture management capacity (OMMC), wet heat flux, drying time, and drying rate for cold weather fabric systems. Levene's homogeneity of variance test was conducted on each variable to determine equal variance between samples. When significant differences occurred and homogeneity of variance was satisfied, similar groupings were identified using Tukey's HSD (honestly significant difference) test. If homogeneity of variance between samples was not satisfied, similar groupings were identified with Tamhane's T2 post-hoc tests. A different post-hoc test was required when variance was unequal to reduce the chance of a Type II error through a more conservative statistical analysis using the Tamhane T2 post-hoc test. Pearson correlations were conducted using mean data to determine significant relationships between the physical, thermal, and moisture related properties of the fabric and fabric systems. All statistical data can be found in Appendices B through H.

CHAPTER 4: RESULTS AND DISCUSSION

The physical properties of the underwear fabrics can be found in Table 3. The physical properties of the lining, insulation, and shell fabrics can be found in Table 4. Thermal and liquid moisture management properties of the underwear fabrics can be found in Table 5. Table 6 contains the thermal and liquid moisture management properties of the lining, insulation, and shell fabrics. Table 7 contains the wet heat flux, drying time, and drying rate of the underwear fabrics. The thermal properties of cold weather fabric systems can be found in Table 8. The liquid moisture management properties of two-layer composites can be found in Table 9. Wet heat flux, drying time, and drying rate for each cold weather fabric system is presented in Table 10. Table 11 provides mean data for wet heat flux, drying time, and drying rate by underwear type. Table 12 presents mean data for wet heat flux, drying time, and drying rate by lining type. Saturation levels of underwear fabrics exposed to 248 g/m^2 of moisture can be found in Table 13. As the statistical analyses and data do not take into account the shape of the heat flux curves, the discussion includes a review of visible differences in the heat flux curves for single layer fabrics and cold weather systems. The heat flux curves for selected comparisons between underwear fabrics or cold weather fabric systems are plotted in Figures 12, 13, 16, 17, 19, & 25, using averaged data for each sample until the mean drying time is reached. Heat flux curves for all of the underwear fabrics tested alone can be found in Appendix I. The heat flux curves for all of the cold weather fabric systems can be found in Appendix J.

Table 3. Physical properties of underwear fabrics

Sample ID	Fibre content	Construction	Fabric count	Mass*	Thickness	Air permeability
			wales x courses per cm	g/m^2 (std. dev.)	mm (std. dev.)	cm^3/cm^2/s (std. dev.)
UNDERWEAR						
A	95% cotton, 5% spandex	single jersey knit	23 x 17	179 (2.1)	0.56 (0.002)^a	27 (1.2)^a
B	95% polyester, 5% spandex	single jersey knit	27 x 16	164 (2.0)	0.61 (0.002)^b	103 (4.5)^b
C	95% cotton, 5% spandex with moisture management finish	single jersey knit	23 x 17	185 (1.8)	0.58 (0.002)^c	31 (1.9)^c
D	95% polyester, 5% spandex with moisture management finish	single jersey knit	25 x 16	155 (1.0)	0.59 (0.003)^c	128 (5.3)^d
E	100% polyester with activated carbon granules	single jersey knit	23 x 24	122 (1.0)	0.48 (0.005)^d	105 (3.2)^b
G	92% polyester (46% trilobal, 46% hollow), 8% spandex	single jersey knit	24 x 17	234 (2.1)	0.74 (0.009)^e	23 (0.7)^e
Y	55% cotton, 45% micro denier polyester with activated carbon granules	double jersey knit	Face = 20 x 15 Back = 20 x 16	159 (2.3)	0.77 (0.010)^f	135 (3.1)^d

*all fabrics were significantly different from each other as per the designated property ($p<0.05$)

$^{a, b, c, d, e, f}$ for each underwear fabric, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 4. Physical properties of lining, insulation, and shell fabrics

Sample ID	Fibre content	Construction	Fabric count	Mass*	Thickness*	Air permeability
			warp x filling per cm	g/m^2 (std. dev.)	mm (std. dev.)	cm^3/cm^2/s (std. dev.)
LINING						
H	100% polyester	Plain weave	45 x 37	87 (0.5)	0.15 (0.001)	2 (0.3)^a
I	60% polyester, 40% polyester with activated carbon granules	Plain weave	46 x 36	88 (0.5)	0.14 (0.000)	1 (0.3)^a
J	100% nylon	Plain weave	24 x 19	66 (0.6)	0.11 (0.000)	18 (0.9)^b
X	100% polyester with activated carbon powder in dyes	Plain weave	49 x 35	73 (0.6)	0.09 (0.000)	0 (0.1)^c
INSULATION						
K	100% polyester	nonwoven	n/a	70^e	1.23 (0.088)	n/a
SHELL						
L	100% polyester with laminated polyurethane microporous membrane	2 x 2 twill weave	51 x 56	196 (1.2)	0.37 (0.004)	0 (0.0)

*all fabrics were significantly different from each other as per the designated property ($p<0.05$)

$^{a, b, c}$ for each lining fabric, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

n/a = not applicable

^{e}data provided by manufacturer

Table 5. Thermal and liquid moisture management properties of underwear fabrics

Sample ID	Thermal Resistance	Moisture management mechanism	Liquid moisture management properties								
	Rct		LAC	OMMC	OWTC	SS_b	SS_t	MWR_b	MWR_t	Shape of wetted area	Direction of greatest spreading
	m^2C/W (std. dev.)		% (std. dev.)	index (std. dev.)	% (std. dev.)	mm/sec (std. dev.)	mm/sec (std. dev.)	mm (std. dev.)	mm (std. dev.)		
UNDERWEAR											
A†	0.013 (0.0000)^{a}	none	227 (7.2)^{a,b}	0.52 (0.106)^{a,b}	496 (255.7)	0.8 (0.69)	0.3 (0.19)	6 (1.6)	5 (0.0)	small circle	equal
B	0.011 (0.0005)^{b}	none	245 (13.5)^{b,c}	0.48 (0.098)^{a,b}	42 (101.9)	5.1 (0.46)	5.0 (0.53)	25 (0.0)	24 (2.4)	elliptical	crosswise
C	0.014 (0.0005)^{a}	one-way transport finishing treatment	217 (10.9)^{a}	0.66b (0.304)^{b,c}	347 (495.4)	3.8 (1.35)	0.8 (0.30)	29 (3.4)	8 (3.5)	elliptical	lengthwise
D	0.012 (0.0008)^{a,b}	one-way transport finishing treatment	215 (13.7)^{a}	0.76 (0.141)^{c}	941 (367.1)	4.0 (2.18)	2.4 (1.73)	27 (3.5)	24 (7.5)	elliptical	lengthwise
E	0.009 (0.0004)^{c}	activated carbon granules in fibre	250 (7.5)^{c}	0.54 (0.137)^{a,b}	94 (142.2)	6.7 (0.15)	6.7 (0.18)	30 (0.0)	30 (0.0)	circular	equal
G	0.016 (0.0005)^{d}	trilobal & hollow fibre morphology	194 (5.1)^{d}	0.45 (0.051)^{a}	22 (25.9)	3.9 (0.78)	3.9 (0.72)	23 (2.6)	23 (2.6)	elliptical	crosswise
Y	0.020 (0.0034)^{e}	one-way transport construction	346 (12.1)^{e}	0.57 (0.019)^{a,b,c}	131 (22.4)	4.1 (0.73)	4.0 (0.41)	30 (0.0)	21 (1.6)	elliptical	crosswise

†indicates moisture pooled in bottoms sensors

$^{a, b, c, d, e}$ for each underwear fabric, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 6. Thermal and liquid moisture management properties of lining, insulation, and shell fabrics

Sample ID	**Thermal Resistance****	**Moisture management mechanism**	**Liquid moisture management properties**								
	Rct		LAC	OMMC	OWTC	SS_b	SS_t	MWR_b	MWR_t	Shape of wetted area	Direction of greatest spreading
	m^2C/W (std. dev.)		% (std. dev.)	index (std. dev.)	%	mm/sec	mm/sec	mm	mm		
LINING											
H†	0.005 (0.0009)	wicking finish	70 (0.8)[a]	0.53 (0.062)[a]	121 (50.6)	7.6 (7.03)	5.3 (0.49)	30 (0.0)	30 (1.6)	circular	equal
I†	0.006 (0.0019)	wicking finish & activated carbon granules in fibre	69 (6.8)[a]	0.53 (0.078)[a]	86 (60.2)	7.2 (0.91)	3.1 (13.50)	30 (0.0)	30 (0.0)	circular	equal
J†‡	0.005 (0.0025)	none	0 (0.0)[b]	0.21 (0.273)[b]	-144 (564.6)	0.5 (0.50)	0.4 (0.25)	4 (2.4)	5 (1.6)	n/a	n/a
X†	0.005 (0.0015)	wicking finish & activated carbon powder in dye	46 (7.0)[c]	0.17 (0.081)[b]	-215 (110.7)	4.5 (7.28)	6.3 (9.79)	11 (1.6)	9 (2.4)	circular	equal
INSULATION											
K	0.224 (0.0082)	none	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
L	0.007 (0.0004)	microporous membrane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

**all lining fabrics were of equal thermal resistance ($F_{3,16} = 0.4$, p=0.76)

[a, b, c] for each lining fabric, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

† indicates moisture pooled in bottoms sensors

‡indicates liquid water bead formed on top of fabric

n/a = not applicable

Table 7. Average wet heat flux, drying time, and drying rate of underwear fabrics

Sample ID	**Wet heat flux**	**Drying Time**	**Drying rate**
	W/m^2 (std. dev.)	minutes (std. dev.)	$g/m^2 \cdot min$ (std. dev.)
UNDERWEAR			
A	1029 (31.7)^{b,c}	18 (0.6)^{a}	14 (0.5)^{a}
B	1117 (20.4)^{a,b}	14 (0.6)^{b}	18 (0.7)^{b}
C	1005 (29.5)^{b,c}	18 (1.0)^{a}	14 (0.8)^{a}
D	1091 (2.3)^{a,b}	14 (1.0)^{b}	18 (1.3)^{b}
E	1196 (8.2)^{a}	13 (0.6)^{b}	20 (0.9)^{b}
G	907 (1.7)^{d}	19 (0.6)^{a}	13 (0.4)^{a,c}
Y	983 (8.6)^{c,d}	22 (0.6)^{c}	11 (0.3)^{c}

$^{a, b, c, d}$ for each underwear fabric, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 8. Thermal properties of cold weather fabric systems

Sample ID	**Thermal Resistance****
	m^2C/W (std. dev.)
AH	0.230 (0.0062)
AI	0.229 (0.0067)
AJ	0.233 (0.0098)
AX	0.224 (0.0118)
BH	0.229 (0.0083)
BI	0.229 (0.0066)
BJ	0.229 (0.0073)
BX	0.227 (0.0076)
CH	0.228 (0.0086)
CI	0.228 (0.0075)
CJ	0.233 (0.0103)
CX	0.229 (0.0072)
DH	0.230 (0.0066)
DI	0.229 (0.0078)
DJ	0.230 (0.0092)
DX	0.228 (0.0056)
EH	0.226 (0.0082)
EI	0.225 (0.0081)
EJ	0.227 (0.0092)
EX	0.225 (0.0057)
GH	0.237 (0.0089)
GI	0.235 (0.0059)
GJ	0.236 (0.0104)
GX	0.235 (0.0103)
YH	0.237 (0.0089)
YI	0.235 (0.0059)
YJ	0.236 (0.0104)
YX	0.235 (0.0103)

**all cold weather fabric systems were of equal thermal resistance ($F_{27, 112} = 1$, $p=0.40$)

Table 9. Liquid moisture management properties of two-layer composites by sample ID

Sample ID	**Liquid moisture management properties**					
	OMMC	OWTC	SS_b	SS_t	MWR_b	MWR_t
	index (std. dev.)	% (std. dev.)	mm/sec (std. dev.)	mm/sec (std. dev.)	mm (std. dev.)	mm (std. dev.)
AH†	0.80 (0.023)[j]	538 (84.6)	4.6 (0.52)	0.8 (0.31)	30 (0.0)	12 (2.6)
AI†	0.79 (0.019)[j]	531 (65.0)	5.4 (0.98)	1.0 (0.79)	30 (0.0)	11 (2.1)
AJ	0.00 (0.000)[a]	-805 (75.6)	0.0 (0.00)	0.5 (0.11)	0 (0.0)	9 (3.2)
AX†	0.15 (0.035)[b]	-94 (48.9)	2.7 (0.37)	0.7 (0.31)	13 (4.2)	10 (0.0)
BH	0.60 (0.029)[f,g,h]	134 (21.9)	5.7 (0.17)	3.8 (0.12)	30 (0.0)	20 (0.0)
BI	0.62 (0.041)[h]	159 (30.1)	6.6 (0.56)	4.1 (0.36)	30 (0.0)	20 (0.0)
BJ	0.00 (0.000)[a]	-1044 (40.6)	0.0 (0.13)	5.0 (0.17)	1 (1.6)	25 (0.0)
BX	0.43 (0.055)[d]	4 (45.7)	5.2 (0.33)	4.3 (0.19)	30 (0.0)	23 (2.6)
CH	0.80 (0.089)[j]	573 (219.0)	4.8 (0.60)	0.8 (0.39)	30 (0.0)	7 (2.6)
CI	0.82 (0.065)[j,k]	714 (152.8)	5.3 (0.40)	0.8 (0.23)	30 (0.0)	7 (2.6)
CJ	0.00 (0.000)[a]	-374 (115.5)	0.0 (0.00)	1.1 (0.37)	0 (0.0)	9 (2.4)
CX	0.82 (0.035)[j,k]	665 (94.5)	4.6 (0.30)	0.9 (0.21)	30 (0.0)	9 (2.4)
DH	0.90 (0.014)[l]	975 (172.2)	7.0 (0.61)	2.0 (0.88)	30 (0.0)	14 (4.6)
DI	0.90 (0.020)[l]	994 (122.0)	7.4 (0.51)	1.9 (0.72)	30 (0.0)	13 (4.2)
DJ	0.00 (0.000)[a]	-386 (116.7)	0.0 (0.00)	3.0 (1.24)	0 (0.0)	22 (7.8)
DX	0.87 (0.029)[k,l]	887 (109.6)	6.2 (0.88)	2.4 (0.82)	29 (2.4)	18 (5.9)
EH	0.54 (0.034)[e,f,g]	86 (29.0)	6.3 (0.13)	5.3 (0.17)	30 (0.0)	26 (2.1)
EI	0.61 (0.042)[g,h]	151 (31.4)	7.0 (0.60)	5.1 (0.44)	30 (0.0)	25 (0.0)
EJ	0.00 (0.000)[a]	-1130 (28.6)	0.0 (0.00)	6.6 (0.90)	0 (0.0)	30 (0.0)
EX	0.43 (0.033)[d]	-19 (29.5)	6.2 (0.16)	5.9 (0.24)	30 (0.0)	30 (1.6)
GH	0.54 (0.033)[e,f]	106 (25.6)	4.9 (0.30)	3.2 (0.19)	30 (0.0)	20 (0.0)
GI	0.61 (0.051)[h]	162 (41.9)	6.1 (1.00)	3.7 (0.96)	30 (0.0)	20 (0.0)
GJ	0.00 (0.000)[a]	-967 (57.0)	0.0 (0.00)	4.1 (0.37)	0 (0.0)	23 (2.6)
GX	0.35 (0.029)[c]	-64 (46.2)	4.2 (0.77)	4.0 (0.54)	25 (2.8)	21 (1.6)
YH	0.73 (0.034)[i]	276 (27.0)	4.8 (0.05)	3.2 (0.22)	30 (0.0)	20 (1.6)
YI	0.78 (0.041)[i,j]	319 (30.4)	5.5 (0.11)	3.2 (0.19)	30 (0.0)	20 (1.6)
YJ	0.00 (0.000)[a]	-864 (51.3)	0.0 (0.00)	4.0 (0.17)	0 (0.0)	21 (2.1)
YX	0.50 (0.077)[e]	97 (55.0)	4.2 (0.29)	3.5 (0.18)	30 (0.0)	20 (0.0)

†indicates moisture pooled in bottoms sensors

[a,b,c,d,e,f,g,h,i,j,k,l] for each two-layer composite, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 10. Average wet heat flux, drying time, and drying rate of cold weather fabric systems

Sample ID	**Wet heat flux**	**Drying Time**	**Drying rate**
	W/m^2 (std. dev.)	minutes (std. dev.)	g·m^2/min (std. dev.)
AH	259 (8.1)^{b,c,d,e}	133 (6.7)^{a,b,c,d,e}	1.9 (0.10)^{a,b,c,d,e,f}
AI	262 (11.0)^{c,d,e}	146 (8.1)^{d,e,f}	1.7 (0.10)^{a,b,c}
AJ	237 (2.0)^{a,b,c,d,e}	129 (11.9)^{a,b,c,d,e}	2.0 (0.21)^{a,b,c,d,e,f}
AX	255 (11.5)^{a,b,c,d,e}	140 (6.7)^{c,d,e,f}	1.8 (0.06)^{a,b,c,d}
BH	265 (5.1)^{e}	135 (1.5)^{b,c,d,e,f}	1.8 (0.06)^{a,b,c,d,e}
BI	256 (10.0)^{b,c,d,e}	139 (7.9)^{c,d,e,f}	1.8 (0.10)^{a,b,c,d}
BJ	233 (9.2)^{a,b,c}	112 (8.1)^{a,b}	2.2 (0.17)^{e,f}
BX	256 (11.1)^{a,b,c,d,e}	124 (12.0)^{a,c,d}	2.0 (0.20)^{b,c,d,e,f}
CH	255 (12.2)^{a,b,c,d,e}	134 (3.2)^{a,b,c,d,e,f}	1.8 (0.06)^{a,b,c,d,e}
CI	254 (12.7)^{a,b,c,d,e}	137 (5.7)^{b,c,d,e,f}	1.8 (0.10)^{a,b,c,d}
CJ	231 (2.5)^{a,b}	126 (2.0)^{a,b,c,d,e}	2.0 (0.06)^{a,b,c,d,e,f}
CX	255 (13.0)^{a,b,c,d,e}	130 (5.1)^{a,b,d,e}	1.9 (0.10)^{a,b,c,d,e,f}
DH	253 (10.1)^{a,b,c,d,e}	126 (0.6)^{a,b,c,d,e}	2.0 (0.00)^{b,c,d,e,f}
DI	257 (7.5)^{b,c,d,e}	132 (11.0)^{a,b,c,d,e}	1.9 (0.17)^{a,b,c,d,e,f}
DJ	231 (7.2)^{a,b}	112 (5.5)^{a,b}	2.2 (0.10)^{e,f}
DX	251 (7.6)^{a,b,c,d,e}	124 (12.4)^{a,b,c,d}	2.0 (0.17)^{b,c,d,e,f}
EH	263 (7.8)^{d,e}	122 (10.1)^{a,b,c,d}	2.1 (0.15)^{c,d,e,f}
EI	262 (9.7)^{c,d,e}	117 (4.2)^{a,b,c}	2.1 (0.10)^{d,e,f}
EJ	235 (11.9)^{a,b,c,d}	109 (11.6)^{a}	2.3 (0.25)^{f}
EX	259 (9.5)^{b,c,d,e}	125 (8.6)^{a,b,c,d}	2.0 (0.10)^{b,c,d,e,f}
GH	243 (9.7)^{a,b,c,d,e}	151 (7.8)^{e,f}	1.7 (0.06)^{a,b}
GI	246 (8.1)^{a,b,c,d,e}	140 (9.0)^{c,d,e,f}	1.8 (0.10)^{a,b,c,d}
GJ	227 (12.5)^{a}	133 (11.2)^{a,b,c,d,e,f}	1.8 (0.15)^{a,b,c,d,e}
GX	240 (2.9)^{a,b,c,d,e}	142 (4.5)^{c,d,f}	1.7 (0.06)^{a,b,c,d}
YH	255 (8.1)^{a,b,c,d,e}	129 (9.5)$^{a,b,c,d.e}$	1.9 (0.15)^{a,b,c,d,e,f}
YI	257 (5.9)^{b,c,d,e}	132 (4.9)$^{a,b,c,d.e}$	1.9 (0.06)^{a,b,c,d,e}
YJ	241 (4.7)^{a,b,c,d,e}	130 (3.5)^{a,b,c,d,e}	1.9 (0.00)^{a,b,c,d,e,f}
YX	250 (4.6)^{a,b,c,d,e}	159 (11.5)^{f}	1.6 (0.10)^{a}

$^{a,\ b,\ c,\ d,\ e,\ f}$ for each fabric system, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 11. Average wet heat flux, drying time, and drying rate of cold weather fabric systems by underwear choice

Sample ID	Wet heat flux	Drying Time	Drying rate
	W/m^2 (std. dev.)	minutes (std. dev.)	g·m^2/min (std. dev.)
A	253 (12.7)^{b}	137 (10.2)^{c,d}	1.8 (0.16)^{a,b,c}
B	252 (14.5)^{b}	127 (13.1)^{a,b,c}	2.0 (0.21)^{b,c,d}
C	249 (14.2)^{a,b}	132 (5.7)^{b,c,d}	1.9 (0.10)^{a,b,c}
D	248 (12.7)^{a,b}	124 (10.6)^{a,b}	2.0 (0.16)^{c,d}
E	255 (14.7)^{b}	118 (10.0)^{a}	2.1 (0.17)^{d}
G	239 (10.8)^{a}	142 (9.8)^{d}	1.8 (0.11)^{a}
Y	251 (8.1)^{b}	138 (14.6)^{c,d}	1.8 (0.16)^{a,b}

$^{a,\ b,\ c,\ d}$ for each underwear choice, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Table 12. Average wet heat flux, drying time, and drying rate of cold weather fabric systems by lining choice

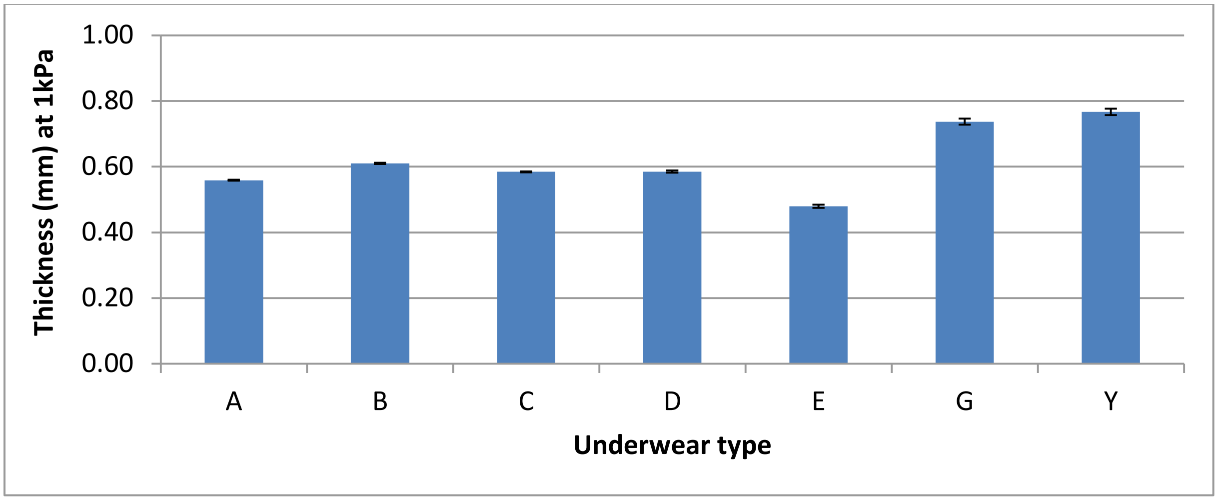
Sample ID	Wet heat flux	Drying Time	Drying rate
	W/m^2 (std. dev.)	minutes (std. dev.)	g·m^2/min (std. dev.)
H	256 (10.3)^{b}	133 (10.4)^{b}	1.9 (0.15)^{b}
I	256 (9.4)^{b}	135 (10.7)^{b}	1.9 (0.15)^{b}
J	234 (8.1)^{a}	122 (12.1)^{a}	2.0 (0.21)^{a}
X	252 (9.6)^{b}	135 (14.5)^{b}	1.9 (0.18)^{b}

$^{a,\ b,\ c,\ d}$ for each underwear choice, values with the same superscript letter do not differ significantly from each other for the specific property being measured (columns)

Analysis of physical properties of underwear fabrics

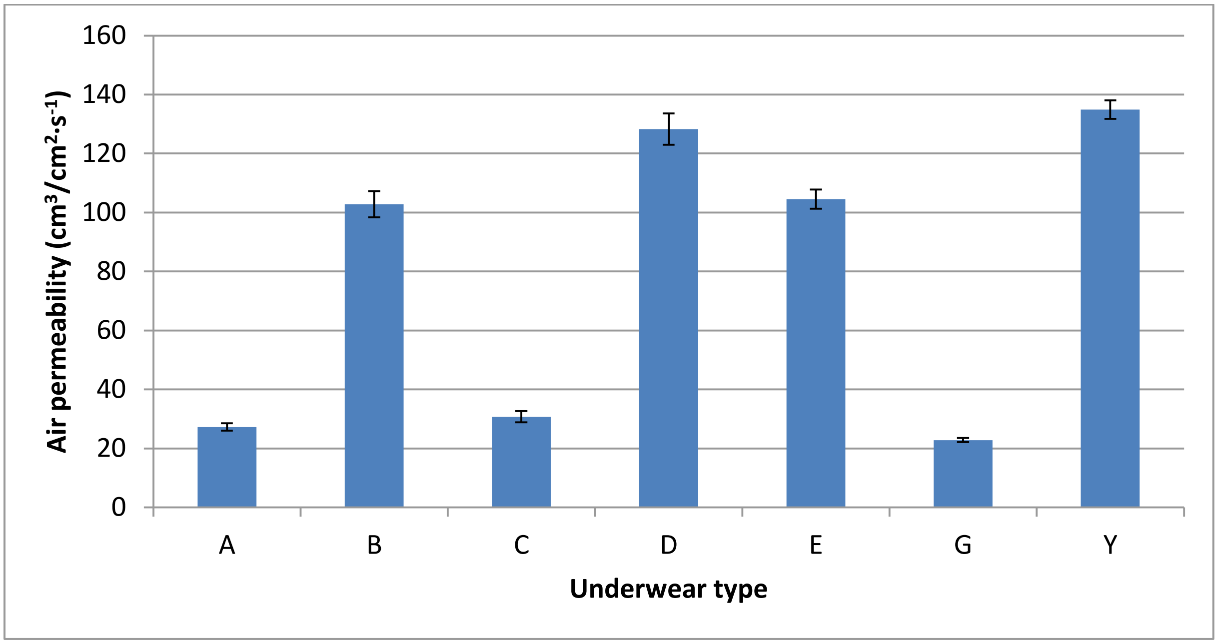
One-way ANOVA revealed significant differences among the underwear fabrics in terms of their mass ($F_{6,63}$ = 3515, p<0.001), thickness ($F_{6,63}$ = 3077, p<0.001), and air permeability ($F_{6,63}$ = 2366, p<0.001). Levene's homogeneity of variance test demonstrates equal variance for mass measurements, but not for thickness and air permeability. Post-hoc analyses showed that all underwear fabrics had significantly different mass per unit area from one another (p<0.05). Mean mass was 171g/m^2 across all underwear fabrics, where fabrics G (234g/m^2) and E (122g/m^2) represent the range of fabric weights and were considerably different from the other materials. All of the underwear fabrics also had significantly different thicknesses from one another except for fabric C (0.58mm) and fabric D (0.59mm). Fabrics G (0.74mm) and Y (0.77mm) had considerably greater thickness than the other fabrics, as seen in Figure 4. Notably, Fabric E has the lowest thickness (0.48mm) and mass per unit area of all the underwear fabrics.

Figure 4. Mean thickness of underwear fabrics



The air permeability of the underwear fabrics generally fell into two categories, high or low air permeability (Figure 5). Fabrics A, C, & G have air permeabilities below 35cm^3/cm^2/sec, whereas fabrics B, D, E, and Y all have values above 100cm^3/cm^2/sec. Despite fabrics A & C being from the same fabric roll, there were significant differences in their physical properties (fabric A being untreated, while C was treated). Significant differences were also noted for fabrics B (untreated) and D (treated), which were manufactured at the same time. The processing required to apply the treatment seems to have altered the physical properties of the fabrics. Comparing fabric A to C, there is a slight increase in the mass, thickness, and air permeability. It is suggested the mass and thickness increases are due to the moisture management resin bonding to the internal structure of the cotton fibres. Resin bonds with the internal structure of the cotton and is cross-linked when the treatment is cured at a high temperature (Rearick & Anderson, 2006). The weight of the resin increases the total mass per unit area of the fabric. The fabric is slightly thicker due to the swelling of the cotton fibres absorbing the resin, in the same way cotton fibres swell with increased moisture absorption when relative humidity rises (Wehner et al., 1987). The air permeability changes between fabrics A and C are statistically significant ($p<0.05$), but do not seem substantial enough to be caused by treatment application. It is suggested that the differences are due to fabric variability rather than treatment application. However, the marked increase in air permeability of fabric D (128cm^3/cm^2/sec) compared to fabric B (103cm^3/cm^2/sec) may be due to processing required to apply the treatment. As polyester is a thermoplastic, it is more temperature sensitive and vulnerable to deformation in comparison to cotton. It is possible the polyester fabric was not heat-set at a high enough temperature to prevent deformation prior to the application of the treatment. Therefore, the increased air permeability is a result of the high curing temperatures and pressure exerted by the rollers when the treatment is printed on the fabric. Pressure from the printing rollers may have stretched the fabric and opened up the knit. It then passes through a high temperature oven required to dry and crosslink the resin. Crosslinking the resin fixes the fabric in a more open state and prevents the fabric from returning to its relaxed state. Extension of the fabric can be confirmed by the reduced thickness (0.61mm to 0.59mm) and mass per unit area (164g/m^2 to 155g/m^2) when comparing fabrics B and D.

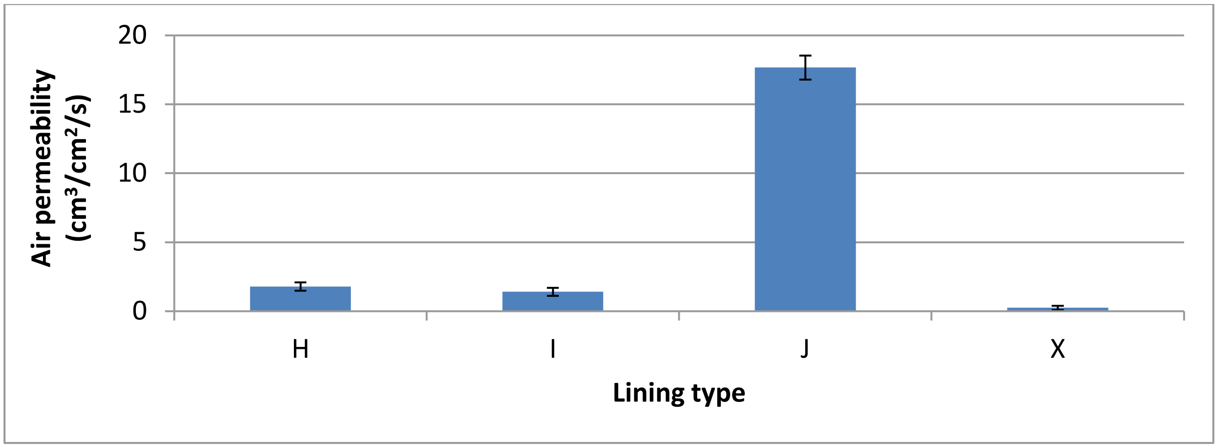
Figure 5. Mean air permeability of underwear fabrics



Analysis of physical properties of lining, insulation, and shell fabrics

One-way ANOVAs revealed there were significant differences among the lining fabrics in terms of their mass ($F_{3, 36}$ = 3759, p<0.001), thickness ($F_{3, 36}$ = 32673, p<0.001), and air permeability ($F_{3, 36}$ = 2870, p<0.001). Homogeneity of variance was satisfied for mass measurements, but not for thickness and air permeability. All fabrics were considered significantly different from each other with regards to their mass and thickness (p<0.05). Mean mass for the lining fabrics was 78g/m^2, where fabric J (66g/m^2) was much lighter than the other fabrics. While differences in thickness between lining fabrics were statistically significant, the fabrics were all approximately 0.1mm thick. The air permeability measurements of the lining fabrics are presented in Figure 6, where fabric J (18cm^3/cm^2/s) was significantly different from all other linings by a large magnitude. The higher air permeability and lower mass of fabric J were likely due to its low fabric count (24 x 19 yarns per cm), indicating there were fewer yarns per cm in comparison to the other lining fabrics. Fabrics H, I, and X were manufactured using the same specifications and contain approximately double the amount of yarns per cm in both warp and weft direction as fabric J.

Figure 6. Mean air permeability of lining fabrics



Statistical analyses were not carried out for the insulation and shell fabric as they were kept constant throughout the experiments. The mass of the insulation (70g/m^2) provided by the manufacturer was used to express the weight of the insulation because weighing small portions of nonwoven fabric is variable and would not be equal to the accuracy provided by the manufacturer. The shell fabric had an air permeability of 0cm^3/cm^2/s, which is typical for fabrics incorporating a membrane. The low air permeability is desirable for protection against heat loss in cold environments as it provides a barrier to wind removing heat via forced convection. This also indicated all moisture evaporating during the experiment would have to diffuse through the membrane in order to escape.

Analysis of thermal and liquid moisture management properties of underwear fabrics

With reference to Table 5, significant differences were noted between underwear fabrics in terms of their thermal resistance ($F_{6, 28} = 231$, $p<0.01$), liquid absorption capacity (LAC) ($F_{6, 28} = 110$, $p<0.001$), and overall moisture management capacity (OMMC) ($F_{6, 63} = 5$, $p<0.001$). Homogeneity of variance was satisfied for LAC, but not for thermal resistance and OMMC. Fabrics treated with moisture management finishes (fabrics C and D) did not have significantly different thermal resistance in comparison to their untreated versions (fabrics A and B). This was surprising, as air permeability was slightly higher for treated fabrics and previous research has demonstrated that moisture management finishes generally reduce the thermal resistance of fabrics (Sampath et al., 2012). Moisture management treatments are known to reduce thermal resistance because they provide a smoother fabric surface and reduce the amount of air trapped within a fabric (Sampath et al., 2012). An increase in contact area with the skin and reduction of air voids provides more efficient pathways for conduction to occur, thus reducing the thermal insulation of a fabric. However, this effect was not apparent for the untreated and treated fabric in this research. Fabric E had the lowest thermal resistance of all the underwear fabrics and was significantly different from the rest of the fabrics as determined by Tukey's post-hoc analysis. Fabric E had the lowest thickness (0.48mm), lowest mass per unit area ($122 g/m^2$), highest fabric count (23 by 24 yarns per cm), and had an air permeability above $100 cm^3/cm^2/s$. All of these factors contributed to a low thermal resistance measurement for fabric E, with previous research suggesting its thickness had the most significant effect on its thermal insulation (Morris, 1955; Ukponmwan, 1994; Woo, Shalev, & Barker, 1994). Hence, the thermal resistance of fabric G ($0.016 m^2C/W$) and fabric Y ($0.020 m^2C/W$) were the highest in comparison to the other underwear fabrics, corresponding to their greater thickness. The hollow fibres in fabric G did not appear to have a significant effect on the fabric's dry thermal resistance when compared to fabric Y, which was of comparable thickness and higher air permeability.

Underwear fabrics had a wide liquid absorption capacity (LAC) range of 194% to 346%, where analysis of variance revealed significant differences ($p<0.05$) in the quantity of moisture required to saturate each fabric (Figure 7). Fabrics treated with moisture management finishes (fabrics C and D) had a reduced LAC in comparison to their untreated version (fabric A and B). This was expected as the treatment creates hydrophobic regions on the inner surface of fabrics and is known to reduce the total quantity of moisture a fabric can hold (Rearick & Anderson, 2006). The treatment had a significant effect ($p<0.05$) on the LAC of the polyester fabrics, where fabric B had an initial LAC of 245% and was reduced to 215% (fabric D) after treatment. While the reduction in LAC was significant for the polyester fabrics, the treatment did not have a significant effect on cotton. The cotton fabrics had an initial LAC of 227% (fabric A) which was only reduced to 217% (fabric C). It is possible that the reduction in LAC was less for cotton fabric because it was not properly scoured and many fibres were initially hydrophobic due to natural waxes or knitting oils present on the fibre surfaces. This can be supported by examination of OMMC observations, where moisture pooled in the bottom sensors (Table 5; fabric A). Observations indicate droplets from the moisture management testing apparatus fell through the spaces between yarns without being absorbed into the cotton fibres and pooled in the bottom sensors. Hence, the treated and untreated cotton fabrics show marginal differences in LAC because of the low initial LAC of the untreated fabric.

Figure 7. Mean thermal resistance of underwear fabrics

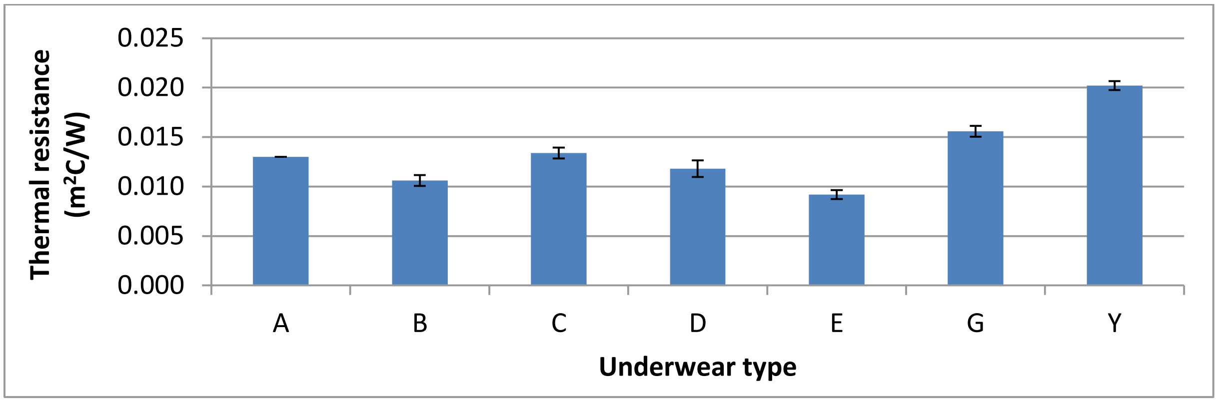
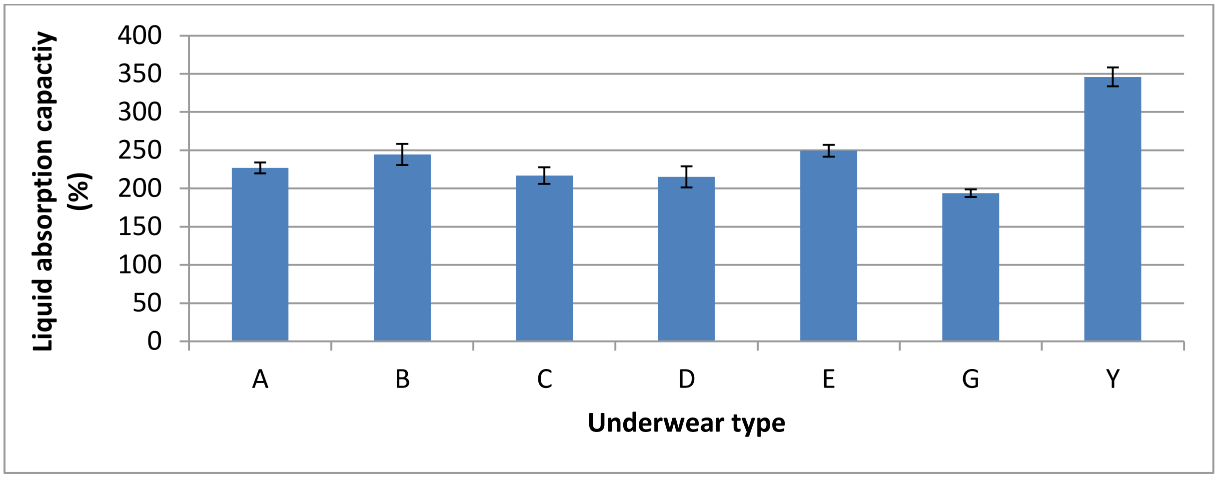


Figure 8. Mean liquid absorption capacity (LAC) of underwear fabrics

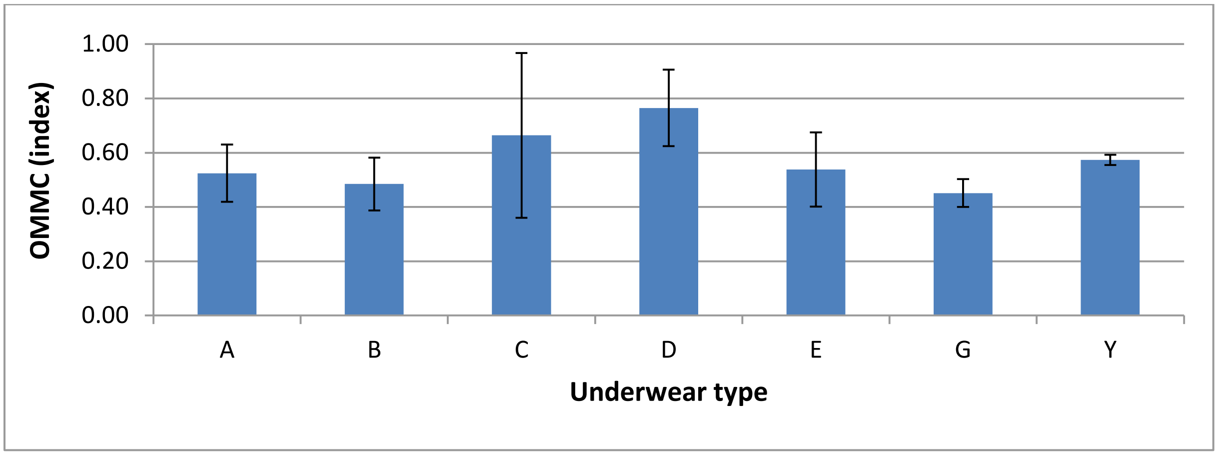


Fabric E (with activated carbon granules) demonstrated the highest LAC (250%) out of all the single jersey knit constructions and was significantly different ($p<0.05$) than all the other underwear fabrics, except for fabric B (untreated polyester). As the total volume of liquid a material can hold is positively correlated with its thickness, it is surprising to see the material with the lowest thickness has the highest liquid absorption capacity when comparing it to the other single jersey constructions (Crow & Osczevski, 1998). However, the high LAC of fabric E can be explained by the properties of polyester fibres doped with activated carbon granules. Previous research has shown that polyester fibres containing activated carbon demonstrate an increased absorption capacity in comparison to regular polyester fibres (Splendore et al., 2010). The higher sorption capacity is attributed to an increase in surface area when activated carbon is added, providing more surface area for moisture to adhere to on a fibre. The liquid absorption capacity data presented in this research provides further evidence that the sorption capacity of polyester can be improved by adding activated carbon granules. Hence, fabric Y consists of polyester doped with activated carbon granules and cotton, which combine to provide an extremely high LAC (346%) in comparison to the other underwear fabrics. As thicker materials have more air spaces for liquid moisture to be held, fabric Y also has a very high LAC due to its thickness. What is unclear and does not align with previous research, is the low LAC for fabric G (Crow & Osczevski, 1998). It is one of the thicker fabrics with hollow and trilobal fibres, yet it has a low LAC of 194%. A possible explanation for the low LAC of fabric G is that the fibres do not absorb any moisture and the tightly knit construction (as indicated by its low air permeability) prevents large quantities of moisture from being held within its structure.

Despite a low range in overall moisture management capacity (OMMC) among fabrics (0.45 – 0.76), significant differences ($p<0.05$) were noted. Examination of both Figure 9 and Table 5 reveals that fabrics varied in their ability to transport and spread moisture from the inner surface of the fabric to the outer surface. The untreated polyester (fabric B) showed the most significant increase ($p<0.05$) in OMMC when treated with the moisture management finish (fabric D). Further examination of results between fabrics B and D in Table 5 demonstrate that the moisture management treatment radically improved the one-way transport capacity, but decreased the spreading speed of moisture on both sides of the fabric (top and bottom). This indicates the moisture management treatment forces liquid moisture to the outer surface of a fabric, where it can be held away from the skin at the cost of a slightly reduced spreading speed. The OMMC was also improved by the moisture management treatment when comparing the untreated (fabric A) and treated (fabric C) cotton fabrics, but not significantly. The high variability in OMMC for fabric C (Figure 9) would suggest an uneven application of the finishing treatment. OMMC results were dependent on moisture droplets landing on evenly or unevenly treated sections of the fabric. Another reason for the marginal increase is due to incorrect measurements of OMMC for fabric A. Visual observations for fabric A show that moisture pooled in the bottom sensors, providing misleading OWTC and OMMC values as the sensors measure a high OWTC when droplets pass through to the bottom sensors (Table 5). The visual observation, low max wet radius, and low spreading speed for Fabric A signify that the OMMC should be much lower. Such observations confirm the limitations other authors have noted about the moisture management test apparatus (McQueen et al., 2013).

Fabric E's OMMC (0.54) was not significantly different from any underwear fabrics (except fabric B), even though it had the highest values for spreading speed (6.7mm/sec) and max wetted radius (30mm). This was unexpected as literature had shown that activated carbon granules increase the quantity of moisture that is absorbed per unit area (Splendore et al., 2010). This should have resulted in a decrease in spreading speed and distance, as more moisture is absorbed in a specific area. However, the higher fabric count of fabric E (23 by 24 yarns per cm) may have countered the slow spreading associated with activated carbon by creating a greater number of capillaries than the other fabrics. More capillaries would result in moisture spreading more rapidly (Hsieh, 1995). Fabric Y's inner surface also consisted of polyester fibre doped with activated carbon granules and serves as a good comparison for determining the effects fabric count had on improving the spread of moisture. Fabric Y had a lower fabric count (20 by 16 yarns per cm) than fabric E and demonstrates a lower spreading speed (SS_t) and max wetted radius (MWR_t), as seen in Table 5. It would seem the higher fabric count improved the spreading speed and distance of moisture spread, when comparing fabrics E and Y. Fabrics B, E, and G showed a low OMMC as the rating is heavily dependent (50%) on one-way transport capability (OWTC). Hence, fabric B, E, and G spread moisture evenly on both side of the fabrics. Whereas the fabrics engineered to provide one-way transport (fabric C, D, & Y) demonstrated higher OMMC values (Table 5). OMMC is therefore useful in determining which fabrics are better at transporting moisture from the inner surface of the fabric to the outer surface, rather than how quickly and far moisture spreads on a fabric. It is best to directly examine spreading speed and max wet radius results when understanding how quickly and far fabrics spread moisture.

Figure 9. Mean overall moisture management capacity (OMMC) of underwear fabrics



Analysis of thermal and liquid moisture management properties of lining, insulation, and shell fabrics

Although fabric J had a lower fabric count and higher air permeability than the other lining fabrics, thermal resistance measurements among lining fabrics were equal ($p<0.05$; Table 6). Homogeneity of variance was satisfied for thermal resistance measurements of lining fabrics. Not surprisingly, the nonwoven insulation had the highest thermal resistance out of all materials in this research (0.224 m^2C/W). The shell fabric demonstrated a thermal resistance similar to the lining fabrics (0.007 m^2C/W).

Insulation and shell fabrics were not tested for their liquid moisture management properties. Comparison of liquid absorption capacity (LAC) and overall moisture management capacity (OMMC) results in Table 6 indicate significant differences among lining fabrics (LAC: $F_{3, 16} = 226$, $p<0.001$; OMMC: $F_{3, 36} = 18$, $p<0.001$). Homogeneity of variance was not satisfied for LAC or OMMC, likely because there was zero variance for fabric J. Fabrics H and I were not significantly different from one another, even though fabric I contained activated carbon granules. Examination of the error bars in Figure 10 suggests the addition of activated carbon made the LAC of the lining more variable. This meant that some areas of the fabric contained more activated carbon granules than others. The effects of activated carbon granules in lining fabrics do not appear to have the same effect as they did in underwear fabrics. The properties imparted by activated carbon granules may be minimized by the quantity of fibres present in a fabric, where thicker fabrics (i.e. underwear) are more dependent on fibre properties than thinner fabrics (i.e. linings). However, the activated carbon in the underwear fabrics E and Y is also from a different source than the lining fabrics I and X. As the properties of activated carbon are largely dependent on the precursor material they are made from (Mesik & Cerny, 1970), it’s possible a better precursor was used to make the activated carbon in the underwear. Fabric J was significantly different ($p<0.05$) than the other lining fabrics, as it did not absorb any liquid moisture. Fabric X had a significantly lower LAC of 46%, in comparison to fabric H (70%) and fabric I (69%). Notably, fabric X had a lower air permeability, mass, and thickness in comparison to the other two lining fabrics that absorbed moisture (fabrics H and I). This would suggest fabric X had less air space for liquid moisture to be held, resulting in a low LAC in comparison to the other moisture absorbing linings.

The overall moisture management capacity (OMMC) of lining fabrics were measured and compared. Visual observations indicate that moisture pooled in the bottom sensors for all fabrics, even when fabrics spread liquid to the maximum wetted radius of the sensors (i.e. 30mm). This meant the volume of liquid moisture supplied by the apparatus was too much for the lining fabrics to manage. It would be recommended to reduce the quantity of moisture supplied by the apparatus in future testing with thin fabrics. Results presented in Figure 11 should be taken with caution as moisture pooling in the bottom sensors can lead to incorrect one-way transport capacity values (OWTC), therefore influencing the OMMC rating (by 50%) (McQueen et al., 2013). Fabrics H and I did not significantly differ from one another in terms of their OMMC. Further analysis of the spreading speed and max wet radius between fabrics H and I also indicate there were no differences between them. Fabric X was significantly different from the other lining fabrics ($p<0.05$). In comparison to fabrics H and I, fabric X had a much lower max wetted radius and spreading speed.

Figure 10. Mean liquid absorption capacity (LAC) of lining fabrics

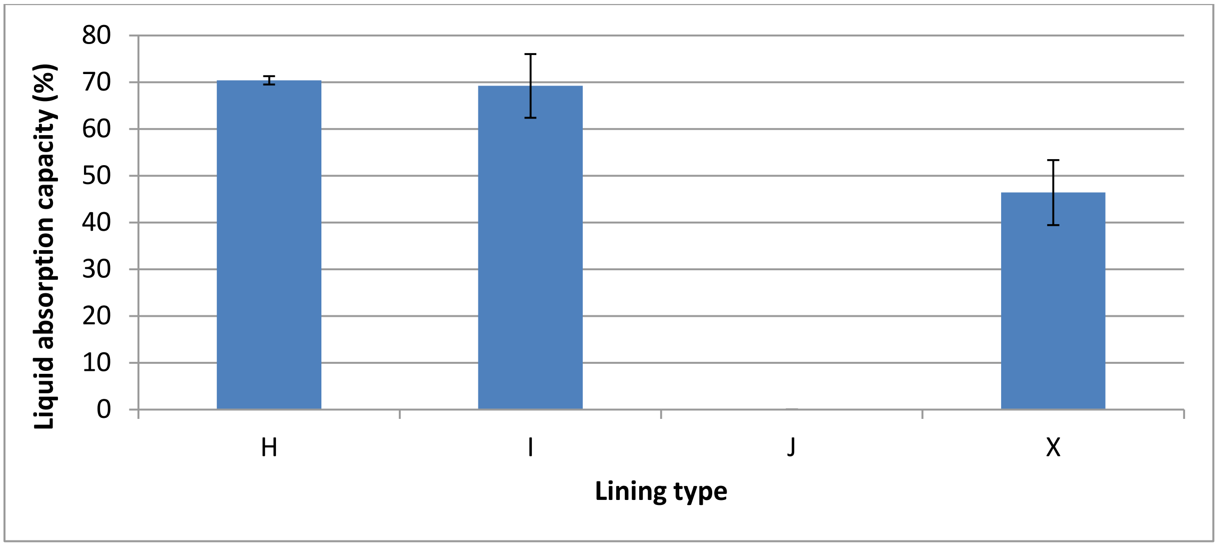
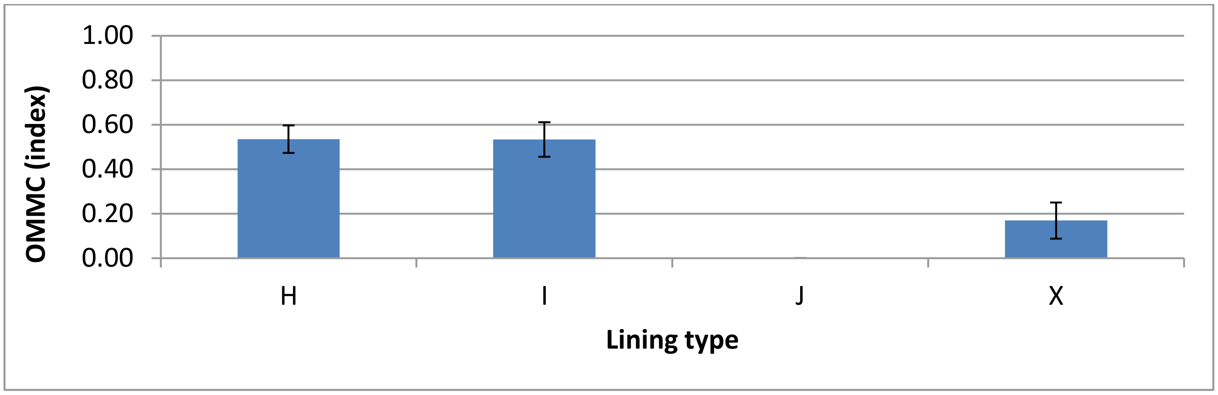


Figure 11. Mean overall moisture management capacity (OMMC) of lining fabrics



Analysis of wet heat flux of underwear fabrics

When underwear fabrics were tested as a single layer on the advanced sweating guarded hot plate and exposed to the same quantity of liquid moisture (25g), significant differences were noted between underwear fabrics in terms of their wet heat flux ($F_{6, 14}$ = 78, p<0.001). Homogeneity of variance was not satisfied for wet heat flux measurements of the underwear fabrics. Fabrics with moisture management treatments (fabric C & D) did not have a significantly different wet heat flux from the untreated versions (fabrics A & B). However, it was apparent from the heat flux curves (Figures 12 & 13) that the treatment reduced the amount of energy loss while in a wet state in comparison to the untreated fabrics. The moisture management treatment pushed moisture to the outer surface of the fabric, which resulted in a slight improvement in thermal insulation (as indicated by lower heat flux values). This finding supports previous research that also demonstrated energy loss is reduced by increasing the distance between moisture and the heat source (i.e. skin or hot plate) (Nielsen, 1994). Note that the energy loss can be related to thermal comfort experienced by a human wearing the fabric, as previous research has demonstrated a strong correlation between heat flux values and thermal sensations (Kawabata & Akagi, 1977). Thus, by increasing the distance between moisture and the heat source, energy loss can be reduced and thermal comfort can be improved when wet fabrics are against the skin. While moisture management treatment did not significantly influence wet heat flux, two-way ANOVA of wet heat flux by fibre type and moisture management treatment between fabrics A, B, C, & D revealed that fibre type had a significant effect ($F_{3, 8}$ = 39, p<0.001). As shown in Figure 14, cotton fabrics (A and C) had a slightly lower wet heat flux in comparison to the polyester fabrics (B and D). As fabrics B & D were manufactured to have similar physical properties as fabrics A & C, it is most appropriate to compare the effects of fibre type between these groups of fabrics. Differences in wet heat flux between cotton and polyester fabrics were thought to be related to the hairiness of yarns. Previous research has indicated the hairiness of yarns influence the amount of contact a fabric has with the skin, where hairier yarns provides less contact area and improve thermal sensations of warmth (Hopkins, 1950; Ozdil, Marmaral, & Kretzschmar, 2007; Pac et al., 2001; Schneider & Holcombe, 1991). Polyester yarns tend to be very smooth, whereas cotton yarns are much hairier. Even in wet condition, hairy yarns create a rough fabric surface where more air space exists between the inner surface of the fabric and skin (Hopkins, 1950). As the conductivity of air is much lower than fibres, maintaining air space between wet underwear and skin is important for reducing heat loss (Varshney et al., 2010). Thus, fabrics with hairy cotton yarns demonstrated a lower wet heat flux than polyester fabrics by maintaining more air space between the fabric and hot plate in wet condition. Underwear fabric E had the highest wet heat flux (Figure 14) which was a result of its fibre content (activated carbon granules), low thickness, and high fabric count. Activated carbon increases the quantity of moisture that can be held in a fabric by increasing the amount of surface available for moisture to adhere to per unit area (Splendore et al., 2010). As previously described, the distance between moisture and the heat source will influence energy loss. Hence, the low thickness accelerated energy loss. The high fabric count increased the amount of surface area in contact with the hot plate and total quantity of moisture held per unit area. As the conductivity of water is greater than that of fibres (Schneider et al., 1992), a high concentration of moisture per unit area leads to more rapid heat loss. The combination of these factors resulted in Fabric E having the highest wet heat flux out of all the underwear fabrics tested. Fabric G on the other hand, had the lowest wet heat flux out of all the underwear fabrics (Figure 14). This was surprising since Fabric G did not have the highest thermal resistance measurement when dry. Fabric Y had a higher thermal resistance (0.020m^2C/W) in comparison to fabric G (0.016m^2C/W). It appears the hollow and trilobal fibres in fabric G provided improved thermal insulation when wet. While OMMC results (Table 5) indicated that moisture was not transferred from the inner to outer fabric surface, OMMC does not account for moisture held within the middle of a fabric. It's possible moisture was pushed into the middle of fabric G and spread by the trilobal fibres, resulting in greater fibre contact with the heat source than moisture contact. The hollow fibres provided additional insulation when wet, as the conductivity of air is significantly less than fibres or water (Varshney et al., 2010). Maintenance of the air within fibres provided excellent thermal insulation when the fabric was saturated with moisture. The insulation provided by hollow fibres and keeping moisture away from the inner surface is also apparent when comparing the wet heat flux values of fabrics G and Y. While fabric Y was warmer than fabric G when dry, fabric Y was much colder when wet than fabric G due to differences in their moisture absorption properties (Figure 14). Fabric Y had polyester fibres doped with activated carbon on the inner surface and cotton on the outer fabric surface. This resulted in a large quantity of moisture being held on both the inner and outer surface of the fabric. As such, fabric Y showed large changes when comparing its dry and wet insulation values (i.e. thermal resistance and wet heat flux).

Figure 12. Heat flux plot of untreated and treated cotton fabrics

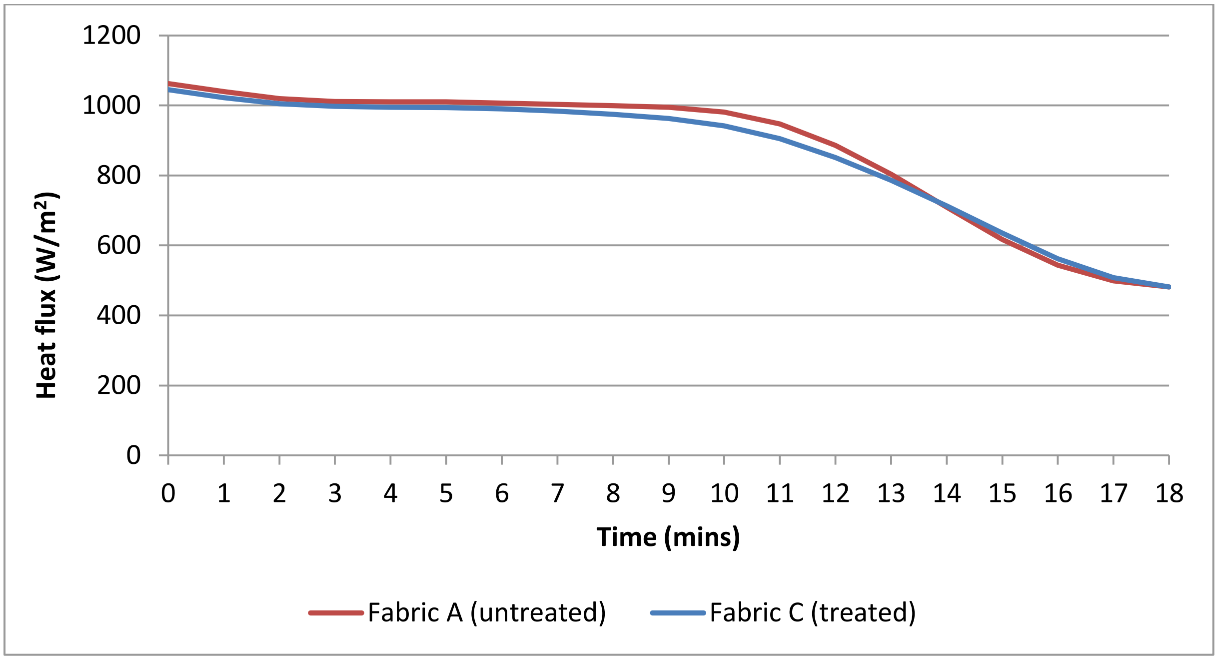


Figure 13. Heat flux plot of untreated and treated polyester fabrics

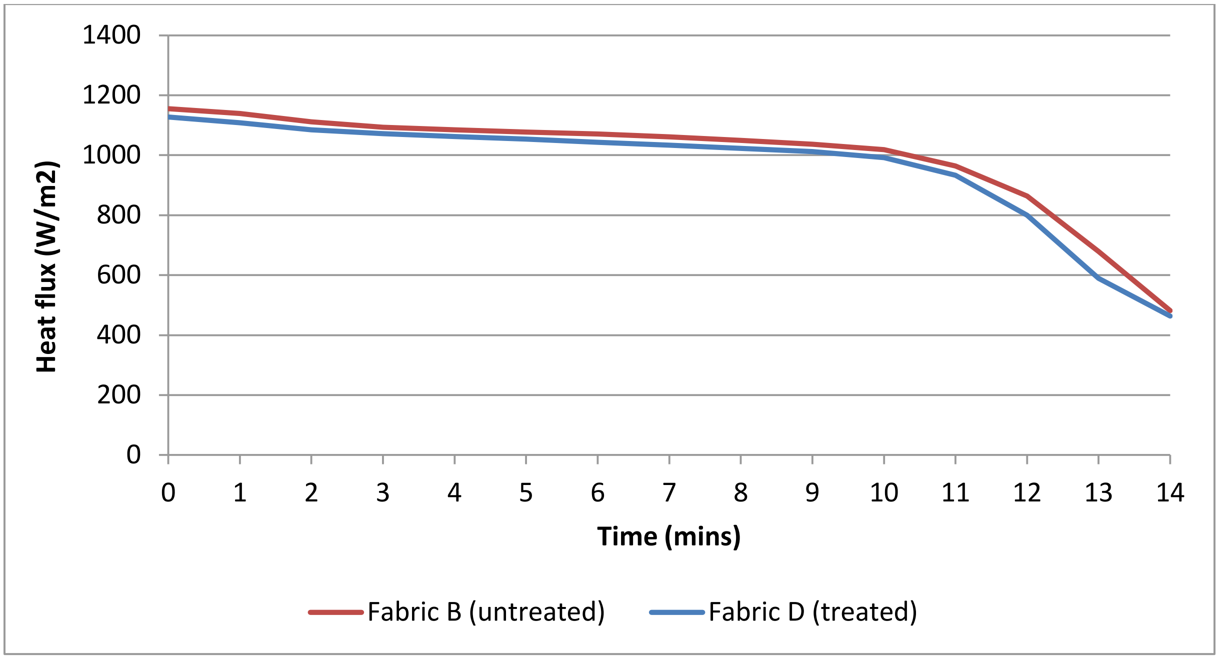
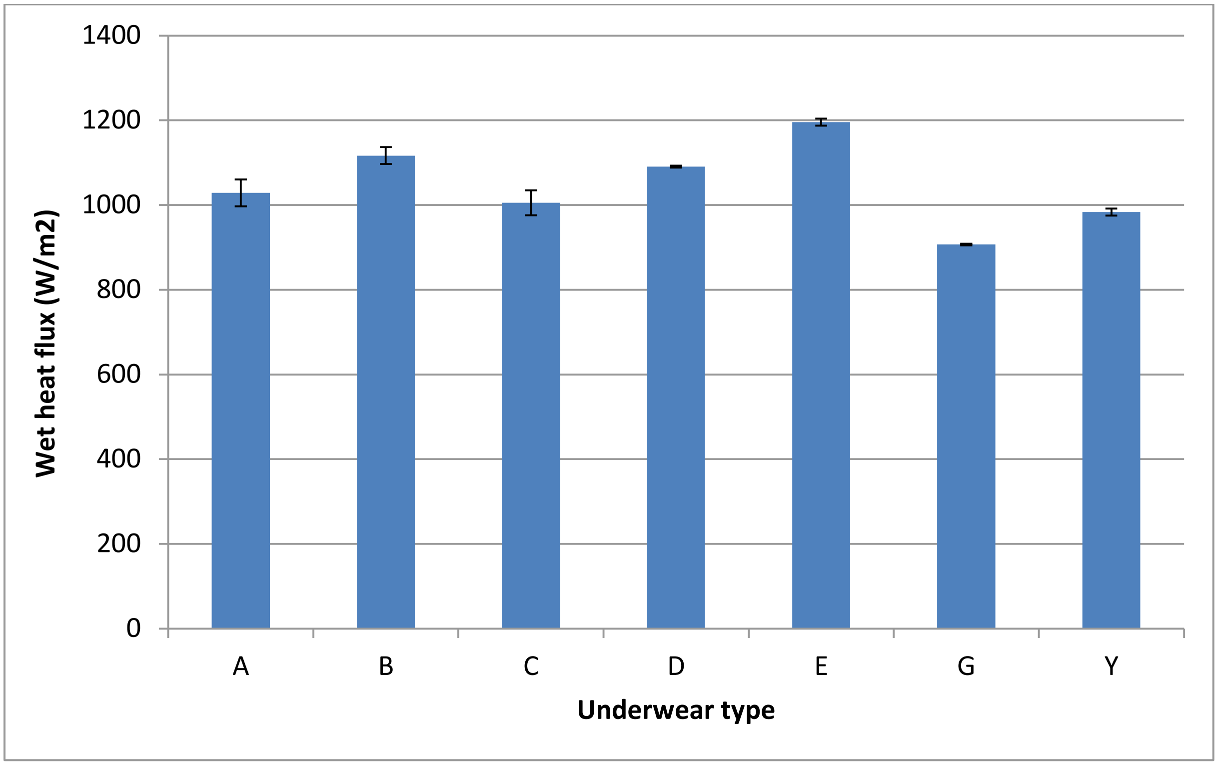


Figure 14. Mean wet heat flux of underwear fabrics



Analysis of drying time and drying rate of underwear fabrics

Significant differences were noted between underwear fabrics in terms of their drying time ($F_{6, 14} = 60$, $p<0.001$) and drying rate ($F_{6, 14} = 43$, $p<0.001$). Homogeneity of variance was satisfied for both drying time and drying rate measurements. As drying time is used to calculate drying rate, the values are directly related ($R^2=1$). Hence, this discussion will largely focus on drying time, yet it is important to note drying rate values are inverted from drying time values (Figure 15). While the moisture management treatment applied to fabrics C and D slightly improved the thermal insulation of wet underwear, it did not significantly impact the drying time or drying rate of the fabrics (Figures 12 & 13). In fact, mean drying time of the untreated and treated underwear fabrics were exactly the same. However, two-way ANOVA of drying time by fibre type and moisture management treatment between fabrics A, B, C, & D revealed that fibre type had a significant effect ($F_{3, 8} = 61$, $p<0.001$). Fabrics composed of polyester were found to dry more rapidly than cotton fabrics (Figure 16). It is worth noting that wet heat flux measurements were also significantly affected ($p<0.05$) by fibre type, where cotton fabrics drew less energy than polyester. Therefore, polyester fabrics draw more energy than cotton, but dry much faster. This can be understood by examining differences in the way cotton holds moisture in comparison to polyester. Cotton is hygroscopic and contains many bonding sites for water molecules (Rengasamy, 2011). Moisture is held within the internal structure of the cotton fibres, whereas polyester only holds moisture on the surface of fibres. The evaporation process from polyester fibres is therefore quicker than for cotton fibres, as more energy is required to break the hydrogen bonds between moisture and cotton fibres. The slower desorption process is apparent when examining Figure 16, where both fabrics begin to release moisture at the same time (as indicated by a steep drop in heat flux), yet the cotton fabric takes longer to reach a completely dry state. Therefore, fibres with higher moisture regain will demonstrate a slower drying rate because their regain is directly related to the quantity of hydrophilic sites that are available for moisture to bond with (Crow & Osczevski, 1998). The more hydrophilic sites available for moisture to bond, the higher amount of energy required to break all the hydrogen bonds and evaporate moisture. Another reason for the differences in drying time between the cotton and polyester fabrics can be understood by examining the amount of energy required for moisture to evaporate (i.e. enthalpy of vaporization). Water (or perspiration) requires a specific amount of thermal energy to evaporate, known as the enthalpy of vaporization (ASHRAE, 2005). At the surface of the hot plate set to 35°C, the enthalpy of vaporization of water at saturation is theoretically 2418kJ/kg$_w$; which is 2418 kilojoules of energy per kilogram of water (ASHRAE, 2005). The temperature of the inner surface of the underwear fabric should be very close to the temperature of the hot plate, meaning moisture on the inner surface of the underwear will require approximately 2418kJ/kg$_w$ to evaporate. As the polyester fabrics have a higher wet heat flux, the rate of energy transfer through the polyester fabrics is greater than the amount transferring through the cotton fabrics. Thus, moisture held on the surface of polyester fibres reaches its enthalpy of vaporization much quicker than moisture held within the cotton fibres. However, not all the moisture within the cotton fabric is held within the internal structure. Some moisture is surely held on the surface in a similar manner as the polyester fibres (by process of adsorption). Yet cotton displays a slower drying rate because it must evaporate all moisture (on the surface of fibres and within) before it can be considered completely dry. The reduced energy transfer rate into the fabric, combined with the greater quantity of energy required to break hydrogen bonds, results in slower drying times for cotton fabrics. Understanding the enthalpy of vaporization of water also explains why fabric E (activated carbon) with the highest wet heat flux demonstrated the fastest drying time (Figure 15). In fact, the polyester fabrics with similar physical properties (fabrics B, D, and E) formed a homogenous group in terms of wet heat flux, drying time, and drying rate (Table 7). Fabric G (hollow & trilobal fibres) had a similar construction to fabrics B, D, and E, but was significantly warmer when wet ($p<0.05$) than fabrics B, D, & E (as indicated by a lower wet heat flux). As previously explained, this was due to the insulating effects of the hollow fibres and the way fabric G held moisture away from the hot plate. This significantly reduced the energy transfer through the fabric and resulted in a slower drying time than the other single jersey knits (Figure 15). This is apparent when examining the long, flat heat flux plot of fabric G in comparison to fabric D (treated polyester) in Figure 17. Fabric D is plotted against fabric G, as fabric D had the lowest wet heat flux out of homogenous group of fabric B, D, and E.

Figure 15. Mean drying time and drying rate of underwear fabrics

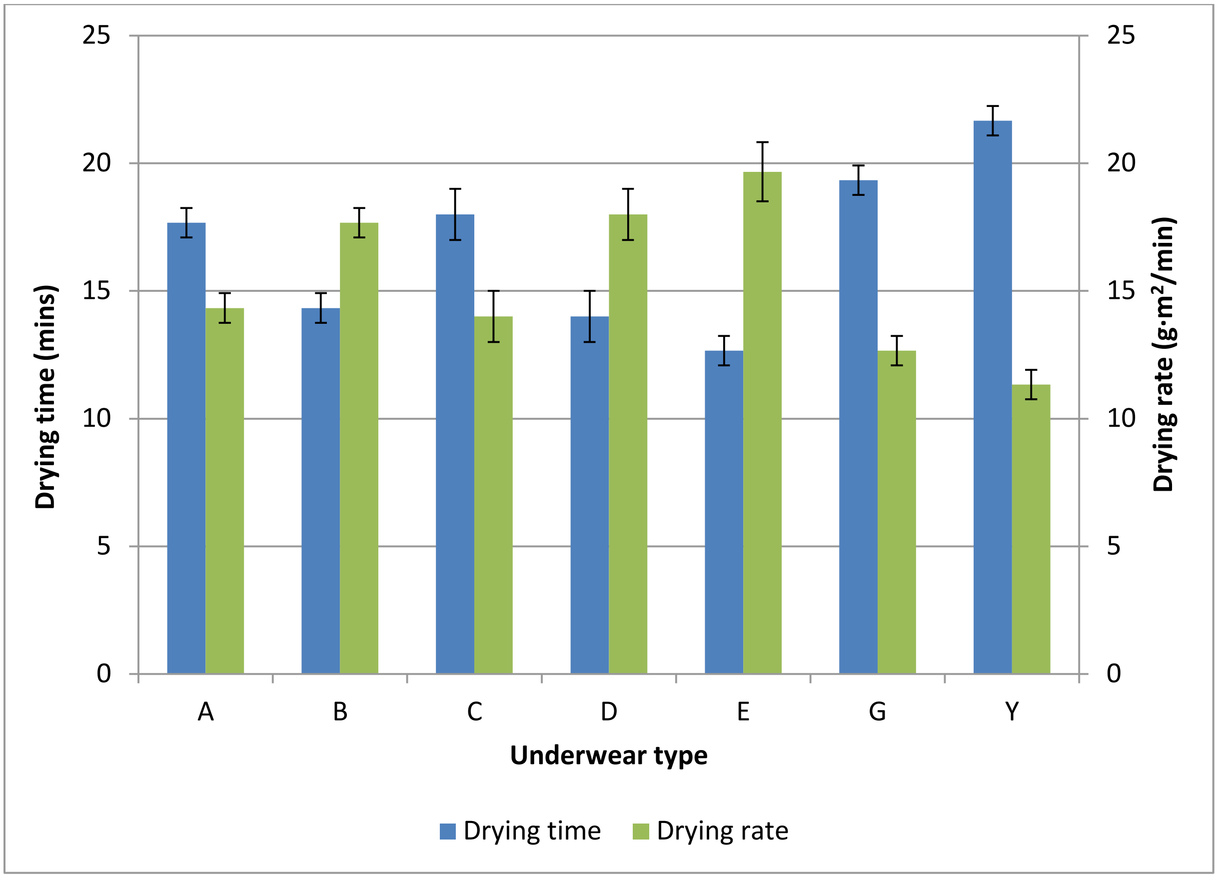


Figure 16. Heat flux plot of untreated cotton (fabric A) and polyester (fabric B)

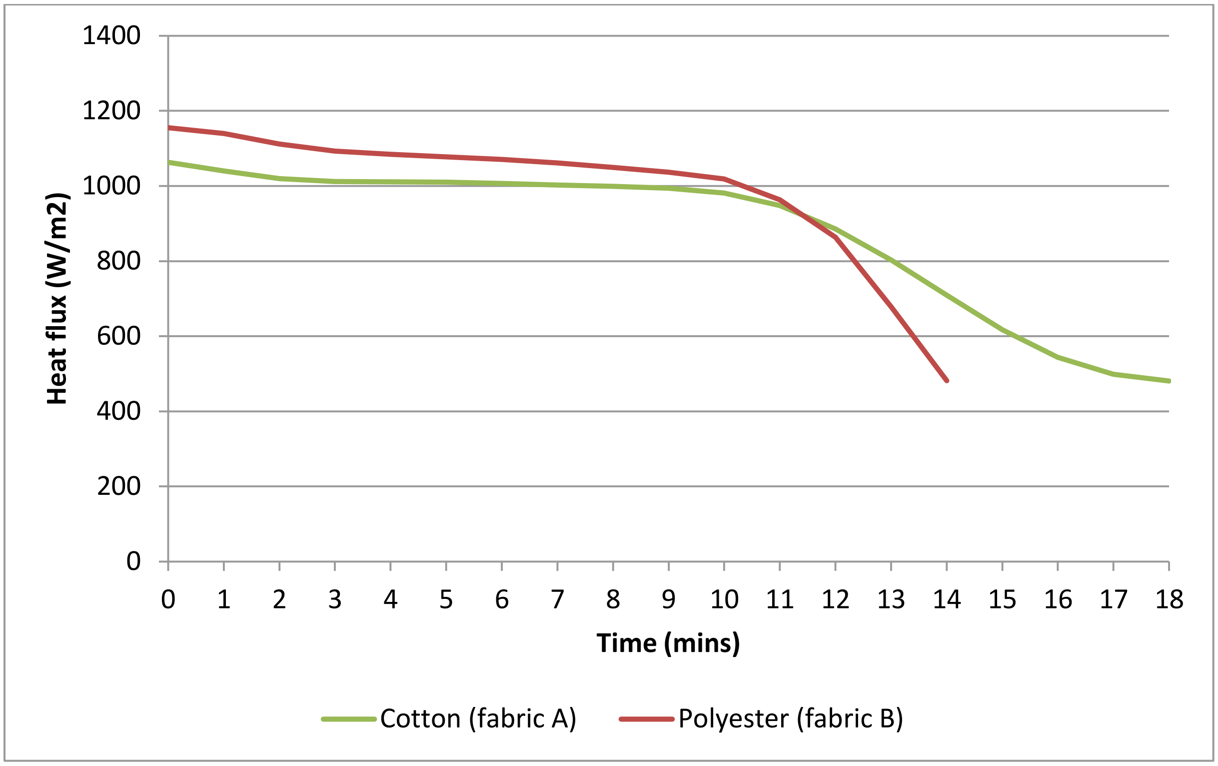
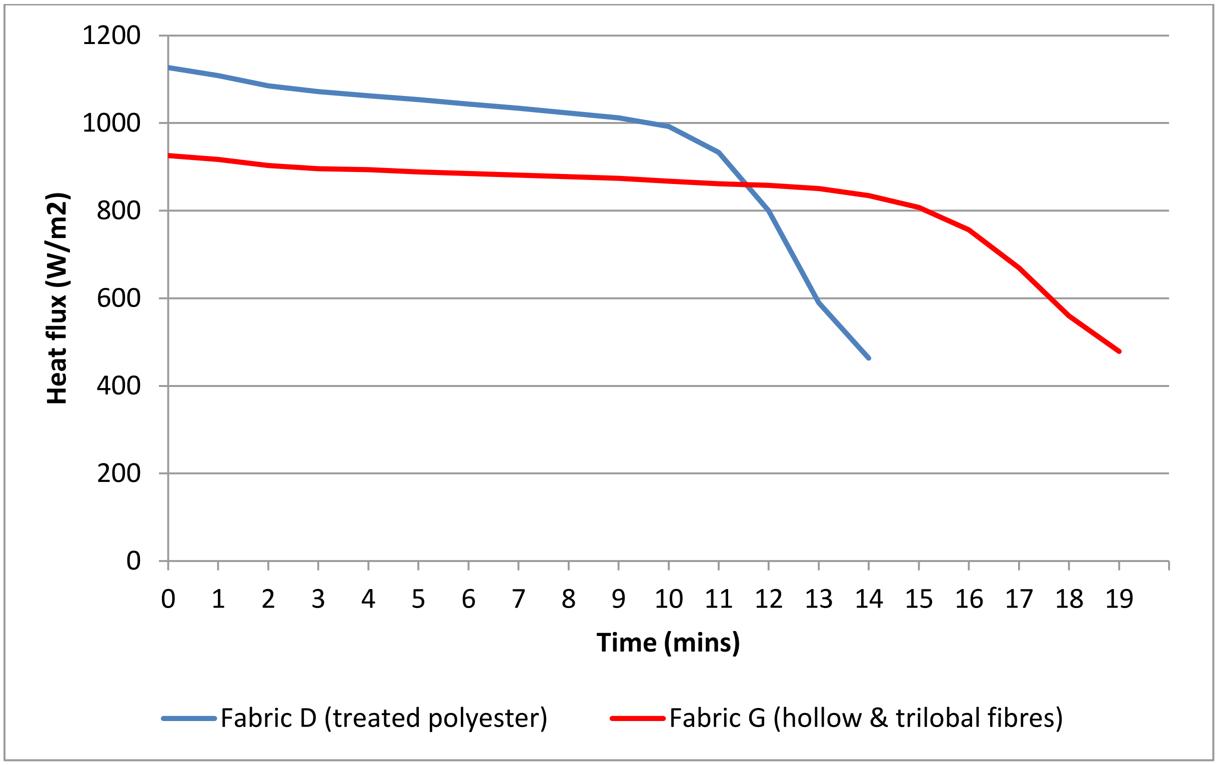


Figure 17. Heat flux curve of fabric G and fabric D



Understanding the enthalpy of vaporization reveals that fabrics with higher wet heat flux should dry more rapidly than those that draw less energy. Hence, a strong correlation (R^2=0.81) was found between wet heat flux and drying rate (Figure 18). Yet fabric Y's wet heat flux of 983 W/m^2 was higher than fabric G (907 W/m^2) and did not dry as quickly (Figure 19). Analysis of the heat flux curve in Figure 19 reveals why this has occurred. Fabric Y (one-way transport construction) starts off at a much higher heat flux than fabric G (hollow & trilobal fibres). As the fabrics begin to absorb energy from the hot plate, fabric Y appears to constantly decrease while fabric G remains constant. The heat flux curve for fabric Y begins to decrease its slope over time and eventually flattens out around minute twelve. This decrease in slope and flattening of the heat flux curve represents moisture moving from the inner fabric layer of the double knit to the outer fabric layer. It is unclear if the moisture moving between the layers is liquid or vapor; all that is certain is that it is moving. Moisture moves into the second layer (made of cotton) and is absorbed. For the fabric to continue drying, moisture in the second layer must reach its enthalpy of vaporization in order to evaporate. However, the second layer of the double knit will be a different temperature than the inner fabric layer, due to a temperature gradient that exists between the fabric surfaces. Hence, the enthalpy of vaporization of moisture from the second layer will be greater than the inner surface. For example, assume the second layer of the knit is 30°C and the first layer of the knit is 35°C. The enthalpy of vaporization of water at saturation from the first fabric layer is 2418kJ/kg_w, while the second (outer) fabric layer will require 2430kJ/kg_w (ASHRAE, 2005). Thus, more energy is required to evaporate moisture that moved into the second layer of the fabric and results in a slower drying time.

Figure 18. Correlation between drying rate and wet heat flux of underwear

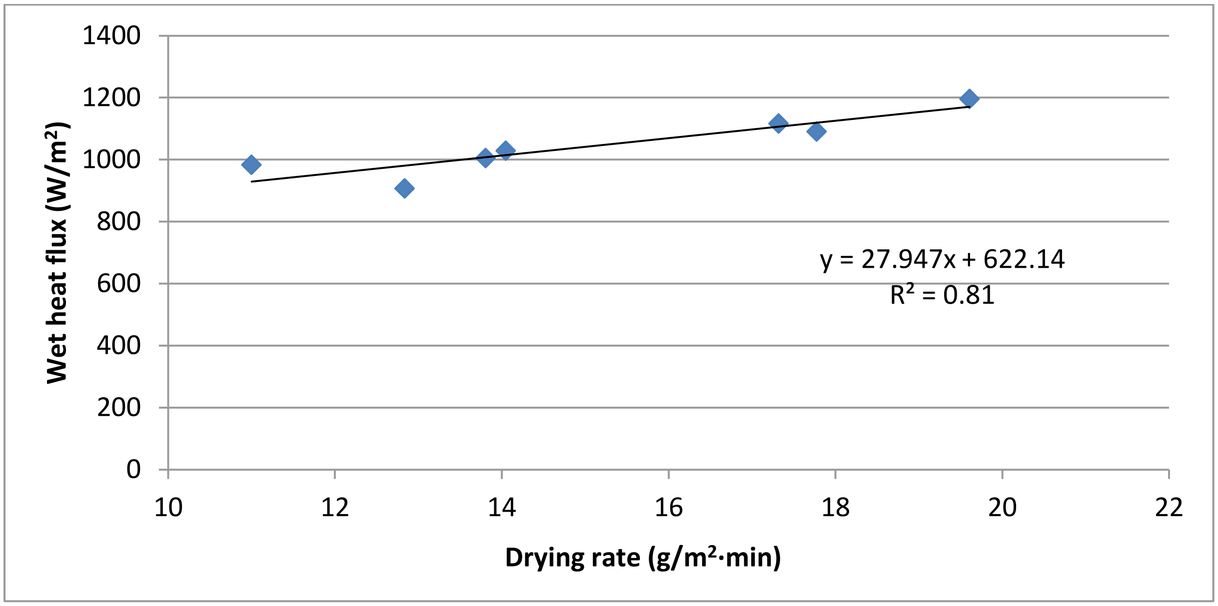
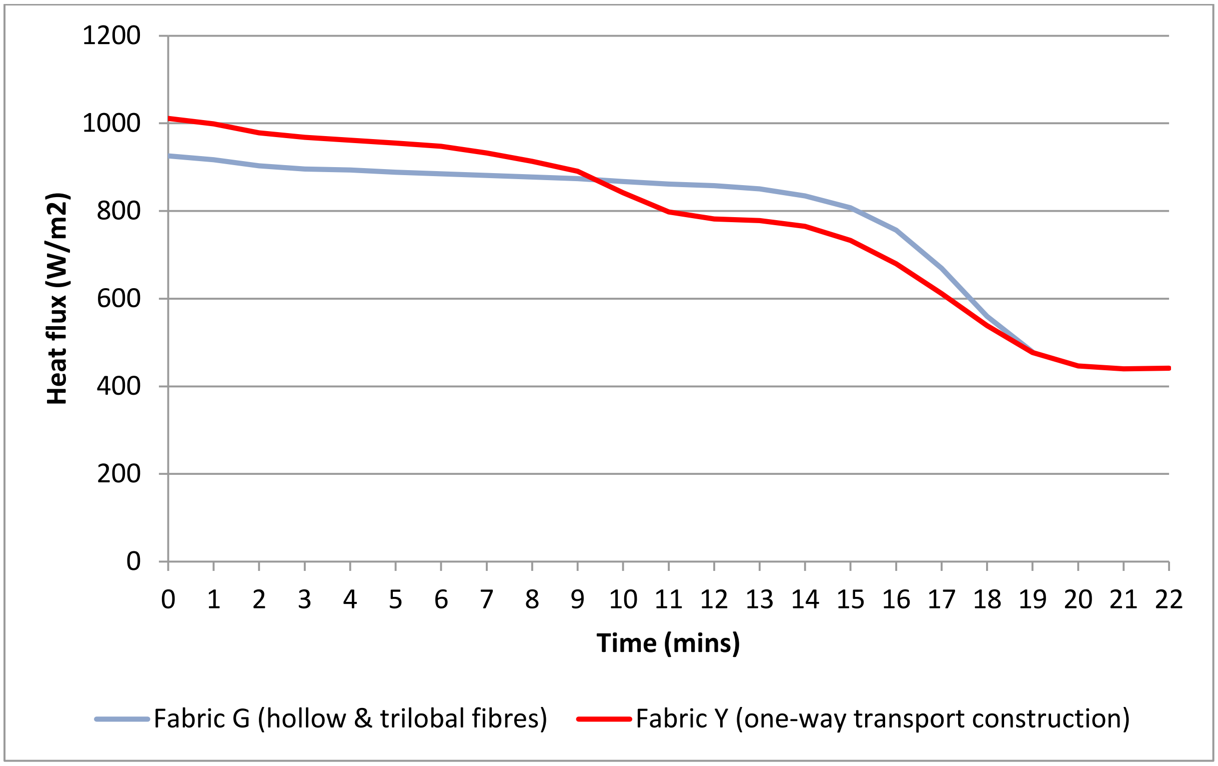


Figure 19. Heat flux plot of fabric G and fabric Y



Upon further examination of the data collected on the drying time of underwear fabrics, it was hypothesized that correlating saturation levels to drying time may be of value. As such, saturation levels were determined by calculating the quantity of moisture per unit area added to the hot plate specimens and the quantity of moisture per unit area required to saturate fabrics during the liquid absorption capacity (LAC) experiments. Saturation levels for each underwear fabric were calculated using Equation 8, where S is the saturation level of the fabric expressed as a percent of its LAC (%), M is the quantity of moisture per unit area added to the hot plate specimens in grams per metre squared (g/m^2), and L is the liquid absorption capacity of specimens in gram per metre squared (g/m^2). Results are displayed in Table 13.

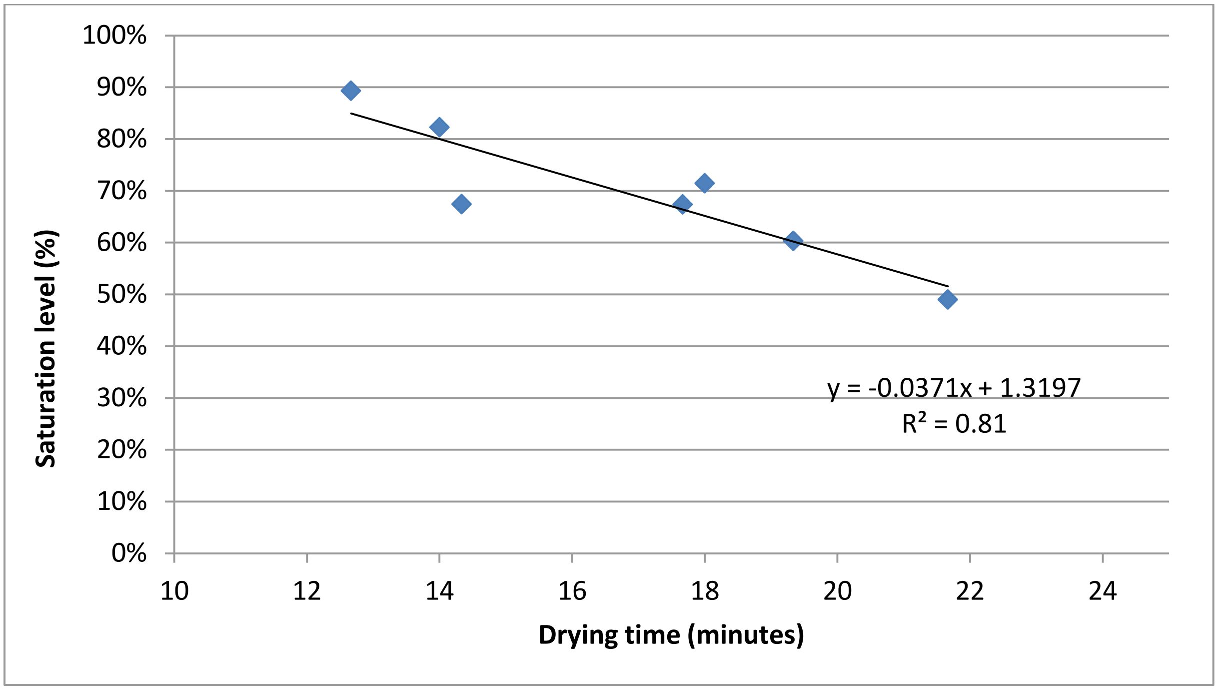
$$S = \frac{M}{L} \tag{8}$$

When saturation levels were correlated with drying time of underwear fabrics (Figure 20), a strong negative relationship was found (R^2=0.81). This meant that higher saturation levels resulted in shorter drying times. It is possible that a higher saturation level makes moisture more accessible for evaporation to occur by being exposed to the environment, where wind can directly affect the rate of evaporation from the fabric. In thicker fabrics, moisture is spread and trapped within the fabric structure where wind may not be able to influence evaporation rates. Additionally, if moisture is trapped within the structure of the fabric it will be more difficult for moisture to evaporate due to a slower rate of energy transfer directly to the moisture.

Table 13. Saturation levels of underwear fabrics exposed to 248g/m^2 of moisture

ID CODE	LAC	Saturation level
	(g/m2)	(%)
A	368	67.4%
B	368	67.4%
C	347	71.5%
D	301	82.3%
E	278	89.3%
G	411	60.3%
Y	506	49.0%

Figure 20. Correlation between drying time and saturation level



CHAPTER 4: RESULTS AND DISCUSSION

Analysis of thermal properties of cold weather fabric systems

The thermal resistance of the twenty eight different cold weather fabric systems were measured and compared. Despite significant differences ($p<0.05$) between the thermal resistance of underwear fabrics, the thermal resistance of the cold weather fabric systems were not significantly different from one another ($F_{27, 112} = 1$, $p=0.40$). Notably, the only variation in thermal resistance could come from the underwear fabrics, as the same shell fabric was used for each fabric system and the linings were found to be of equal thermal resistance. The nonwoven insulation (fabric K) had a thermal resistance of ($0.224 m^2 \cdot C/W$) which provided at least ten times more thermal insulation than the rest of the fabrics compiled in all of the cold weather fabric systems. Due to the exceptionally high thermal resistance provided by the nonwoven insulation, the thermal resistance of the cold weather fabric systems were not affected by differences between the underwear fabrics. This means for the range of thermal resistance of the underwear fabrics in this research ($0.009 – 0.020\ m^2 \cdot C/W$), any of the fabrics can be chosen without an individual experiencing significant differences in heat loss. Therefore, the underwear fabrics within the jacket systems can be compared in terms of their moisture related properties (i.e. wet heat flux, drying time, and drying rate) without there being differences in thermal comfort when wearing these cold weather fabric systems dry.

Analysis of liquid moisture management properties of two-layer composites

Two-layer composites consisted of all possible combinations of underwear and lining fabrics within the cold weather fabric systems. The composites were measured for overall moisture management capacity (OMMC) to determine how different underwear and lining fabrics interact and transfer moisture between them (Table 9 & Figure 21). As the OMMC calculation is largely based on the properties of the bottom fabric (the lining), two-layer OMMC was also graphed by lining type (Figure 22). As expected, there were significant differences noted between two-layer composites in their ability to transport moisture from the underwear into the lining fabric ($F_{27, 252} = 780$, $p<0.001$). Homogeneity of variance between OMMC measurements for two-layer composites was not satisfied. Underwear choice was irrelevant when combined with lining J (hydrophobic), as moisture remained in the underwear and was not transported between fabric layers no matter how well the underwear transported moisture (Figure 22). Hence, any underwear fabrics that combined with lining J demonstrated an OMMC of 0.00. Notably, the trends seen in Figure 22 follow similar patterns as found when the lining fabrics were tested on their own (Figure 11 or Table 6). Composites with lining fabrics H (wicking) and I (activated carbon granules) did not demonstrate significant differences in their ability to transport moisture from the underwear fabrics. This was not surprising as these fabrics also had similar measurements when tested on their own. However, composites with lining H and I did result in the highest OMMC ratings due to their ability to remove moisture from the underwear and spread it rapidly. Hence, lining type had a significant influence on the OMMC of two-layer composites ($F_{3, 252}$ = 5608, p<0.001). Two-layer composites incorporating lining X (OMMC of 0.51) had lower OMMC than composites with lining fabrics H (OMMC of 0.70) or I (OMMC of 0.73). This was due to fabric X's slower absorption and spreading speed, which is apparent in single layer testing results (Table 6). The underwear fabrics also had a significant role in influencing the OMMC of the two-layer composite ($F_{6, 252}$ = 361, p<0.001). Examination of Figure 21 and OMMC ratings for underwear fabrics tested alone (Table 5) demonstrate that when an underwear and lining fabric both have a high OMMC, there will be excellent one-way transport of moisture from the inner fabric layer to the outer fabric layer. For example, underwear fabric C (OMMC of 0.66), fabric D (OMMC of 0.76), and fabric Y (OMMC of 0.57) had the highest OMMC's out of all the other underwear fabrics when tested as a single layer. When these fabrics were combined with lining H or I (both with an OMMC of 0.53), they had very high OMMC's (Figure 21). When the underwear with the highest OMMC (fabric D) was combined with lining H or I, the composite had the best performance (Figure 21). Hence, a significant interaction effect between underwear and lining fabrics for OMMC results was found ($F_{18, 252}$ = 115, p<0.001). Note the high OMMC for fabric A (in both single layer and two-layer composite testing) is an error due to moisture falling through the fabric and pooling in the sensors. OMMC ratings of both single layer and two-layer composite testing are therefore a useful tool for characterizing one-way transport of moisture between adjacent fabrics layers.

Figure 21. OMMC of two-layer composites

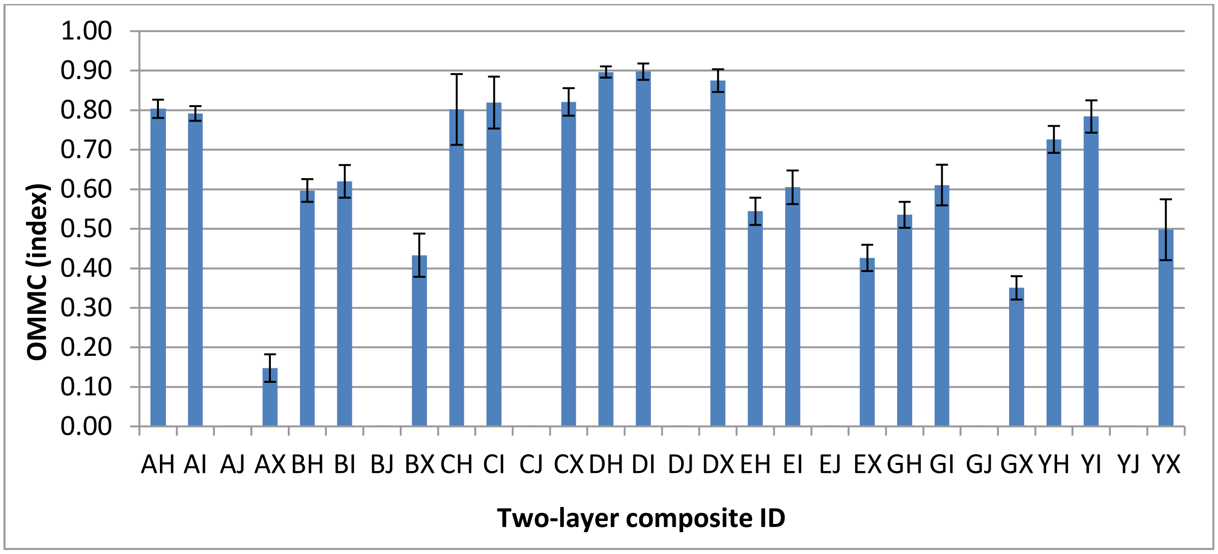
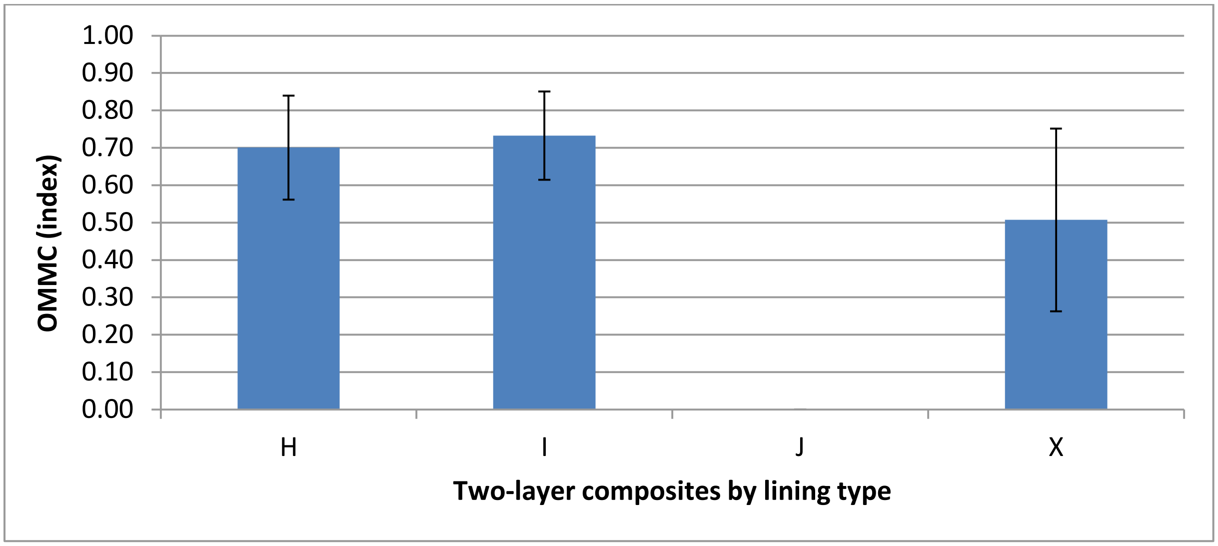


Figure 22. OMMC of two-layer composites by lining type



Analysis of wet heat flux of cold weather fabric systems

Each underwear fabric was exposed to the same quantity of moisture (25g) and placed on the advanced sweating guarded hot plate under the four different jacket systems (i.e. jacket systems with lining fabric H, I, J, or X). Two-way ANOVA of cold weather fabric systems by underwear and lining type revealed significant differences in wet heat flux measurements ($F_{27, 56} = 5$, $p<0.001$). Homogeneity of variance was satisfied for the wet heat flux measurements. As it is difficult to see meaningful trends when cold weather fabric systems were analyzed by sample ID, this discussion will largely focus on the differences of the fabric systems when analyzed by underwear and lining type (Figure 23 & 24).

Underwear type was found to have a significant effect of the wet heat flux of the cold weather fabric systems, where jacket systems with underwear G (hollow fibres) were significantly different from the rest ($F_{6, 56} = 4$, $p<0.01$). As there were no significant differences in the thermal resistance of the jacket systems when tested dry, an exceptionally large change in thermal insulation would be required to make a significant difference on the heat loss of the cold weather fabric system when wet. The largest difference in wet heat flux between cold weather fabric systems was noted when underwear fabric G was selected, which followed a similar trend as seen in single layer wet heat flux results (Figure 14 & 23). The hollow fibres in fabric G that made a significant difference in energy loss when underwear fabrics were tested in single layer form were also effective in keeping the cold weather fabric systems warmer when wet ($p<0.05$). This was clearly not the case for all underwear fabrics, as most cold weather fabric systems had similar wet heat flux measurements (within 7 W/m^2 if fabric G is excluded).

Examination of Figure 24 reveals that lining type had a significant influence on the wet heat flux of the cold weather fabric systems ($F_{56, 3} = 30$, $p<0.001$). Even though lining fabrics were of equal thermal resistance, jacket systems that incorporated lining fabric J were significantly ($p<0.05$) warmer when wet in comparison to those with lining H, I, or X. This was a result of differences in the moisture absorption properties between the lining fabrics. Fabric J was completed hydrophobic and did not absorb any moisture, as indicated by its liquid absorption capacity (LAC) value of zero (Table 6). When wet underwear was placed under jacket systems with the other lining fabrics (i.e. H, I, or X), the lining fabrics removed moisture from the underwear (as indicated by OMMC results; Figure 22). The absorption of moisture into the lining fabric caused the underwear and lining fabrics to stick together due to the transfer of moisture and increase in weight of the lining. This completely reduced the air gap that existed between the underwear and lining fabric. As air layers between fabric layers provide insulation (Morris, 1955), using lining J (hydrophobic) resulted in lower wet heat flux because insulating air layers between

Figure 23. Wet heat flux of cold weather fabric systems by underwear type

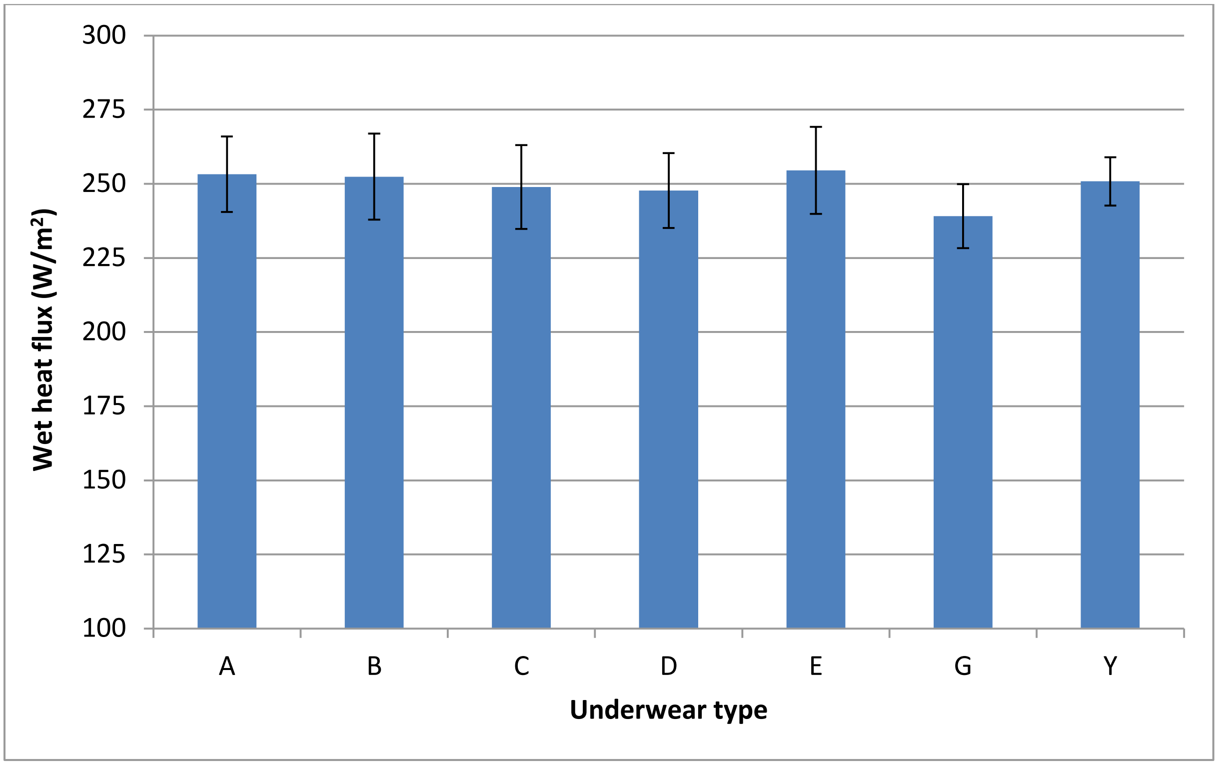
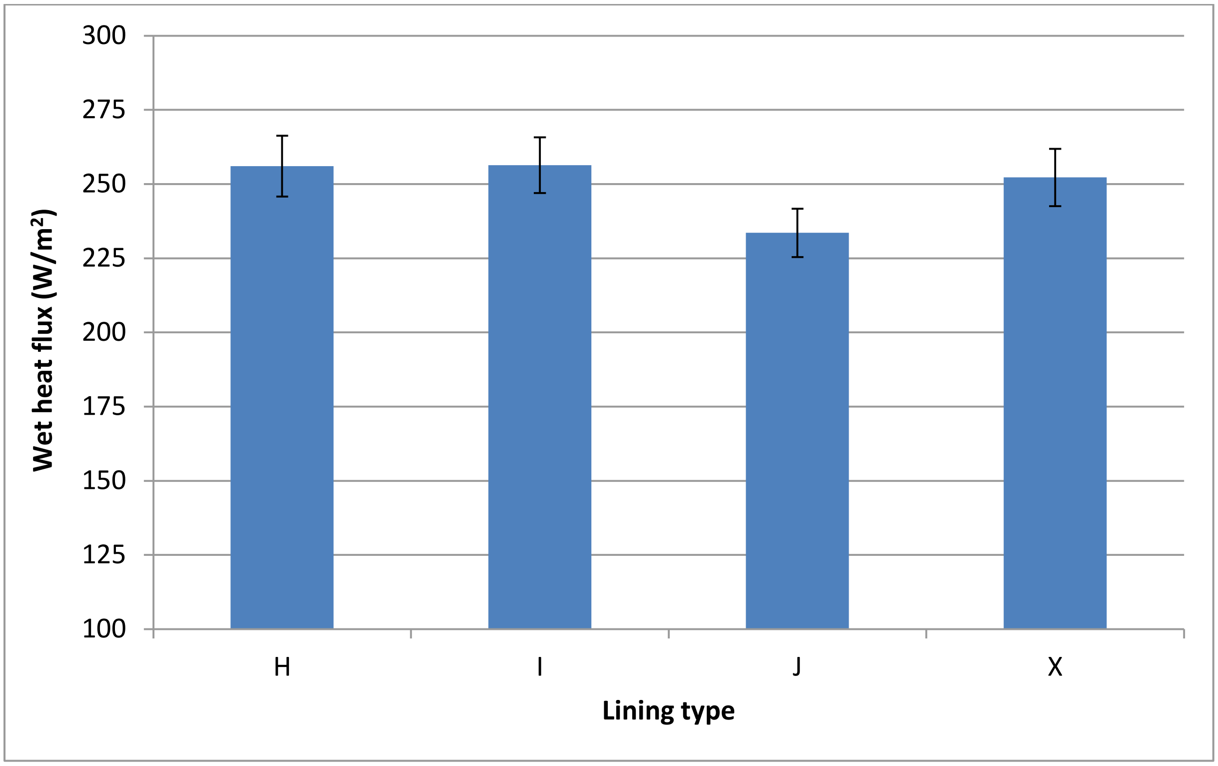
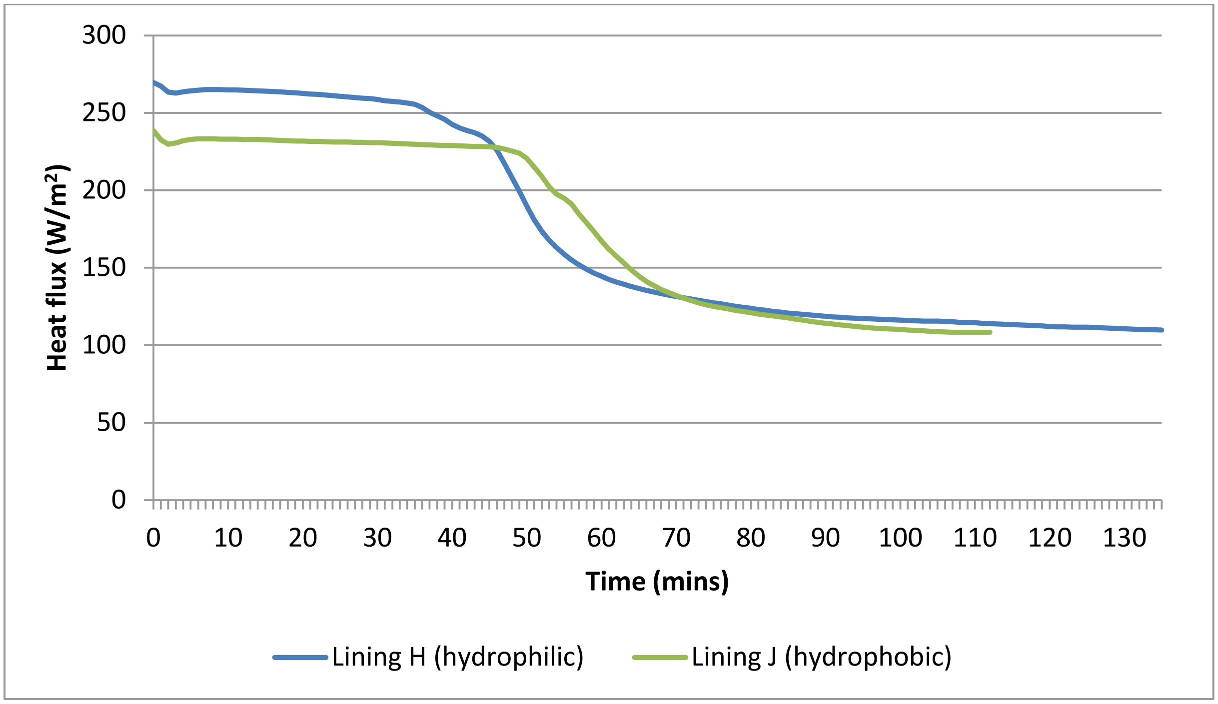


Figure 24. Wet heat flux of cold weather fabric systems by lining type



the underwear and jacket system were maintained. This is most apparent when examining the heat flux plot comparing jacket systems with lining H (hydrophilic) to lining J (hydrophobic) when placed on top of same underwear fabric (Figure 25). There were no significant differences between wet heat flux measurements for cold weather fabric systems that used hydrophilic linings (i.e. H, I, or X), as the changes in wet heat flux were largely dependent on whether or not the lining fabric absorbed any moisture (Figure 24). As fabric systems were tested in a horizontal configuration, the absorption and weight increase of linings may have overestimated the influence moisture absorption can have on wet heat flux measurements. In a horizontal configuration, gravity will have a large influence on the reduction of the air gap and may not necessarily represent real wearing conditions. However, previous research on thermal manikins has demonstrated similar findings where a significant reduction in thermal insulation was noted due to wet fabric layers clinging or sticking to one another (Nielsen, 1994). Therefore the findings in this research can be considered representative of actual wearing conditions (i.e. in a vertical arrangement). This research provides evidence that the moisture absorbing properties of lining fabrics and wet heat flux of underwear both have a significant influence on the thermal insulation of winter clothing in wet conditions. No significant interaction effects between lining type and underwear type were noted for wet heat flux results.

Figure 25. Heat flux plot of jacket systems with hydrophilic (H) and hydrophobic (J) linings on top of underwear fabric B (untreated polyester)



Analysis of drying time and drying rate of cold weather *fabric systems*

The drying times and drying rates of cold weather fabrics systems were measured and compared to understand if underwear or lining types could influence the drying behaviour of winter clothing (Tables 10 – 12). Two-way ANOVA by underwear and lining type revealed significant differences between the drying times and drying rates of cold weather fabric systems (drying time: $F_{27, 56} = 6$, $p<0.001$; drying rate: $F_{27, 56} = 5$, $p<0.001$). Homogeneity of variance was satisfied among the drying time measurements for cold weather fabric systems, but not for drying rate measurements. As it is difficult to see meaningful trends when cold weather fabric systems were analyzed by sample ID, this discussion will largely focus on the differences of the fabric systems when analyzed by underwear (Figure 26 & 27) and lining type (Figures 29 & 30). As previously mentioned in the analysis of underwear fabrics tested alone, drying time was negatively correlated with drying rate ($R^2=1$), where higher drying rates provided lower drying times.

Significant differences were noted between the drying times of cold weather fabric systems when analyzed by underwear type ($F_{6, 56} = 13$, $p<0.001$). The findings in single layer testing (Figure 15) appear to translate to cold weather testing (Figure 26 & 27), but are limited by the evaporative resistance of the jacket system placed on top of it. Hence, much lower drying rates were noted for cold weather fabric testing in comparison to single layer results (Figure 27). Yet the ability of underwear to evaporate moisture had a significant role in determining the drying rate of the cold weather fabric systems. A strong positive correlation (R^2=0.90) was found between the wet heat flux of underwear fabrics tested alone and the drying rate of the cold weather fabric systems by underwear type (Figure 28). As explained in the analysis of drying times and drying rates of underwear tested alone, quicker drying times are associated with the amount of energy required to evaporate moisture (i.e. the enthalpy of vaporization). The results for cold weather fabric systems demonstrate that wet underwear fabrics that draw more energy lead to quicker drying times. Hence, cold weather fabric systems with wet polyester underwear fabrics (B, D, and E) demonstrated the quickest drying times (Figure 26). A detailed analysis of the differences between the drying times of underwear fabrics can be found in the previous section entitled, "Analysis of the drying times and drying rates of underwear fabrics."

Figure 26. Drying time of cold weather fabric systems by underwear type

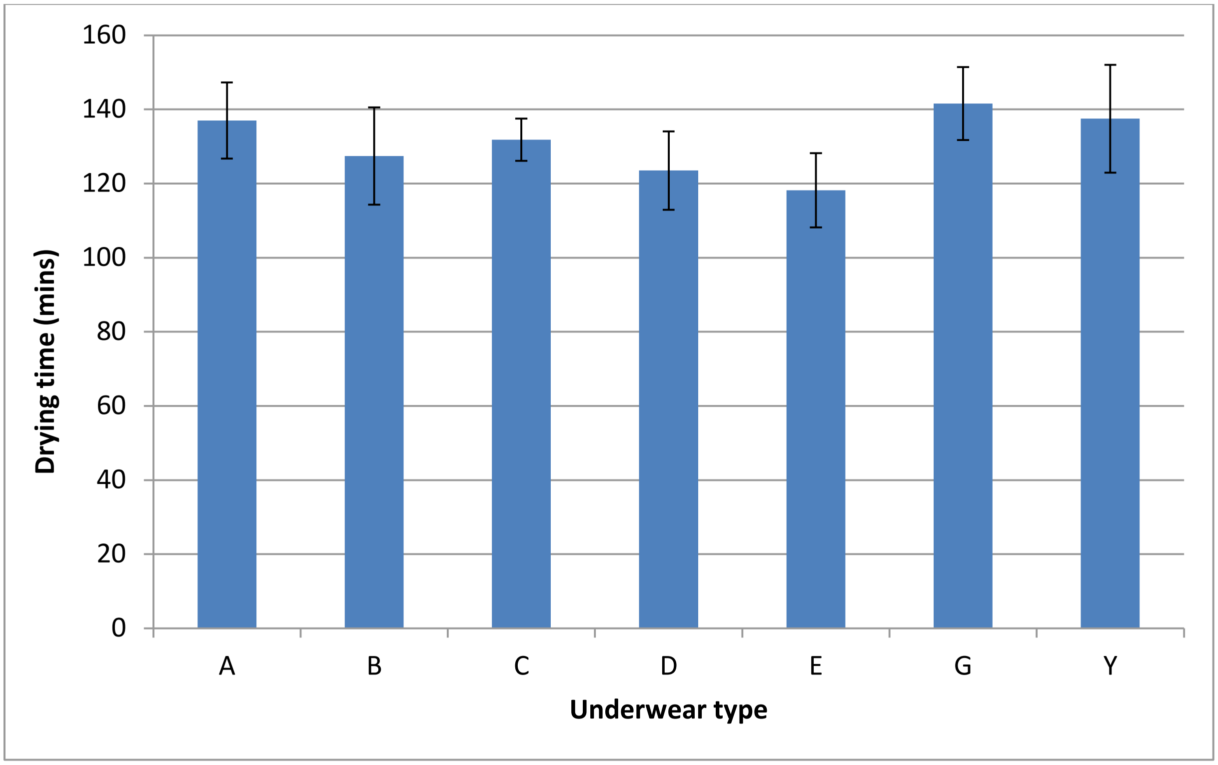


Figure 27. Drying rate of single and cold weather fabric systems by underwear type

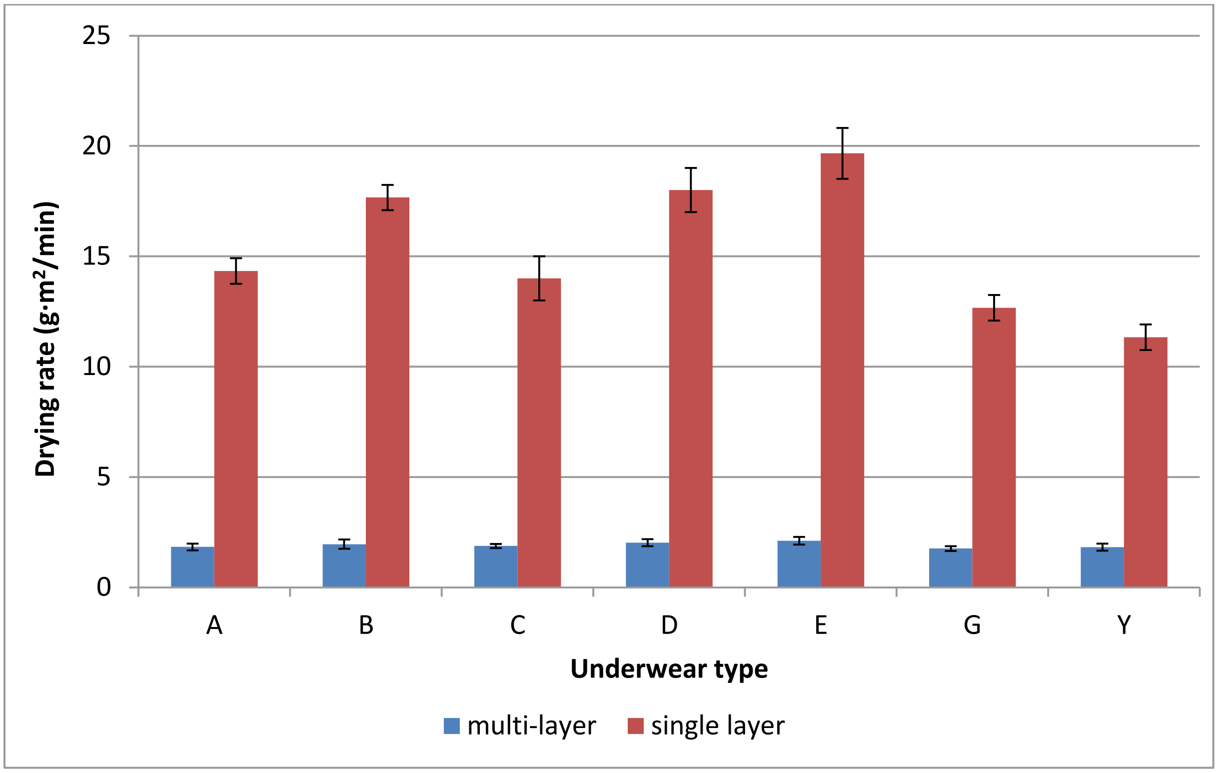
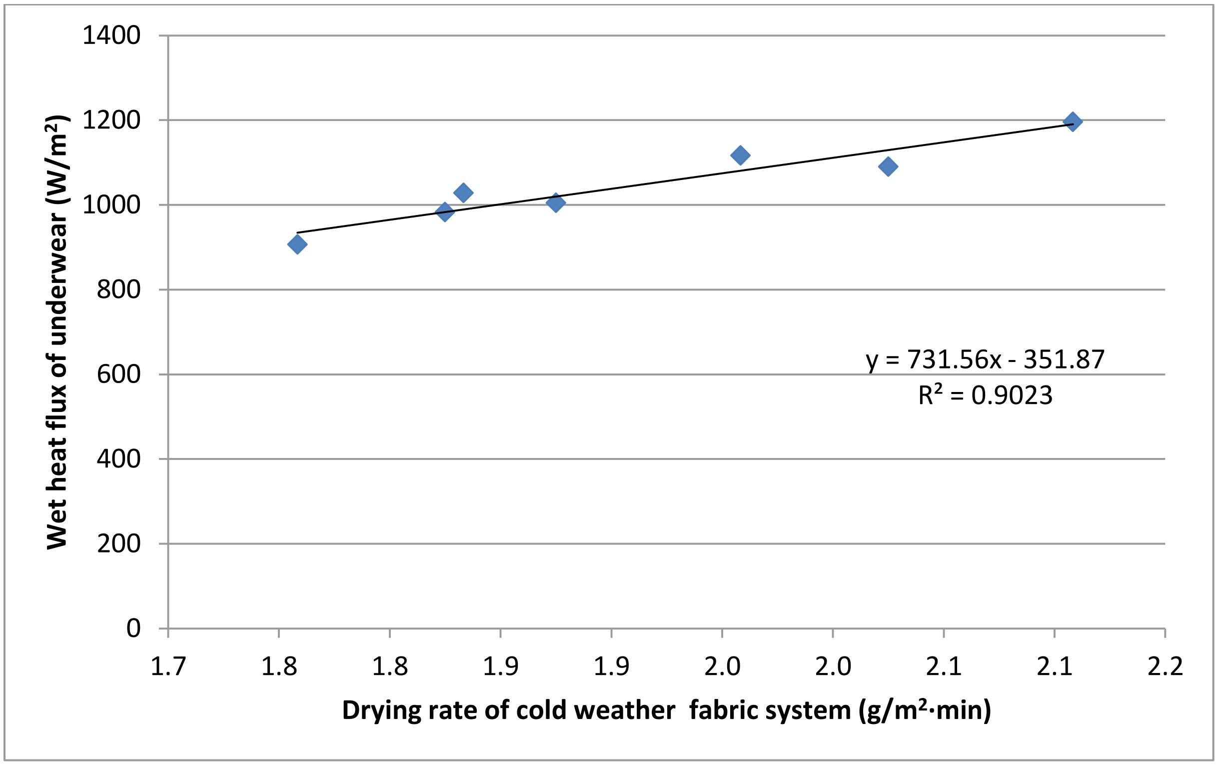


Figure 28. Correlation between underwear wet heat flux and drying rate of cold weather fabric systems



As seen in Figure 29 & 30, lining type also had a significant influence on the drying time and drying rate of the fabric systems ($F_{3, 56}$ = 13, $p<0.001$). Fabric systems incorporating lining J (hydrophobic) had significantly ($p<0.05$) lower drying times. As the wet heat flux of jacket systems with lining J was lower than jacket systems that incorporated hydrophilic linings (H, I, or X), it is interesting that they had a much quicker drying time. Upon analysis of the physical properties of the lining fabrics (Table 4), quicker drying times for cold weather fabric systems with lining J are due to its higher air permeability ($18cm^3/cm^2/s$) in comparison to the other lining fabrics ($0 – 2cm^3/cm^2/s$). Fabrics which are more permeable to air will also exhibit higher water vapour transmission rates (Adler & Walsh, 1984). This is simply because the rate of vapour diffusion through air is significantly quicker than the rate of water vapour diffusion through fibres (Adler & Walsh, 1984). Jacket systems with lining J therefore reduced the evaporative resistance of the cold weather fabric systems and decreased the amount of time required for the fabric layers to dry. However, the air permeability of fabric J was not the only reason for the decreased drying time. Two-way ANOVA of drying time by underwear and lining type revealed there was a significant interaction effect between underwear and lining fabrics in determining the drying time of cold weather fabric systems ($F_{18, 56}$ = 2, $p<0.01$). When jacket systems with lining fabric J (hydrophobic) were used, moisture was trapped in the underwear fabric as lining J was hydrophobic, presenting a barrier to liquid moisture transport. This is evidenced by OMMC results where two-layer composites with fabric J had a rating of 0.00 (Figure 22). When jacket systems with hydrophilic linings were used (i.e. H, I, or X), moisture was removed from the underwear fabric and spread across the surface of the associated lining fabric. The ability of lining fabrics to absorb and spread moisture is characterized by their OMMC ratings (Figure 22), where higher OMMC rating indicate a higher quantity of moisture is transported out of the underwear fabric. Moisture that was removed from fabric was forced to dry from the lining, rather than the underwear. The temperature of the lining will be lower than the temperature of the underwear fabric, especially on the inner surface of the underwear fabric. As the enthalpy of vaporization is dependent on temperature, the amount of energy required for moisture to evaporate from the lining fabrics will be significantly greater than the amount of energy required to evaporate moisture within the underwear fabric (ASHRAE, 2005). Hence, jacket systems with lining J (hydrophobic) dry faster because moisture is trapped in the underwear layer and requires less energy to evaporate than moisture in the lining (Figure 25). The air permeability and lower enthalpy of vaporization when moisture is trapped in the underwear fabric result in much more rapid drying times for jacket systems with lining J. No significant differences were noted between the drying times of jacket systems with lining H, I, or X. Thus, the drying time of cold weather systems is dependent on both the underwear and lining type. The quickest drying times resulted when underwear fabrics with a high wet heat flux are combined with air permeable and hydrophobic linings.

Figure 29. Drying time of cold weather fabric system by lining type

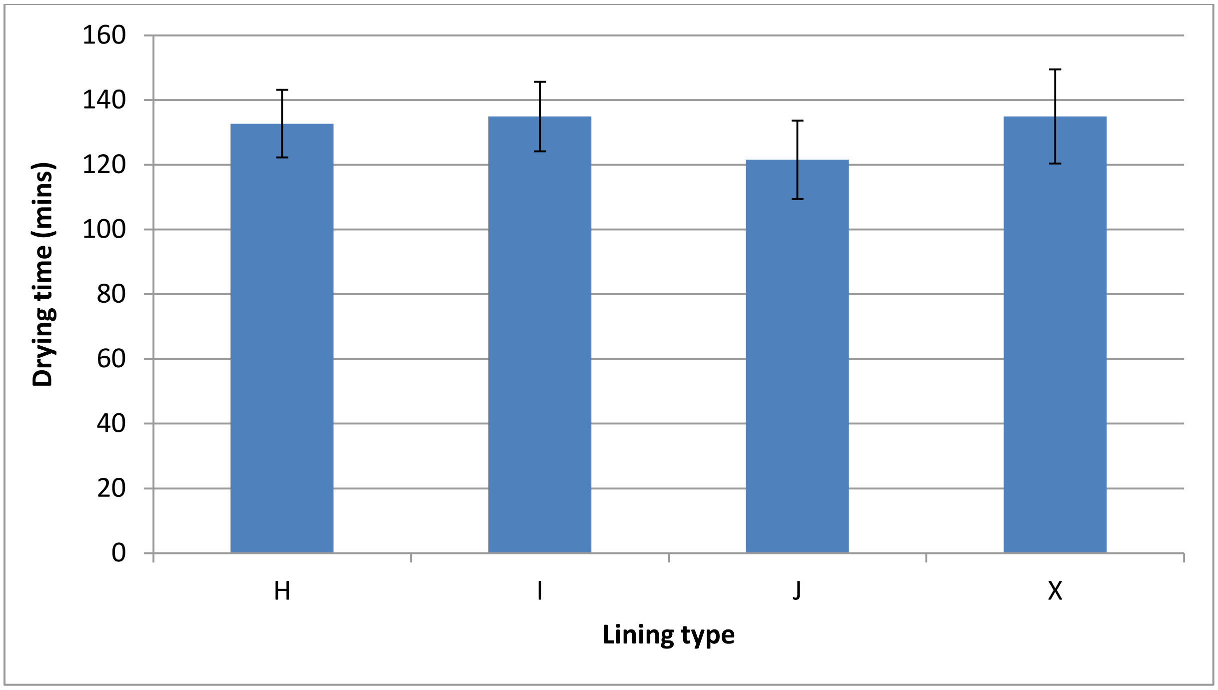
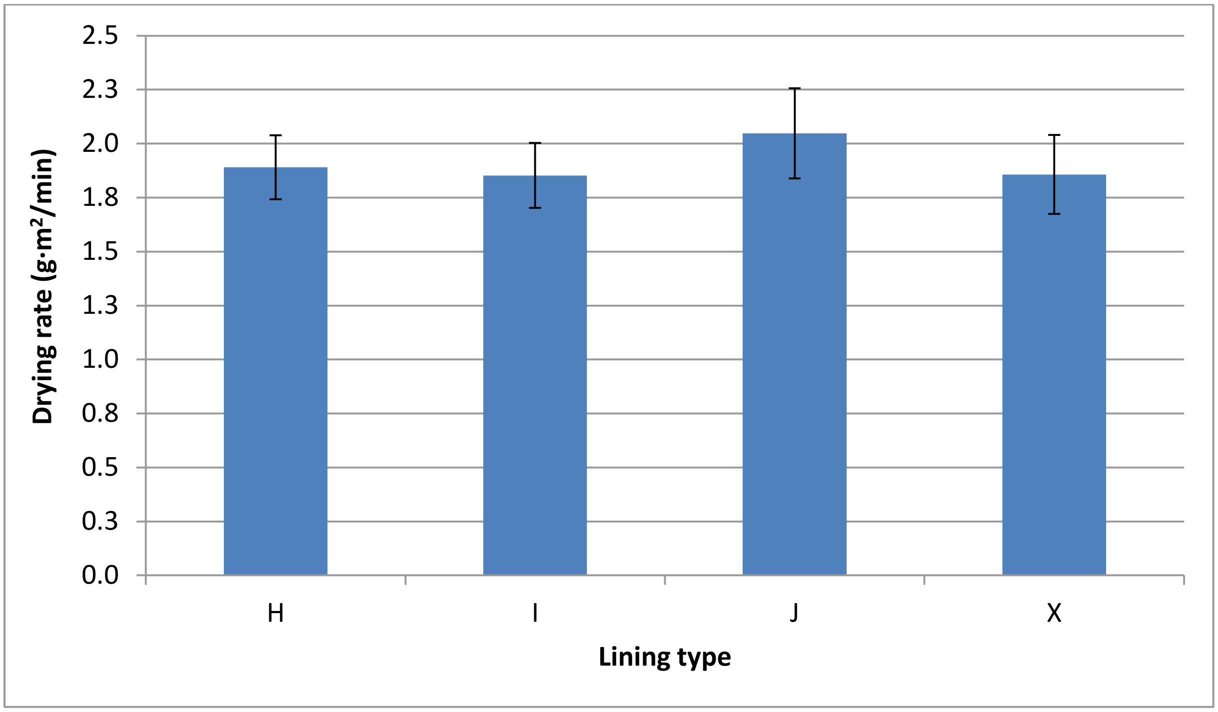


Figure 30. Drying rate of cold weather fabric systems by lining type



CHAPTER 5: CONCLUSIONS, RECCOMENDATIONS, & FUTURE WORK

Conclusions

The research presented in this thesis offers insight on material factors that can be manipulated to improve the thermophysiological comfort of clothing intended for cold weather. Significant differences in thermal insulation were noted between underwear fabrics when tested as a single layer in both a dry and wet state (rejection of Hypothesis 1a). As found in previous research, the thermal insulation of dry underwear fabrics was related to the volume of air within the textile, rather than chemical differences in fibres (Rossi, 2009; Ukponmwan, 1994). Dry thermal insulation was greatest for underwear fabrics with hollow fibres and high thickness. The thermal insulation of wet underwear was significantly affected by the fibre morphology and moisture management properties of fabrics. When comparing polyester and cotton underwear fabrics with similar dry thermal resistance, polyester fabrics lost heat more rapidly when wet. Differences in heat loss between the wet underwear fabrics were explained by the hairiness of yarns, where yarns with smoother surfaces (i.e. polyester) have more surface area in contact with the hot plate than hairy yarns (i.e. cotton). Greater surface area contact leads to higher rates of heat loss, as the conductivity of wet fibres are higher than air (Varshney et al., 2010). Hollow fibres also helped maintain a high volume of air within fabrics when wet, which resulted in the highest thermal insulation when wet in comparison to the other underwear fabrics. Wet fabrics treated with a one-way moisture management finish had better thermal insulation than untreated fabrics throughout the entire drying period. This was attributed to a decrease in the quantity of moisture present on the inner fabric surface because the treatment creates hydrophobic regions on inner surface of fabrics (Rearick & Anderson, 2006). As the conductivity of water is greater than that of fibres (Schneider et al., 1992), decreasing the amount of moisture in contact with the hot plate improved the thermal insulation of the treated fabrics in comparison to their untreated versions.

Underwear type did not have a significant difference on the thermal insulation of cold weather fabric systems in a dry state, but did affect insulation when wet (rejection of Hypothesis 1b). The thermal insulation of the cold weather fabric systems was governed by the layer of non-woven insulation which provided the majority of thickness and thermal resistance. Differences in thermal resistance between underwear fabrics when dry were not high enough to influence the total insulation provided by the cold weather fabric system. However, when underwear fabrics were wet, hollow fibres were found to significantly influence the thermal insulation of the jacket systems (i.e. lining, insulation, & shell). The type of lining fabric used in the jacket system also had a significant influence on the thermal insulation of the cold weather fabric system with wet underwear. Jacket systems with linings that did not absorb any moisture (i.e. hydrophobic) demonstrated significantly higher thermal insulation when compared to jacket systems with linings that absorbed moisture (i.e. hydrophilic). The hydrophobic lining prevented the underwear from sticking and clinging to the adjacent fabric layers. This helped to maintain the insulating air gap that exists between the underwear and jacket system, which in turn provided higher thermal insulation for the cold weather fabric system with a hydrophobic lining.

Significant differences were noted between the drying time and drying rate of underwear fabrics when tested as single layers (rejection of Hypothesis 2a). Drying time was negatively correlated with drying rate (R^2=1), where higher drying rates provided shorter drying times. Fibre type had a significant influence on the drying time and drying rate of underwear fabrics. When comparing polyester and cotton underwear fabrics with similar dry thermal resistance, cotton fabrics took longer to dry than polyester fabrics. Differences in drying time were attributed to the moisture regain and amount of energy required to evaporate moisture (i.e. enthalpy of vaporization). Moisture regain is directly related to the quantity of hydrophilic sites that are available for moisture to bond with (Crow & Osczevski, 1998). Cotton's significantly higher moisture regain (≈7%) compared to polyester (≈0.4%) resulted in a slower drying rate, as more energy is required to break the hydrogen bonds between moisture and the cellulose polymers within the cotton fibres (ASTM, 2004). Polyester fabrics also dried more quickly than fabrics composed of cotton because moisture present on the fibre surfaces reached its enthalpy of vaporization more rapidly. The amount of energy drawn by a wet fabric (i.e. wet heat flux) demonstrated a strong correlation with the drying rate of fabrics (R^2=0.81). If more energy is drawn by a wet fabric, the enthalpy of vaporization can be reached in less time and fabrics will require less time to dry. The reduced energy transfer rate into the fabric, combined with the greater quantity of energy required to break hydrogen bonds, results in slower drying times for cotton fabrics. The polyester fabric with hollow fibres had the slowest drying time, as it had the lowest wet heat flux. The polyester fabric with activated carbon granules had the highest wet heat flux which resulted in the quickest drying time out of all the underwear fabrics when tested as a single layer. The improved evaporation rates associated with polyester doped with activated carbon in comparison to regular polyester seem to be supported by this research (Haggquist et al., 2009). Slower drying times were noted for the double-knit construction that moved moisture from the inside to the outside of the fabric. The reduced drying time was related to the greater quantity of energy required to evaporate moisture from the outer surface of the knit in comparison to moisture held closer to the surface of the hot plate (i.e. inside surface).

Significant differences between the drying time and drying rate of cold weather fabric systems with wet underwear were also found (rejection of Hypotheses 2b). The drying time and drying rate of cold weather fabric systems depended on the air permeability and moisture management properties of the underwear and lining fabrics, where a significant interaction was noted between the two fabric layers in affecting drying time. A strong positive correlation (R^2=0.90) was found between the wet heat flux of underwear fabrics tested alone and the drying rate of the cold weather fabric systems by underwear type. Hence, the conclusions drawn about drying rates in single layer testing appear to translate to multi-layer testing, but are limited by the evaporative resistance of the jacket system placed on top of it. The wet heat flux of underwear fabrics could therefore be measured and compared in single layer form in order to draw conclusions about their drying rates when placed under a jacket system. This could save a significant amount of time if examining the drying rates of underwear fabrics under a jacket with the same components. Lining type had a significant influence on the drying time and drying rate of the cold weather fabric systems, where the air permeability of the lining fabric was found to be very important. One lining demonstrated much higher air permeability than the rest of the lining fabrics. Fabrics which are more permeable to air will also exhibit higher water vapour transmission rates, because the rate of vapour diffusion through air is significantly quicker than the rate of water vapour diffusion through fibres (Adler & Walsh, 1984). The lining with high air permeability was also hydrophobic. Two-layer composite testing indicated the hydrophobic lining prevented moisture from transferring to adjacent fabric layers in comparison to lining fabrics that absorbed moisture (rejection of Hypothesis 3). As the enthalpy of vaporization of water is lower in the underwear than in the lining of the cold weather fabric systems, trapping moisture in the underwear resulted in quicker drying times. Hence, the drying rate and drying time of the cold weather fabric systems was dependent on the wet heat flux of the underwear, air permeability of the lining, and the hydrophobicity of the lining.

Recommendations

Designing comfortable clothing for cold weather environments continues to be a challenge for fabric and garment manufacturers. The moisture management properties of underwear and lining fabrics have demonstrated they can significantly influence the thermal insulation and drying time of winter clothing. This research supports other author’s conclusions stating the presence of moisture in fabric layers increases heat loss rates and reduces thermal insulation, especially as moisture accumulates near the skin (Nielsen, 1994; Schneider et al., 1992). In this research, 90% of the variability in drying rate of the cold weather fabric systems was derived from differences in the thermal and moisture management properties of the underwear fabrics. This supports the notion that the type of underwear chosen for cold weather will have a large influence on the time it takes for someone to feel comfortable after sweating in cold weather. It has also been demonstrated that the lining fabrics chosen for jackets will have an influence on the thermal insulation and drying time of winter clothing because they provide another layer of resistance to heat and moisture transport. Hydrophobic linings should be selected and their air permeability measured prior to use in cold weather jackets. Underwear fabrics should be selected with consideration of the intensity of physical activity and duration of time an individual expects to be in a cold environment. In most cases, people working in cold environment will engage in intermittent activity with periods of rest and physical activity. These people will typically take a break indoors throughout the day, where ambient temperatures are higher and accelerate evaporation rates of moisture from the clothing layers. For these people, it is very important for fabric layers near the skin to return to a dry state as quickly as possible in order to feel comfortable again. Underwear fabrics which demonstrate the quickest drying time should be selected for these individuals. If an individual expects to be in a cold environment for an extremely long period of time with minimal sweating, the underwear fabrics with high thermal insulation when wet may be a better choice as there is little or minimal chance that clothing layers will completely dry.

Future work

Completion of this research has given rise to more research questions. Research is needed to determine if the findings presented in this research correspond to improvements in thermophysiological comfort for humans. A wear trial is needed to confirm and correlate such findings. Research is also needed to establish the magnitude of difference between heat flux measurements that are perceivable by humans. While Kawabata and Akagi (1977) have generally shown that higher heat flux measurements correspond to sensations of warmth and lower heat flux measurements correspond to cooling sensations, it is unclear what magnitude of difference is perceivable (i.e. 100W/m^2 or 10W/m^2). The magnitude of difference will also need to be established for people who are engaged in physical activity versus resting, as it will likely shift with increasing physical activity.

Research is also needed to further establish if the air permeability of jacket linings is linked to higher evaporation rates, regardless of its affinity for moisture. This would require measuring the drying rates of wet underwear fabrics under winter jackets with hydrophilic and hydrophobic linings, which have both high and low air permeability.

Further research is required to investigate the drying time of fabrics exposed to different quantities of moisture. In cold weather conditions, it’s possible that perspiration rates are reduced and the quantity of moisture present in the cold weather fabric systems would be lower. Fabrics may evaporate lower quantities of moisture more effectively than when they are saturated.

With regards to testing fabrics using a sweating guarded hot plate in a cold environment, the surface temperature of the hot plate could also be reduced. In very cold conditions, the skin temperature may be lower than the surface temperature used in this research (35°C). Investigating how the lower surface temperature and different materials evaporate moisture would be of practical interest for designing cold weather clothing.

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Appendix A

List of cold weather fabric systems by sample identification (ID) code

APPENDIX A

COMBINATIONS FOR COLD WEATHER FABRIC SYSTEMS				SAMPLE ID
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
A	H	K	L	AH
A	I	K	L	AI
A	J	K	L	AJ
A	X	K	L	AX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
B	H	K	L	BH
B	I	K	L	BI
B	J	K	L	BJ
B	X	K	L	BX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
C	H	K	L	CH
C	I	K	L	CI
C	J	K	L	CJ
C	X	K	L	CX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
D	H	K	L	DH
D	I	K	L	DI
D	J	K	L	DJ
D	X	K	L	DX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
E	H	K	L	EH
E	I	K	L	EI
E	J	K	L	EJ
E	X	K	L	EX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
G	H	K	L	GH
G	I	K	L	GI
G	J	K	L	GJ
G	H	K	L	GX
UNDERWEAR	LINING	INSULATION	OUTER SHELL	
Y	H	K	L	YH
Y	I	K	L	YI
Y	J	K	L	YJ
Y	X	K	L	YX

Appendix B

Summary of descriptives, homogeneity of variance, and one-way ANOVA tests for underwear fabrics

APPENDIX B

Mass per unit area of underwear fabrics

Descriptives

Mass (g/m2)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	10	179	2.1	0.7	178	181	177	183
B	10	164	2.0	0.6	162	165	161	167
C	10	185	1.8	0.6	183	186	183	189
D	10	155	1.0	0.3	155	156	154	157
E	10	122	1.0	0.3	121	123	121	123
G	10	234	2.1	0.7	232	235	230	236
Y	10	159	2.3	0.7	158	161	156	163
Total	70	171	31.9	3.8	163	179	121	236

Test of Homogeneity of Variances

Mass (g/m2)

Levene Statistic	df1	df2	Sig.
1.673	6	63	.142

ANOVA

Mass (g/m2)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	70067.830	6	11677.972	3514.993	.000
Within Groups	209.307	63	3.322		
Total	70277.137	69			

APPENDIX B

Thickness of underwear fabrics

Descriptives

Thickness (mm)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
A	10	0.56	0.002	0.000	0.56	0.56	.56	.56
B	10	0.61	0.002	0.001	0.61	0.61	.61	.61
C	10	0.58	0.002	0.000	0.58	0.59	.58	.59
D	10	0.59	0.003	0.001	0.58	0.59	.58	.59
E	10	0.48	0.005	0.001	0.48	0.48	.47	.48
G	10	0.74	0.009	0.003	0.73	0.74	.72	.75
Y	10	0.77	0.010	0.003	0.76	0.77	.75	.78
Total	70	0.62	0.094	0.011	0.59	0.64	.47	.78

Test of Homogeneity of Variances

Thickness (mm)

Levene Statistic	df1	df2	Sig.
7.899	6	63	.000

ANOVA

Thickness (mm)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.613	6	.102	3077.333	.000
Within Groups	.002	63	.000		
Total	.615	69			

APPENDIX B

Air permeability of underwear fabrics

Descriptives

Air permeability (cm3/cm2/sec)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	10	27	1.2	0.4	26	28	26	29
B	10	103	4.5	1.4	100	106	93	108
C	10	31	1.9	0.6	29	32	28	34
D	10	128	5.3	1.7	125	132	120	134
E	10	105	3.2	1.0	102	107	100	110
G	10	23	0.7	0.2	22	23	21	24
Y	10	135	3.1	1.0	133	137	128	139
Total	70	79	46.6	5.6	68	90	21	139

Test of Homogeneity of Variances

Air permeability (cm3/cm2/sec)

Levene Statistic	df1	df2	Sig.
4.214	6	63	.001

ANOVA

Air permeability (cm3/cm2/sec)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	149399.742	6	24899.957	2366.256	.000
Within Groups	662.945	63	10.523		
Total	150062.687	69			

APPENDIX B

Thermal resistance of underwear fabrics

Descriptives

Rct

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	5	0.013	0.0000	0.0000	0.013	0.013	.013	.013
B	5	0.011	0.0005	0.0002	0.010	0.011	.010	.011
C	5	0.014	0.0005	0.0002	0.013	0.014	.013	.014
D	5	0.012	0.0008	0.0004	0.011	0.013	.011	.013
E	5	0.009	0.0004	0.0002	0.009	0.010	.009	.010
G	5	0.016	0.0005	0.0002	0.015	0.016	.015	.016
Y	5	0.020	0.0004	0.0002	0.020	0.021	.020	.021
Total	35	0.013	0.0034	0.0006	0.012	0.015	.009	.021

Test of Homogeneity of Variances

Rct

Levene Statistic	df1	df2	Sig.
3.942	6	28	.006

ANOVA

Rct

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	6	.000	231.233	.000
Within Groups	.000	28	.000		
Total	.000	34			

APPENDIX B

Liquid absorption capacity (LAC) of underwear fabrics

Descriptives

LAC

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	5	227	7.2	3.2	218	236	218	235
B	5	245	13.8	6.2	227	262	231	264
C	5	217	10.9	4.9	203	230	206	233
D	5	215	13.7	6.1	198	232	194	226
E	5	249	7.7	3.4	240	259	245	263
G	5	194	5.0	2.2	188	200	187	201
Y	5	346	12.2	5.5	331	361	333	361
Total	35	242	47.6	8.0	225	258	187	361

Test of Homogeneity of Variances

LAC

Levene Statistic	df1	df2	Sig.
1.560	6	28	.196

ANOVA

LAC

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	73894.171	6	12315.695	110.356	.000
Within Groups	3124.800	28	111.600		
Total	77018.971	34			

APPENDIX B

Overall moisture management capacity (OMMC) of underwear fabrics

Descriptives

OMMC

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	10	0.52	0.106	0.033	0.45	0.60	.33	.65
B	10	0.48	0.098	0.031	0.41	0.55	.40	.76
C	10	0.66	0.304	0.096	0.45	0.88	.11	.90
D	10	0.76	0.141	0.045	0.66	0.87	.51	.91
E	10	0.54	0.137	0.043	0.44	0.64	.45	.81
G	10	0.45	0.051	0.016	0.41	0.49	.36	.52
Y	10	0.57	0.019	0.006	0.56	0.59	.54	.60
Total	70	0.57	0.175	0.021	0.53	0.61	.11	.91

Test of Homogeneity of Variances

OMMC

Levene Statistic	df1	df2	Sig.
6.664	6	63	.000

ANOVA

OMMC

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.712	6	.119	5.382	.000
Within Groups	1.389	63	.022		
Total	2.102	69			

APPENDIX B

Wet heat flux of underwear fabrics

Descriptives

Wet heat flux

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	3	1029	31.8	18.4	950	1108	992	1049
B	3	1117	20.0	11.6	1067	1166	1096	1136
C	3	1005	29.7	17.1	932	1079	980	1038
D	3	1091	2.1	1.2	1085	1096	1089	1093
E	3	1196	8.2	4.7	1176	1216	1189	1205
G	3	907	1.7	1.0	903	911	905	908
Y	3	983	8.4	4.8	963	1004	978	993
Total	21	1047	91.9	20.1	1005	1089	905	1205

Test of Homogeneity of Variances

Wet heat flux

Levene Statistic	df1	df2	Sig.
4.390	6	14	.011

ANOVA

Wet heat flux

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	164059.905	6	27343.317	78.455	.000
Within Groups	4879.333	14	348.524		
Total	168939.238	20			

APPENDIX B

Drying time of underwear fabrics

Descriptives

Drying time

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	3	18	0.6	0.3	16	19	17	18
B	3	14	0.6	0.3	13	16	14	15
C	3	18	1.0	0.6	16	20	17	19
D	3	14	1.0	0.6	12	16	13	15
E	3	13	0.6	0.3	11	14	12	13
G	3	19	0.6	0.3	18	21	19	20
Y	3	22	0.6	0.3	20	23	21	22
Total	21	17	3.1	0.7	15	18	12	22

Test of Homogeneity of Variances

Drying time

Levene Statistic	df1	df2	Sig.
.290	6	14	.932

ANOVA

Drying time

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	189.905	6	31.651	60.424	.000
Within Groups	7.333	14	.524		
Total	197.238	20			

APPENDIX B

Drying rate of underwear fabrics

Descriptives

Drying rate

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
A	3	14	0.6	0.3	13	16	14	15
B	3	18	0.6	0.3	16	19	17	18
C	3	14	1.0	0.6	12	16	13	15
D	3	18	1.0	0.6	16	20	17	19
E	3	20	1.2	0.7	17	23	19	21
G	3	13	0.6	0.3	11	14	12	13
Y	3	11	0.6	0.3	10	13	11	12
Total	21	15	3.0	0.7	14	17	11	21

Test of Homogeneity of Variances

Drying rate

Levene Statistic	df1	df2	Sig.
.667	6	14	.678

ANOVA

Drying rate

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	171.619	6	28.603	42.905	.000
Within Groups	9.333	14	.667		
Total	180.952	20			

Appendix C

Summary of descriptives, homogeneity of variance, and one-way ANOVA tests for lining fabrics

APPENDIX C

Mass per unit area of lining fabrics

Descriptives

Mass (g/m2)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
H	10	87	0.5	0.2	87	87	86	88
I	10	88	0.5	0.2	87	88	87	88
J	10	66	0.6	0.2	65	66	65	67
X	10	73	0.6	0.2	73	73	72	74
Total	40	78	9.5	1.5	75	81	65	88

Test of Homogeneity of Variances

Mass (g/m2)

Levene Statistic	df1	df2	Sig.
.494	3	36	.689

ANOVA

Mass (g/m2)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3498.098	3	1166.033	3759.182	.000
Within Groups	11.167	36	.310		
Total	3509.265	39			

APPENDIX C

Thickness of lining fabrics

Descriptives

Thickness (mm)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
H	10	0.15	0.001	0.000	0.15	0.15	.15	.15
I	10	0.14	0.000	0.000	0.14	0.14	.14	.14
J	10	0.11	0.000	0.000	0.11	0.11	.11	.11
X	10	0.09	0.000	0.000	0.09	0.09	.09	.09
Total	40	0.12	0.024	0.004	0.12	0.13	.09	.15

Test of Homogeneity of Variances

Thickness (mm)

Levene Statistic	df1	df2	Sig.
47.250	3	36	.000

ANOVA

Thickness (mm)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.023	3	.008	32673.143	.000
Within Groups	.000	36	.000		
Total	.023	39			

APPENDIX C

Air permeability of lining fabrics

Descriptives

Air permeability (cm3/cm2/sec)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
H	10	2	0.3	0.1	2	2	1	2
I	10	1	0.3	0.1	1	2	1	2
J	10	18	0.9	0.3	17	18	17	19
X	10	0	0.1	0.0	0	0		1
Total	40	5	7.3	1.2	3	8		19

Test of Homogeneity of Variances

Air permeability (cm3/cm2/sec)

Levene Statistic	df1	df2	Sig.
19.212	3	36	.000

ANOVA

Air permeability (cm3/cm2/sec)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2058.229	3	686.076	2869.945	.000
Within Groups	8.606	36	.239		
Total	2066.835	39			

APPENDIX C

Thermal resistance of lining fabrics

Descriptives

Rct

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
H	5	0.005	0.0009	0.0004	0.003	0.006	.004	.006
I	5	0.006	0.0019	0.0009	0.003	0.008	.004	.009
J	5	0.005	0.0025	0.0011	0.002	0.009	.003	.009
X	5	0.005	0.0015	0.0007	0.004	0.007	.004	.007
Total	20	0.005	0.0017	0.0004	0.004	0.006	.003	.009

Test of Homogeneity of Variances

Rct

Levene Statistic	df1	df2	Sig.
2.321	3	16	.114

ANOVA

Rct

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	3	.000	.387	.764
Within Groups	.000	16	.000		
Total	.000	19			

Liquid absorption capacity (LAC) of lining fabrics

Descriptives

LAC

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
H	5	70	0.9	0.4	69	72	70	72
I	5	69	6.8	3.1	61	78	64	80
J	5	0	0.0	0.0	0	0	0	0
X	5	46	6.9	3.1	38	55	41	54
Total	20	47	29.6	6.6	33	60	0	80

Test of Homogeneity of Variances

LAC

Levene Statistic	df1	df2	Sig.
16.547	3	16	.000

ANOVA

LAC

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	16243.800	3	5414.600	226.079	.000
Within Groups	383.200	16	23.950		
Total	16627.000	19			

APPENDIX C

Overall moisture management capacity (OMMC) of lining fabrics

Descriptives

OMMC

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
H	10	0.53	0.062	0.020	0.49	0.58	.47	.66
I	10	0.53	0.078	0.025	0.48	0.59	.41	.65
J	10	0.21	0.273	0.086	0.01	0.40	0.00	.67
X	10	0.17	0.081	0.026	0.11	0.23	.10	.31
Total	40	0.36	0.228	0.036	0.29	0.43	0.00	.67

Test of Homogeneity of Variances

OMMC

Levene Statistic	df1	df2	Sig.
12.161	3	36	.000

ANOVA

OMMC

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.211	3	.404	17.776	.000
Within Groups	.817	36	.023		
Total	2.028	39			

Appendix D

Summary of descriptives, homogeneity of variance, and two-way ANOVA tests of underwear fabrics by moisture management treatment and fibre type (A, B, C, & D)

APPENDIX D

Wet heat flux of underwear fabrics by moisture management treatment and fibre type

Descriptive Statistics

Dependent Variable: Wet heat flux

Moisture management mechanism		Mean	Std. Deviation	N
none	cotton	1029	31.8	3
	polyester	1117	20.0	3
	Total	1073	53.7	6
treatment	cotton	1005	29.7	3
	polyester	1091	2.1	3
	Total	1048	50.4	6
Total	cotton	1017	30.3	6
	polyester	1104	19.1	6
	Total	1060	51.3	12

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Wet heat flux

F	df1	df2	Sig.
3.142	3	8	.087

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + MM + fibre + MM * fibre

Tests of Between-Subjects Effects

Dependent Variable: Wet heat flux

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	24364.000[a]	3	8121.333	14.128	.001
Intercept	13491681.333	1	13491681.333	23470.597	.000
MM	1825.333	1	1825.333	3.175	.113
fibre	22533.333	1	22533.333	39.200	.000
MM * fibre	5.333	1	5.333	.009	.926
Error	4598.667	8	574.833		
Total	13520644.000	12			
Corrected Total	28962.667	11			

a. R Squared = .841 (Adjusted R Squared = .782)

Drying time of underwear fabrics by moisture management treatment and fibre type

Descriptive Statistics

Dependent Variable: Drying time

Moisture management mechanism		Mean	Std. Deviation	N
none	cotton	18	0.6	3
	polyester	14	0.6	3
	Total	16	1.9	6
treatment	cotton	18	1.0	3
	polyester	14	1.0	3
	Total	16	2.4	6
Total	cotton	18	0.8	6
	polyester	14	0.8	6
	Total	16	2.0	12

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Drying time

F	df1	df2	Sig.
.267	3	8	.848

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + MM + fibre + MM * fibre

Tests of Between-Subjects Effects

Dependent Variable: Drying time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	40.667[a]	3	13.556	20.333	.000
Intercept	3072.000	1	3072.000	4608.000	.000
MM	0.000	1	0.000	0.000	1.000
fibre	40.333	1	40.333	60.500	.000
MM * fibre	.333	1	.333	.500	.500
Error	5.333	8	.667		
Total	3118.000	12			
Corrected Total	46.000	11			

a. R Squared = .884 (Adjusted R Squared = .841)

Appendix E

Summary of descriptives, homogeneity of variance, and one-way ANOVA tests for cold weather fabric systems

APPENDIX E

Thermal resistance of cold weather fabric systems by sample ID

Descriptives

Rct

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
AH	5	0.230	0.0062	0.0028	0.222	0.238	.223	.238
AI	5	0.229	0.0067	0.0030	0.220	0.237	.223	.239
AJ	5	0.233	0.0098	0.0044	0.220	0.245	.222	.243
AX	5	0.224	0.0118	0.0053	0.210	0.239	.208	.235
BH	5	0.229	0.0083	0.0037	0.219	0.239	.220	.242
BI	5	0.229	0.0066	0.0030	0.221	0.237	.220	.238
BJ	5	0.229	0.0073	0.0033	0.220	0.238	.223	.238
BX	5	0.227	0.0076	0.0034	0.217	0.236	.217	.236
CH	5	0.228	0.0086	0.0039	0.218	0.239	.219	.236
CI	5	0.228	0.0075	0.0034	0.219	0.238	.219	.239
CJ	5	0.233	0.0103	0.0046	0.220	0.246	.219	.245
CX	5	0.229	0.0072	0.0032	0.220	0.238	.220	.239
DH	5	0.230	0.0066	0.0029	0.222	0.238	.222	.238
DI	5	0.229	0.0078	0.0035	0.220	0.239	.220	.239
DJ	5	0.230	0.0092	0.0041	0.218	0.241	.219	.244
DX	5	0.228	0.0056	0.0025	0.221	0.235	.222	.235
EH	5	0.226	0.0082	0.0037	0.216	0.236	.215	.234
EI	5	0.225	0.0081	0.0036	0.215	0.235	.215	.234
EJ	5	0.227	0.0092	0.0041	0.216	0.239	.217	.240
EX	5	0.225	0.0057	0.0026	0.218	0.232	.218	.232
GH	5	0.237	0.0089	0.0040	0.226	0.248	.224	.246
GI	5	0.235	0.0059	0.0027	0.228	0.243	.228	.242
GJ	5	0.236	0.0104	0.0046	0.223	0.249	.225	.248
GX	5	0.235	0.0103	0.0046	0.222	0.248	.218	.245
YH	5	0.234	0.0091	0.0041	0.222	0.245	.223	.244
YI	5	0.233	0.0086	0.0038	0.223	0.244	.225	.243
YJ	5	0.239	0.0089	0.0040	0.228	0.250	.230	.252
YX	5	0.235	0.0108	0.0049	0.222	0.249	.223	.246
Total	140	0.230	0.0085	0.0007	0.229	0.232	.208	.252

Thermal resistance of cold weather fabric systems by sample ID (continued)

Test of Homogeneity of Variances

Rct

Levene Statistic	df1	df2	Sig.
.670	27	112	.885

ANOVA

Rct

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.002	27	.000	1.061	.398
Within Groups	.008	112	.000		
Total	.010	139			

Appendix F

Summary of descriptives, homogeneity of variance, and two-way ANOVA tests for two-layer composites and cold weather fabric systems

APPENDIX F

Overall moisture management capacity (OMMC) of two-layer composites

Descriptive Statistics

Dependent Variable: OMMC

Underwear ID	Lining ID	Mean	Std. Deviation	N
A	H	0.80	0.023	10
	I	0.79	0.019	10
	J	0.00	0.000	10
	X	0.15	0.035	10
	Total	0.44	0.371	40
B	H	0.60	0.029	10
	I	0.62	0.041	10
	J	0.00	0.000	10
	X	0.43	0.055	10
	Total	0.41	0.254	40
C	H	0.80	0.089	10
	I	0.82	0.065	10
	J	0.00	0.000	10
	X	0.82	0.035	10
	Total	0.61	0.361	40
D	H	0.90	0.014	10
	I	0.90	0.020	10
	J	0.00	0.000	10
	X	0.87	0.029	10
	Total	0.67	0.391	40
E	H	0.54	0.034	10
	I	0.61	0.042	10
	J	0.00	0.000	10
	X	0.43	0.033	10
	Total	0.39	0.241	40
G	H	0.54	0.033	10
	I	0.61	0.051	10
	J	0.00	0.000	10
	X	0.35	0.029	10
	Total	0.37	0.241	40
Y	H	0.73	0.034	10
	I	0.78	0.041	10
	J	0.00	0.000	10
	X	0.50	0.077	10
	Total	0.50	0.316	40
Total	H	0.70	0.139	70

	I	0.73	0.118	70
	J	0.00	0.000	70
	X	0.51	0.244	70
	Total	0.49	0.330	280

Levene's Test of Equality of Error Variances[a]

Dependent Variable: OMMC

F	df1	df2	Sig.
8.824	27	252	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Underwear + Lining + Underwear * Lining

Tests of Between-Subjects Effects

Dependent Variable: OMMC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	30.105[a]	27	1.115	780.267	.000
Intercept	65.893	1	65.893	46111.589	.000
Underwear	3.099	6	.516	361.419	.000
Lining	24.043	3	8.014	5608.461	.000
Underwear * Lining	2.963	18	.165	115.184	.000
Error	.360	252	.001		
Total	96.358	280			
Corrected Total	30.465	279			

a. R Squared = .988 (Adjusted R Squared = .987)

1. Underwear ID

Dependent Variable: OMMC

Underwear ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	0.44	.006	.424	.447
B	0.41	.006	.401	.424
C	0.61	.006	.599	.622
D	0.67	.006	.655	.679
E	0.39	.006	.382	.406
G	0.37	.006	.362	.386
Y	0.50	.006	.490	.514

2. Lining ID

Dependent Variable: OMMC

Lining ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
H	0.70	.005	.692	.710
I	0.73	.005	.724	.741
J	0.00	.005	-.009	.009
X	0.51	.005	.498	.516

3. Underwear ID * Lining ID

Dependent Variable: OMMC

Underwear ID		Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	H	0.80	.012	.780	.827
	I	0.79	.012	.768	.815
	J	0.00	.012	-.024	.024
	X	0.15	.012	.124	.171
B	H	0.60	.012	.573	.620
	I	0.62	.012	.596	.643
	J	0.00	.012	-.024	.024
	X	0.43	.012	.410	.457
C	H	0.80	.012	.778	.825
	I	0.82	.012	.795	.843
	J	0.00	.012	-.024	.024
	X	0.82	.012	.797	.844
D	H	0.90	.012	.873	.920
	I	0.90	.012	.874	.921
	J	0.00	.012	-.024	.024
	X	0.87	.012	.851	.898
E	H	0.54	.012	.521	.568
	I	0.61	.012	.582	.629
	J	0.00	.012	-.024	.024
	X	0.43	.012	.403	.450
G	H	0.54	.012	.512	.559
	I	0.61	.012	.587	.634
	J	0.00	.012	-.024	.024
	X	0.35	.012	.327	.374
Y	H	0.73	.012	.703	.750
	I	0.78	.012	.760	.808
	J	0.00	.012	-.024	.024
	X	0.50	.012	.474	.521

APPENDIX F

Wet heat flux of cold weather fabric systems

Descriptive Statistics

Dependent Variable: Wet heat flux

Lining ID		Mean	Std. Deviation	N
H	A	259	8.1	3
	B	265	5.1	3
	C	255	12.2	3
	D	253	10.1	3
	E	263	7.8	3
	G	243	9.7	3
	Y	255	8.1	3
	Total	256	10.3	21
I	A	262	11.0	3
	B	256	10.0	3
	C	254	12.7	3
	D	257	7.5	3
	E	262	9.7	3
	G	246	8.1	3
	Y	257	5.9	3
	Total	256	9.4	21
J	A	237	2.0	3
	B	233	9.2	3
	C	231	2.5	3
	D	231	7.2	3
	E	235	11.9	3
	G	227	12.5	3
	Y	241	4.7	3
	Total	234	8.1	21
X	A	255	11.5	3
	B	256	11.1	3
	C	255	13.0	3
	D	251	7.6	3
	E	259	9.5	3
	G	240	2.9	3
	Y	250	4.6	3
	Total	252	9.6	21
Total	A	253	12.7	12
	B	252	14.5	12
	C	249	14.2	12
	D	248	12.7	12

	E	255	14.7	12
	G	239	10.8	12
	Y	251	8.1	12
	Total	250	13.2	84

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Wet heat flux

F	df1	df2	Sig.
.950	27	56	.546

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Lining + Underwear + Lining * Underwear

Tests of Between-Subjects Effects

Dependent Variable: Wet heat flux

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9864.893[a]	27	365.366	4.507	.000
Intercept	5230518.107	1	5230518.107	64517.404	.000
Lining	7353.274	3	2451.091	30.234	.000
Underwear	1934.976	6	322.496	3.978	.002
Lining * Underwear	576.643	18	32.036	.395	.984
Error	4540.000	56	81.071		
Total	5244923.000	84			
Corrected Total	14404.893	83			

a. R Squared = .685 (Adjusted R Squared = .533)

1. Lining ID

Dependent Variable: Wet heat flux

Lining ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
H	256	2.0	252	260
I	256	2.0	252	260
J	234	2.0	230	238
X	252	2.0	248	256

2. Underwear ID

Dependent Variable: Wet heat flux

Underwear ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	253	2.6	248	258
B	252	2.6	247	258
C	249	2.6	244	254
D	248	2.6	243	253
E	255	2.6	249	260
G	239	2.6	234	244
Y	251	2.6	246	256

3. Lining ID * Underwear ID

Dependent Variable: Wet heat flux

Lining ID		Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
H	A	259	5.2	249	270
	B	265	5.2	254	275
	C	255	5.2	244	265
	D	253	5.2	243	263
	E	263	5.2	253	273
	G	243	5.2	232	253
	Y	255	5.2	244	265
I	A	262	5.2	251	272
	B	256	5.2	246	267
	C	254	5.2	244	265
	D	257	5.2	246	267
	E	262	5.2	251	272
	G	246	5.2	236	257
	Y	257	5.2	247	268
J	A	237	5.2	227	247
	B	233	5.2	223	243
	C	231	5.2	221	242
	D	231	5.2	220	241
	E	235	5.2	224	245
	G	227	5.2	217	237
	Y	241	5.2	231	252
X	A	255	5.2	245	265
	B	256	5.2	245	266
	C	255	5.2	245	266

D	251	5.2	240	261
E	259	5.2	248	269
G	240	5.2	230	251
Y	250	5.2	240	260

APPENDIX F

Drying time of cold weather fabric systems

Descriptive Statistics

Dependent Variable: Drying time

Lining ID		Mean	Std. Deviation	N
H	A	133	6.7	3
	B	135	1.5	3
	C	134	3.2	3
	D	126	0.6	3
	E	122	10.1	3
	G	151	7.8	3
	Y	129	9.5	3
	Total	133	10.4	21
I	A	146	8.1	3
	B	139	7.9	3
	C	137	5.7	3
	D	132	11.0	3
	E	117	4.2	3
	G	140	9.0	3
	Y	132	4.9	3
	Total	135	10.7	21
J	A	129	11.9	3
	B	112	8.1	3
	C	126	2.0	3
	D	112	5.5	3
	E	109	11.6	3
	G	133	11.2	3
	Y	130	3.5	3
	Total	122	12.1	21
X	A	140	6.7	3
	B	124	12.0	3
	C	130	5.1	3
	D	124	12.4	3
	E	125	8.6	3
	G	142	4.5	3
	Y	159	11.5	3
	Total	135	14.5	21
Total	A	137	10.2	12
	B	127	13.1	12
	C	132	5.7	12
	D	124	10.6	12

	E	118	10.0	12
	G	142	9.8	12
	Y	138	14.6	12
	Total	131	13.1	84

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Drying time

F	df1	df2	Sig.
1.533	27	56	.089

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Lining + Underwear + Lining * Underwear

Tests of Between-Subjects Effects

Dependent Variable: Drying time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	10557.333[a]	27	391.012	5.988	.000
Intercept	1441524.000	1	1441524.000	22076.211	.000
Lining	2584.476	3	861.492	13.193	.000
Underwear	5096.833	6	849.472	13.009	.000
Lining * Underwear	2876.024	18	159.779	2.447	.006
Error	3656.667	56	65.298		
Total	1455738.000	84			
Corrected Total	14214.000	83			

a. R Squared = .743 (Adjusted R Squared = .619)

1. Lining ID

Dependent Variable: Drying time

Lining ID	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
H	133	1.8	129	136
I	135	1.8	131	138
J	122	1.8	118	125
X	135	1.8	131	138

2. Underwear ID

Dependent Variable: Drying time

Underwear ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	137	2.3	132	142
B	127	2.3	123	132
C	132	2.3	127	137
D	124	2.3	119	128
E	118	2.3	113	123
G	142	2.3	137	146
Y	138	2.3	133	142

3. Lining ID * Underwear ID

Dependent Variable: Drying time

Lining ID		Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
H	A	133	4.7	123	142
	B	135	4.7	125	144
	C	134	4.7	124	143
	D	126	4.7	116	135
	E	122	4.7	113	131
	G	151	4.7	142	160
	Y	129	4.7	120	138
I	A	146	4.7	137	156
	B	139	4.7	130	148
	C	137	4.7	128	147
	D	132	4.7	123	142
	E	117	4.7	108	127
	G	140	4.7	130	149
	Y	132	4.7	123	142
J	A	129	4.7	119	138
	B	112	4.7	102	121
	C	126	4.7	117	135
	D	112	4.7	103	122
	E	109	4.7	99	118
	G	133	4.7	124	143
	Y	130	4.7	121	139
X	A	140	4.7	131	150
	B	124	4.7	115	134

C	130	4.7	121	140
D	124	4.7	114	133
E	125	4.7	115	134
G	142	4.7	133	152
Y	159	4.7	149	168

APPENDIX F

Drying rate of cold weather fabric systems

Descriptive Statistics

Dependent Variable: Drying rate

Lining ID		Mean	Std. Deviation	N
H	A	1.9	0.10	3
	B	1.8	0.06	3
	C	1.8	0.06	3
	D	2.0	0.00	3
	E	2.1	0.15	3
	G	1.7	0.06	3
	Y	1.9	0.15	3
	Total	1.9	0.15	21
I	A	1.7	0.10	3
	B	1.8	0.10	3
	C	1.8	0.10	3
	D	1.9	0.17	3
	E	2.1	0.10	3
	G	1.8	0.10	3
	Y	1.9	0.06	3
	Total	1.9	0.15	21
J	A	2.0	0.21	3
	B	2.2	0.17	3
	C	2.0	0.06	3
	D	2.2	0.10	3
	E	2.3	0.25	3
	G	1.8	0.15	3
	Y	1.9	0.00	3
	Total	2.0	0.21	21
X	A	1.8	0.06	3
	B	2.0	0.20	3
	C	1.9	0.10	3
	D	2.0	0.17	3
	E	2.0	0.10	3
	G	1.7	0.06	3
	Y	1.6	0.10	3
	Total	1.9	0.18	21
Total	A	1.8	0.16	12
	B	2.0	0.21	12
	C	1.9	0.10	12
	D	2.0	0.16	12

E	2.1	0.17	12
G	1.8	0.11	12
Y	1.8	0.16	12
Total	1.9	0.19	84

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Drying rate

F	df1	df2	Sig.
1.701	27	56	.047

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Lining + Underwear + Lining * Underwear

Tests of Between-Subjects Effects

Dependent Variable: Drying rate

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.108[a]	27	.078	5.084	.000
Intercept	307.052	1	307.052	19994.078	.000
Lining	.534	3	.178	11.587	.000
Underwear	1.106	6	.184	12.008	.000
Lining * Underwear	.468	18	.026	1.693	.069
Error	.860	56	.015		
Total	310.020	84			
Corrected Total	2.968	83			

a. R Squared = .710 (Adjusted R Squared = .571)

1. Lining ID

Dependent Variable: Drying rate

Lining ID	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
H	1.9	0.03	1.8	1.9
I	1.9	0.03	1.8	1.9
J	2.0	0.03	2.0	2.1
X	1.9	0.03	1.8	1.9

2. Underwear ID

Dependent Variable: Drying rate

Underwear ID	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	1.8	0.04	1.8	1.9
B	2.0	0.04	1.9	2.0
C	1.9	0.04	1.8	1.9
D	2.0	0.04	2.0	2.1
E	2.1	0.04	2.0	2.2
G	1.8	0.04	1.7	1.8
Y	1.8	0.04	1.8	1.9

3. Lining ID * Underwear ID

Dependent Variable: Drying rate

Lining ID		Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
H	A	1.9	0.07	1.8	2.0
	B	1.8	0.07	1.7	2.0
	C	1.8	0.07	1.7	2.0
	D	2.0	0.07	1.9	2.1
	E	2.1	0.07	1.9	2.2
	G	1.7	0.07	1.5	1.8
	Y	1.9	0.07	1.8	2.1
I	A	1.7	0.07	1.6	1.8
	B	1.8	0.07	1.7	1.9
	C	1.8	0.07	1.7	1.9
	D	1.9	0.07	1.8	2.0
	E	2.1	0.07	2.0	2.2
	G	1.8	0.07	1.7	1.9
	Y	1.9	0.07	1.7	2.0
J	A	2.0	0.07	1.8	2.1
	B	2.2	0.07	2.1	2.3
	C	2.0	0.07	1.8	2.1
	D	2.2	0.07	2.1	2.3
	E	2.3	0.07	2.1	2.4
	G	1.8	0.07	1.7	2.0
	Y	1.9	0.07	1.8	2.0
X	A	1.8	0.07	1.6	1.9
	B	2.0	0.07	1.9	2.1
	C	1.9	0.07	1.8	2.0

D	2.0	0.07	1.9	2.1
E	2.0	0.07	1.9	2.1
G	1.7	0.07	1.6	1.9
Y	1.6	0.07	1.5	1.7

Appendix G

Homogenous tables for post-hoc tests on underwear and lining fabrics

APPENDIX G

Thickness of underwear fabrics

Thickness (mm)

ID CODE		N	Subset for alpha = 0.05					
			1	2	3	4	5	6
Tamhane[a]	E	10	0.48					
	A	10		0.56				
	C	10			0.58			
	D	10			0.58			
	B	10				0.61		
	G	10					0.74	
	Y	10						0.77

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Air permeability of underwear fabrics

Air permeability (cm3/cm2/sec)

ID CODE		N	Subset for alpha = 0.05				
			1	2	3	4	5
Tamhane[a]	G	10	23				
	A	10		27			
	C	10			31		
	B	10				103	
	E	10				105	
	D	10					128
	Y	10					135

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

APPENDIX G

Air permeability of lining fabrics

Air permeability (cm3/cm2/sec)

ID CODE		N	Subset for alpha = 0.05	
			1	2
Tamhane[a]	X	10	0	
	I	10	1	
	H	10	2	
	J	10		18

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Thermal resistance of underwear fabrics

Rct (m2·C/W)

ID Code		N	Subset for alpha = 0.05				
			1	2	3	4	5
Tamhane[a]	E	5	.009				
	B	5		.011			
	D	5		.012	.012		
	A	5			.013		
	C	5			.013		
	G	5				.016	
	Y	5					.020

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Liquid absorption capacity (LAC) of underwear fabrics

LAC (%)

ID Code		N	Subset for alpha = 0.05				
			1	2	3	4	5
Tukey HSD[a]	G	5	194				
	D	5		215			
	C	5		217			
	A	5		227	227		
	B	5			245	245	
	E	5				250	
	Y	5					346
	Sig.		1.000	.580	.154	.990	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

Liquid absorption capacity (LAC) of lining fabrics

LAC (%)

ID Code		N	Subset for alpha = 0.05		
			1	2	3
Tamhane[a]	J	5	0		
	X	5		46	
	I	5			69
	H	5			70

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 5.000.

APPENDIX G

Overall moisture management capacity (OMMC) of underwear fabrics

OMMC (index)

ID CODE		N	Subset for alpha = 0.05		
			1	2	3
Tamhane[a]	G	10	.45		
	B	10	.48	.48	
	A	10	.52	.52	
	E	10	.54	.54	
	Y	10	.57	.57	.57
	C	10		.66	.66
	D	10			.76

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Overall moisture management capacity (OMMC) of lining fabrics

OMMC (index)

ID CODE		N	Subset for alpha = 0.05	
			1	2
Tamhane[a]	X	10	.17	
	J	10	.21	
	I	10		.53
	H	10		.53

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Wet heat flux of underwear fabrics

Wet heat flux (W/m^2)

ID Code		N	Subset for alpha = 0.05			
			1	2	3	4
Tamhane[a]	G	3	907			
	Y	3	983	983		
	C	3		1005	1005	
	A	3		1029	1029	
	D	3			1091	
	B	3			1117	1117
	E	3				1196

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Drying time of underwear fabrics

Drying time (mins)

ID Code		N	Subset for alpha = 0.05		
			1	2	3
Tukey HSD[a]	E	3	13		
	D	3	14		
	B	3	14		
	A	3		18	
	C	3		18	
	G	3		19	
	Y	3			22
	Sig.		.139	.139	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Drying rate of underwear fabrics

Drying rate (g·m^2/min)

ID Code		N	Subset for alpha = 0.05		
			1	2	3
Tukey HSD[a]	Y	3	11		
	G	3	13	13	
	C	3		14	
	A	3		14	
	B	3			18
	D	3			18
	E	3			20
	Sig.		.455	.230	.103

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Appendix H

Homogenous tables for post-hoc tests on cold weather fabric systems

Overall moisture management capacity (OMMC) of two-layer composites by sample ID

OMMC (index)

Fabric ID	N	Subset for alpha = 0.05											
		1	2	3	4	5	6	7	8	9	10	11	12
Tamhane[a]													
AJ	10	0.00											
BJ	10	0.00											
CJ	10	0.00											
DJ	10	0.00											
EJ	10	0.00											
GJ	10	0.00											
YJ	10	0.00											
AX	10		0.15										
GX	10			0.35									
EX	10				0.43								
BX	10				0.43								
YX	10					0.50							
GH	10					0.54	0.54						
EH	10					0.54	0.54	0.54					
BH	10						0.60	0.60	0.60				
EI	10							0.61	0.61				
GI	10								0.61				
BI	10								0.62				
YH	10									0.73			
YI	10									0.78	0.78		
AI	10										0.79		
CH	10										0.80		
AH	10										0.80		
CI	10										0.82	0.82	
CX	10										0.82	0.82	
DX	10											0.87	0.87
DH	10												0.90
DI	10												0.90

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 10.000.

Overall moisture management capacity (OMMC) of two layer composites by underwear type

OMMC

Tamhane$_a$

Underwear ID	N	Subset 1	2	3	4	5	6
G	40	0.37					
E	40	0.39	0.39				
B	40		0.41	0.41			
A	40			0.44			
Y	40				0.50		
C	40					0.61	
D	40						0.67
Sig.		.228	.306	.091	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = .001.

a. Uses Harmonic Mean Sample Size = 40.000.

Overall moisture management capacity (OMMC) of two layer composites by lining type

OMMC (index)

Lining ID		N	Subset for alpha = 0.05 1	2	3
Tamhane[a]	J	70	0.00		
	X	70		0.51	
	H	70			0.70
	I	70			0.73

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 70.000.

APPENDIX H

Wet heat flux of cold weather fabric systems by sample ID

Wet heat flux (W/m^2)

Fabric ID		N	Subset for alpha = 0.05				
			1	2	3	4	5
Tukey HSD[a]	GJ	3	227.00				
	DJ	3	230.67	230.67			
	CJ	3	231.33	231.33			
	BJ	3	233.00	233.00	233.00		
	EJ	3	234.67	234.67	234.67	234.67	
	AJ	3	237.00	237.00	237.00	237.00	237.00
	GX	3	240.33	240.33	240.33	240.33	240.33
	YJ	3	241.33	241.33	241.33	241.33	241.33
	GH	3	242.67	242.67	242.67	242.67	242.67
	GI	3	246.33	246.33	246.33	246.33	246.33
	YX	3	250.00	250.00	250.00	250.00	250.00
	DX	3	250.67	250.67	250.67	250.67	250.67
	DH	3	253.00	253.00	253.00	253.00	253.00
	CI	3	254.33	254.33	254.33	254.33	254.33
	CH	3	254.67	254.67	254.67	254.67	254.67
	YH	3	254.67	254.67	254.67	254.67	254.67
	AX	3	255.00	255.00	255.00	255.00	255.00
	CX	3	255.33	255.33	255.33	255.33	255.33
	BX	3	255.67	255.67	255.67	255.67	255.67
	BI	3		256.33	256.33	256.33	256.33
	DI	3		256.67	256.67	256.67	256.67
	YI	3		257.33	257.33	257.33	257.33
	EI	3		258.67	258.67	258.67	258.67
	AH	3		259.33	259.33	259.33	259.33
	AI	3			261.67	261.67	261.67
	EI	3			261.67	261.67	261.67
	EH	3				263.00	263.00
	BH	3					264.67
	Sig.		.052	.052	.052	.058	.074

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Wet heat flux of cold weather fabric systems by underwear type

Wet heat flux

Tukey HSD[a]

		Subset	
Underwear ID	N	1	2
G	12	239	
D	12	248	248
C	12	249	249
Y	12		251
B	12		252
A	12		253
E	12		255
Sig.		.124	.530

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 81.071.

a. Uses Harmonic Mean Sample Size = 12.000.

Wet heat flux of cold weather fabric systems by lining type

Wet heat flux

Tukey HSD[a,b]

		Subset	
Lining ID	N	1	2
J	21	234	
X	21		252
H	21		256
I	21		256
Sig.		1.000	.460

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 81.071.

a. Uses Harmonic Mean Sample Size = 21.000.

APPENDIX H

Drying time of cold weather fabric systems by sample ID

Drying time (mins)

Fabric ID		N	Subset for alpha = 0.05					
			1	2	3	4	5	6
Tukey HSD[a]	EJ	3	108.67					
	BJ	3	111.67	111.67				
	DJ	3	112.33	112.33				
	EI	3	117.33	117.33	117.33			
	EH	3	122.00	122.00	122.00	122.00		
	DX	3	123.67	123.67	123.67	123.67		
	BX	3	124.33	124.33	124.33	124.33		
	EX	3	124.67	124.67	124.67	124.67		
	DH	3	125.67	125.67	125.67	125.67	125.67	
	CJ	3	126.00	126.00	126.00	126.00	126.00	
	AJ	3	128.67	128.67	128.67	128.67	128.67	
	YH	3	129.00	129.00	129.00	129.00	129.00	
	YJ	3	130.00	130.00	130.00	130.00	130.00	
	CX	3	130.33	130.33	130.33	130.33	130.33	
	DI	3	132.33	132.33	132.33	132.33	132.33	
	YI	3	132.33	132.33	132.33	132.33	132.33	
	AH	3	132.67	132.67	132.67	132.67	132.67	
	GJ	3	133.33	133.33	133.33	133.33	133.33	133.33
	CH	3	133.67	133.67	133.67	133.67	133.67	133.67
	BH	3		134.67	134.67	134.67	134.67	134.67
	CI	3		137.33	137.33	137.33	137.33	137.33
	BI	3			139.00	139.00	139.00	139.00
	GI	3			139.67	139.67	139.67	139.67
	AX	3			140.33	140.33	140.33	140.33
	GX	3			142.33	142.33	142.33	142.33
	AI	3				146.33	146.33	146.33
	GH	3					151.00	151.00
	YX	3						158.67
	Sig.		.069	.053	.069	.090	.061	.061

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Drying time of cold weather fabrics systems by underwear type

Drying time (mins)

Underwear ID		N	Subset for alpha = 0.05			
			1	2	3	4
Tukey HSD[a]	E	12	118.17			
	D	12	123.50	123.50		
	B	12	127.42	127.42	127.42	
	C	12		131.83	131.83	131.83
	A	12			137.00	137.00
	Y	12			137.50	137.50
	G	12				141.58
	Sig.		.373	.502	.272	.310

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 12.000.

Drying time of cold weather fabric systems by lining type

Drying time (mins)

Lining ID		N	Subset for alpha = 0.05	
			1	2
Tukey HSD[a]	J	21	121.52	
	H	21		132.67
	I	21		134.90
	X	21		134.90
	Sig.		1.000	.931

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 21.000.

APPENDIX H

Drying rate of cold weather fabric systems by sample ID

Drying rate

			Subset for alpha = 0.05					
Fabric ID		N	1	2	3	4	5	6
Tukey HSD[a]	YX	3	1.600					
	GH	3	1.667	1.667				
	AI	3	1.700	1.700	1.700			
	GX	3	1.733	1.733	1.733	1.733		
	AX	3	1.767	1.767	1.767	1.767		
	CI	3	1.800	1.800	1.800	1.800		
	BI	3	1.800	1.800	1.800	1.800		
	GI	3	1.800	1.800	1.800	1.800		
	BH	3	1.833	1.833	1.833	1.833	1.833	
	CH	3	1.833	1.833	1.833	1.833	1.833	
	GJ	3	1.833	1.833	1.833	1.833	1.833	
	YI	3	1.867	1.867	1.867	1.867	1.867	
	AH	3	1.900	1.900	1.900	1.900	1.900	1.900
	YJ	3	1.900	1.900	1.900	1.900	1.900	1.900
	CX	3	1.900	1.900	1.900	1.900	1.900	1.900
	DI	3	1.900	1.900	1.900	1.900	1.900	1.900
	YH	3	1.933	1.933	1.933	1.933	1.933	1.933
	AJ	3	1.967	1.967	1.967	1.967	1.967	1.967
	CJ	3	1.967	1.967	1.967	1.967	1.967	1.967
	BX	3		2.000	2.000	2.000	2.000	2.000
	DH	3		2.000	2.000	2.000	2.000	2.000
	DX	3		2.000	2.000	2.000	2.000	2.000
	EX	3		2.000	2.000	2.000	2.000	2.000
	EH	3			2.067	2.067	2.067	2.067
	EI	3				2.100	2.100	2.100
	BJ	3					2.200	2.200
	DJ	3					2.200	2.200
	EJ	3						2.267
	Sig.		.105	.223	.105	.105	.105	.105

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 3.000.

Drying rate of cold weather fabric systems by underwear type

Drying rate (g·m^2/min)

Underwear ID		N	Subset for alpha = 0.05			
			1	2	3	4
Tukey HSD[a]	G	12	1.758			
	Y	12	1.825	1.825		
	A	12	1.833	1.833	1.833	
	C	12	1.875	1.875	1.875	
	B	12		1.958	1.958	1.958
	D	12			2.025	2.025
	E	12				2.108
	Sig.		.527	.363	.051	.229

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 12.000.

Drying rate of cold weather fabric systems by lining type

Drying rate (g·m^2/min)

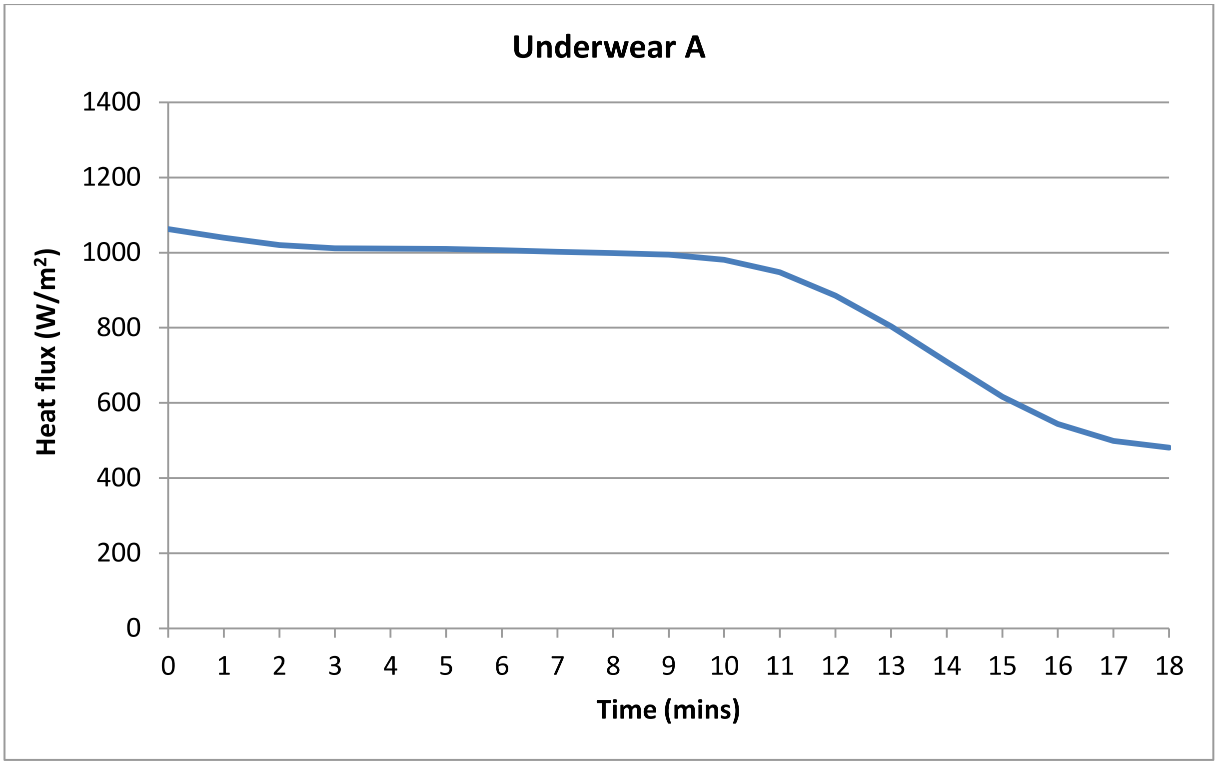
Lining ID		N	Subset for alpha = 0.05	
			1	2
Tukey HSD[a]	I	21	1.852	
	X	21	1.857	
	H	21	1.890	
	J	21		2.048
	Sig.		.894	1.000

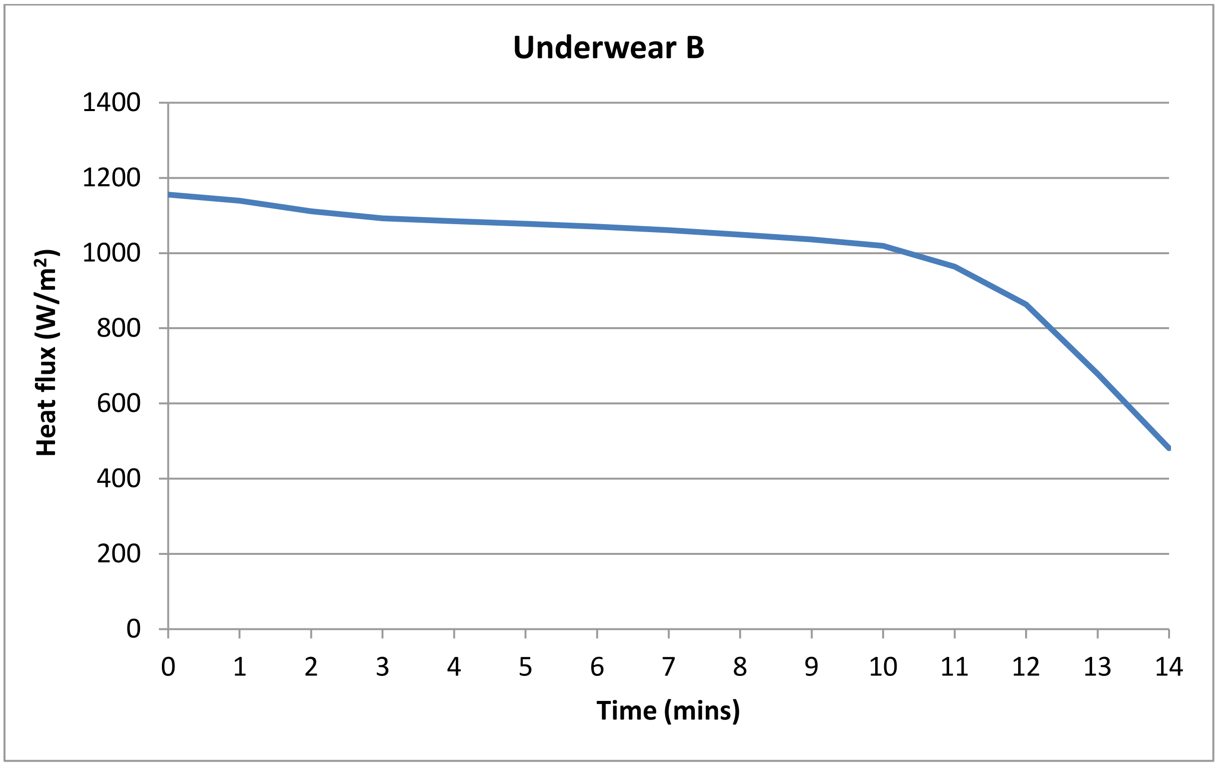
Means for groups in homogeneous subsets are displayed.

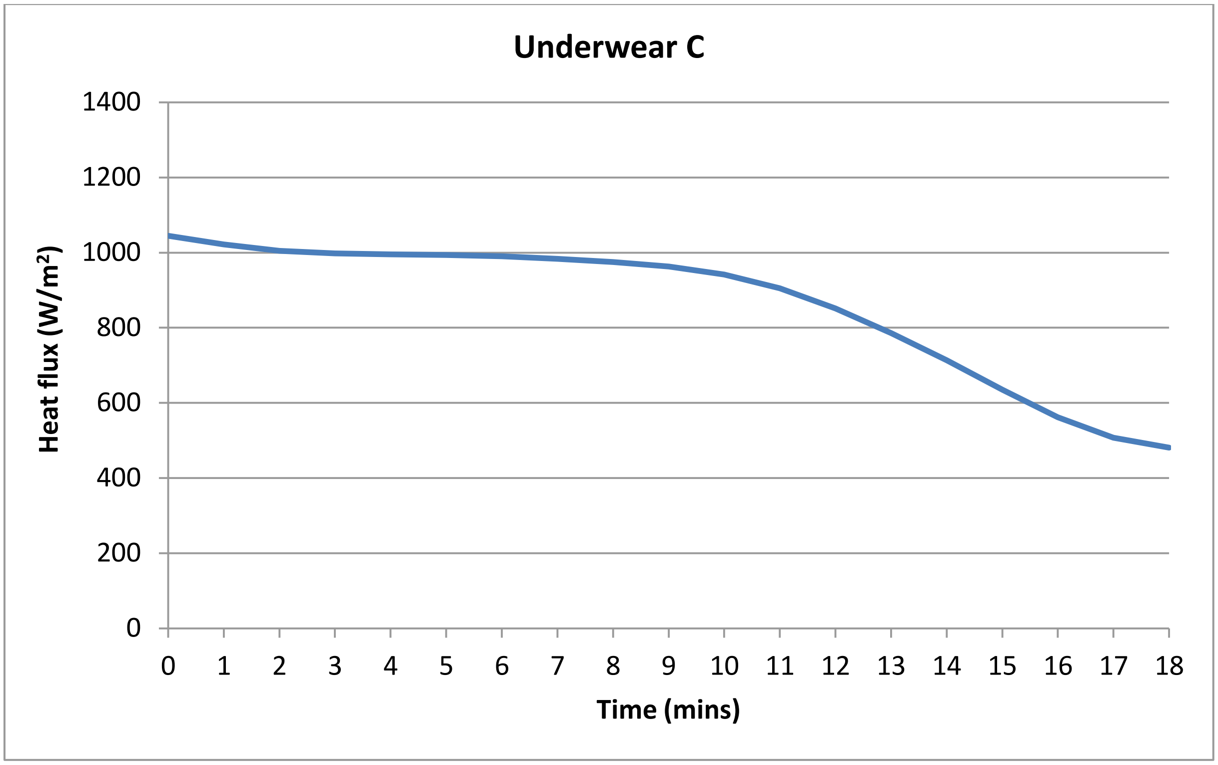
a. Uses Harmonic Mean Sample Size = 21.000.

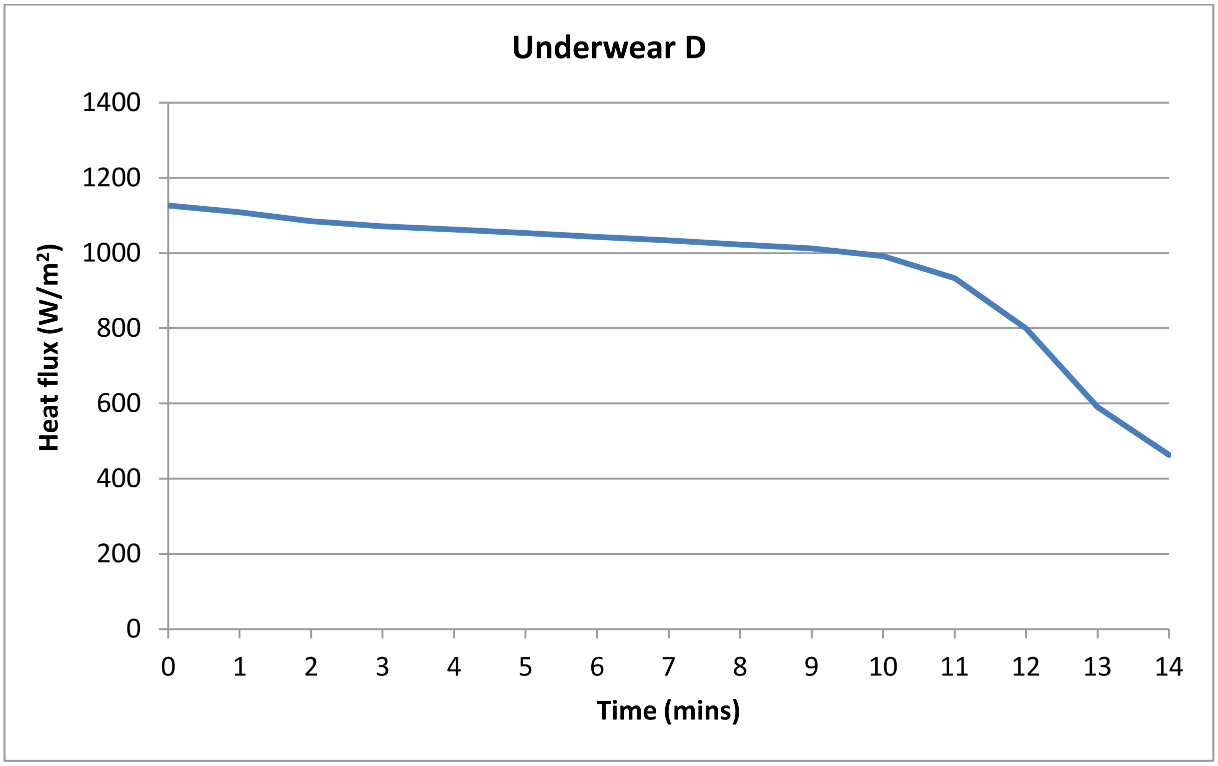
Appendix I

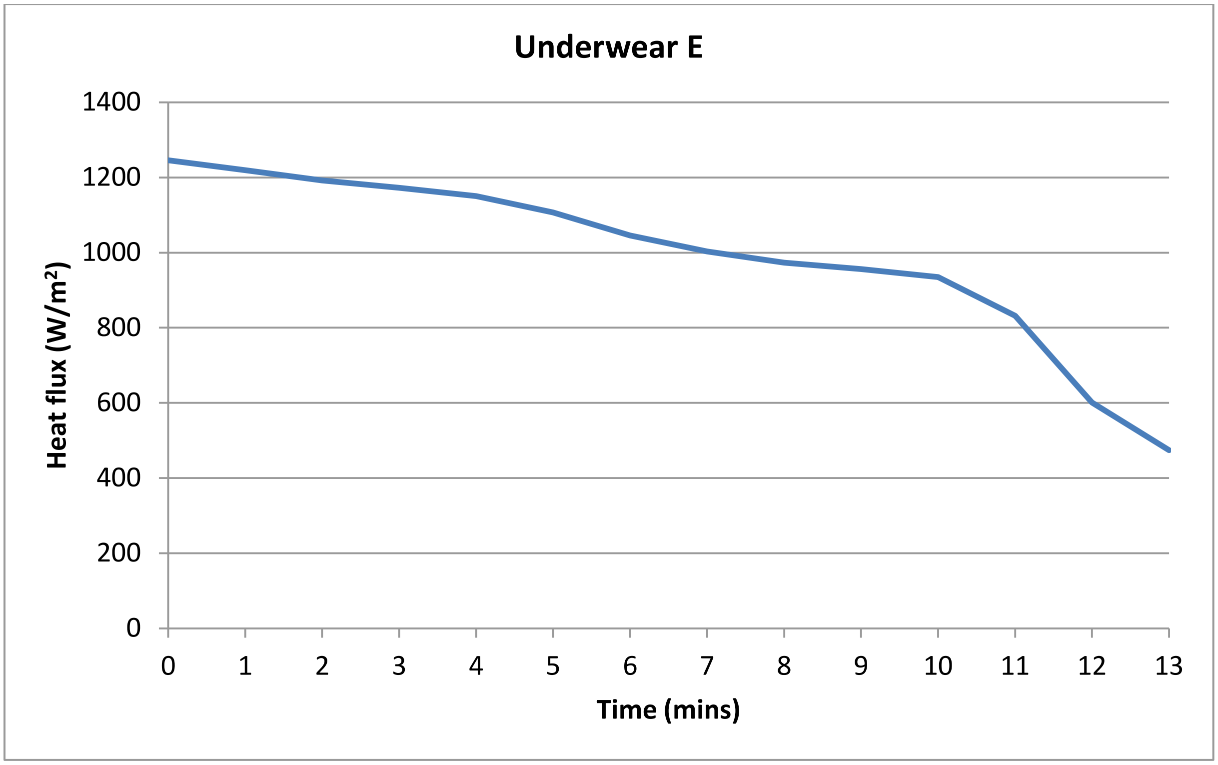
Heat flux plots of underwear fabrics

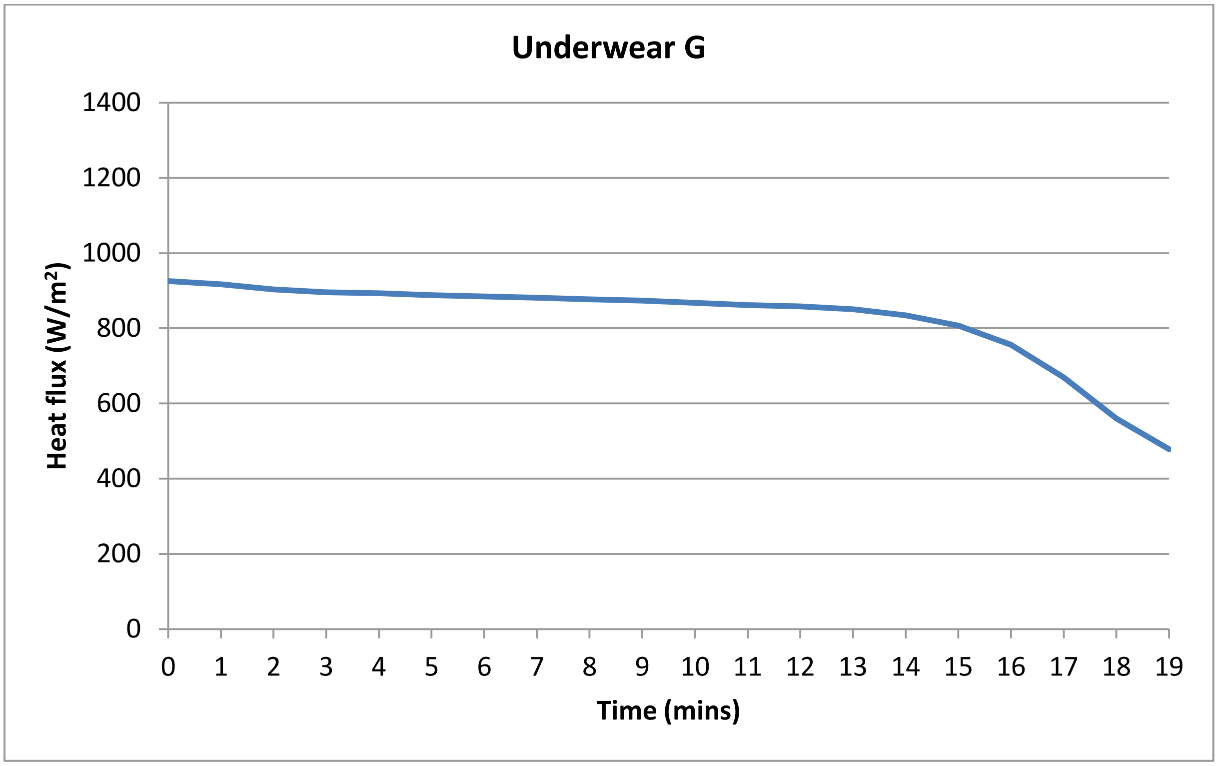

Underwear A
Heat flux (W/m²)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Time (mins)

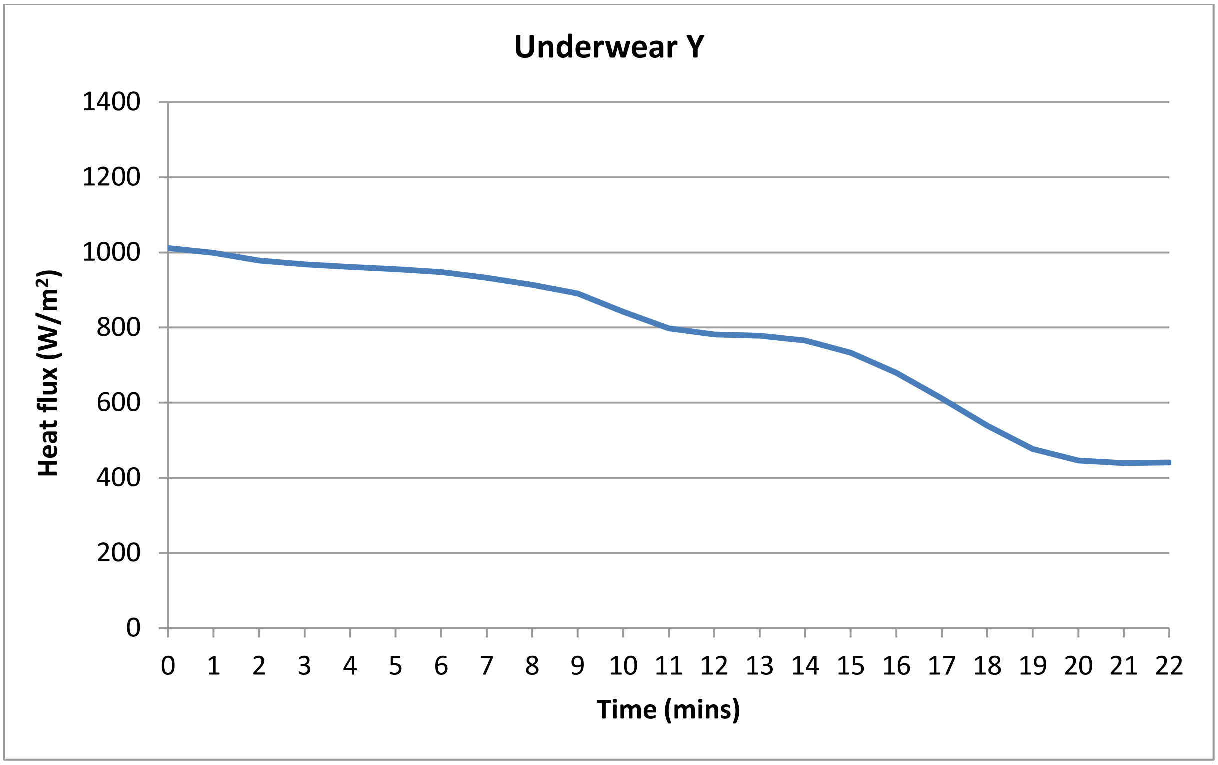

Underwear B
Heat flux (W/m²)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time (mins)


Underwear C
1400
1200
1000
800
600
400
200
0
Heat flux (W/m²)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Time (mins)


Underwear D
1400
1200
1000
800
600
400
200
0
Heat flux (W/m²)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time (mins)

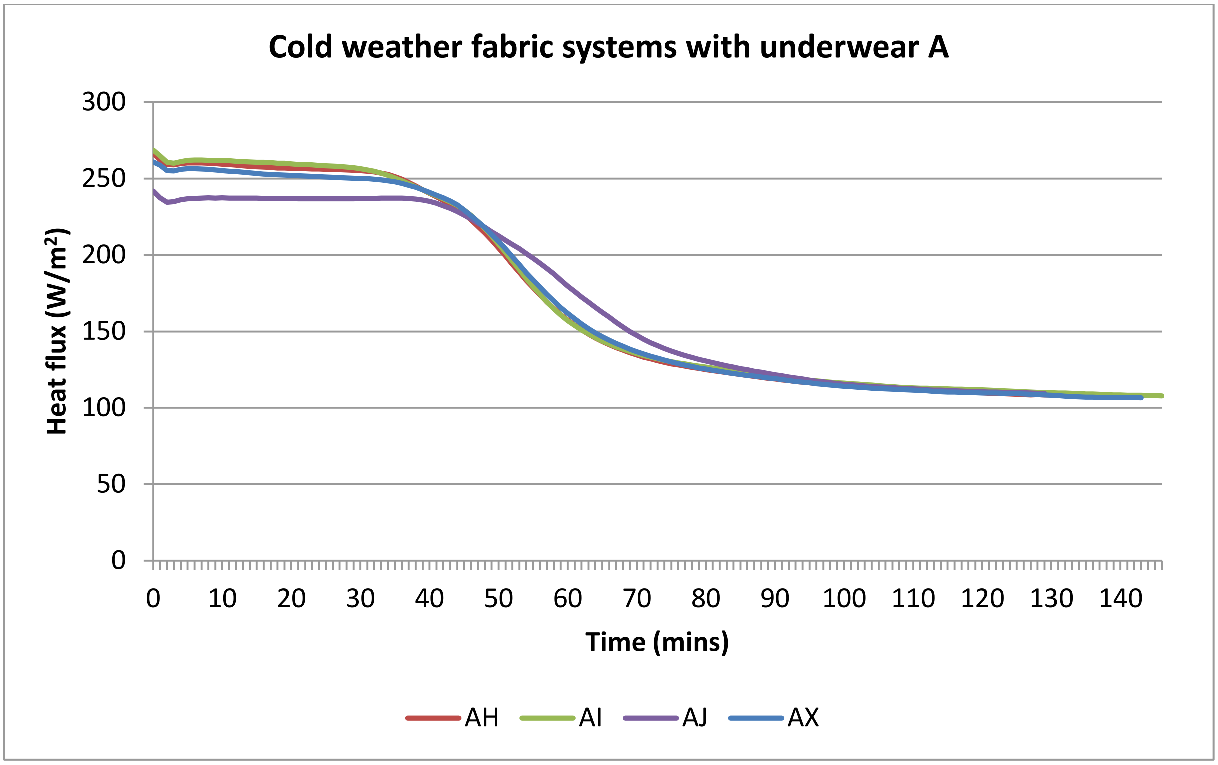

Underwear E
Heat flux (W/m²)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time (mins)

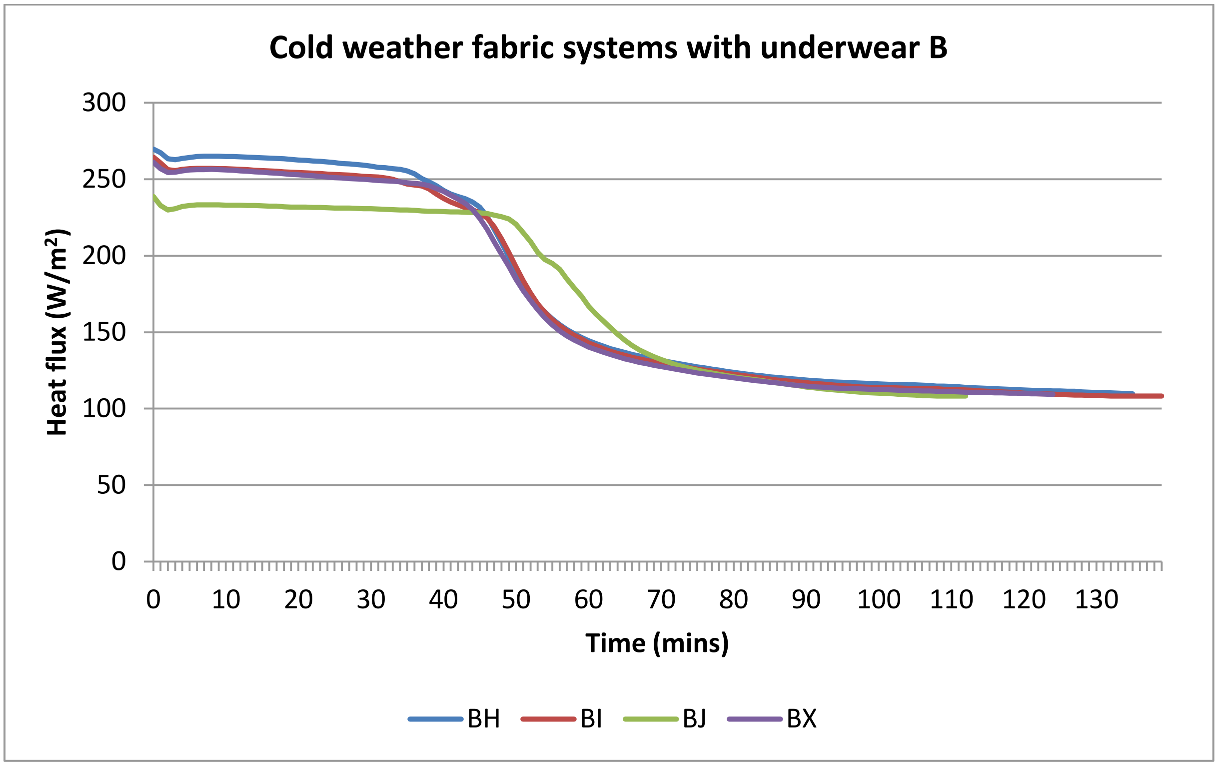

Underwear G
Heat flux (W/m²)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Time (mins)

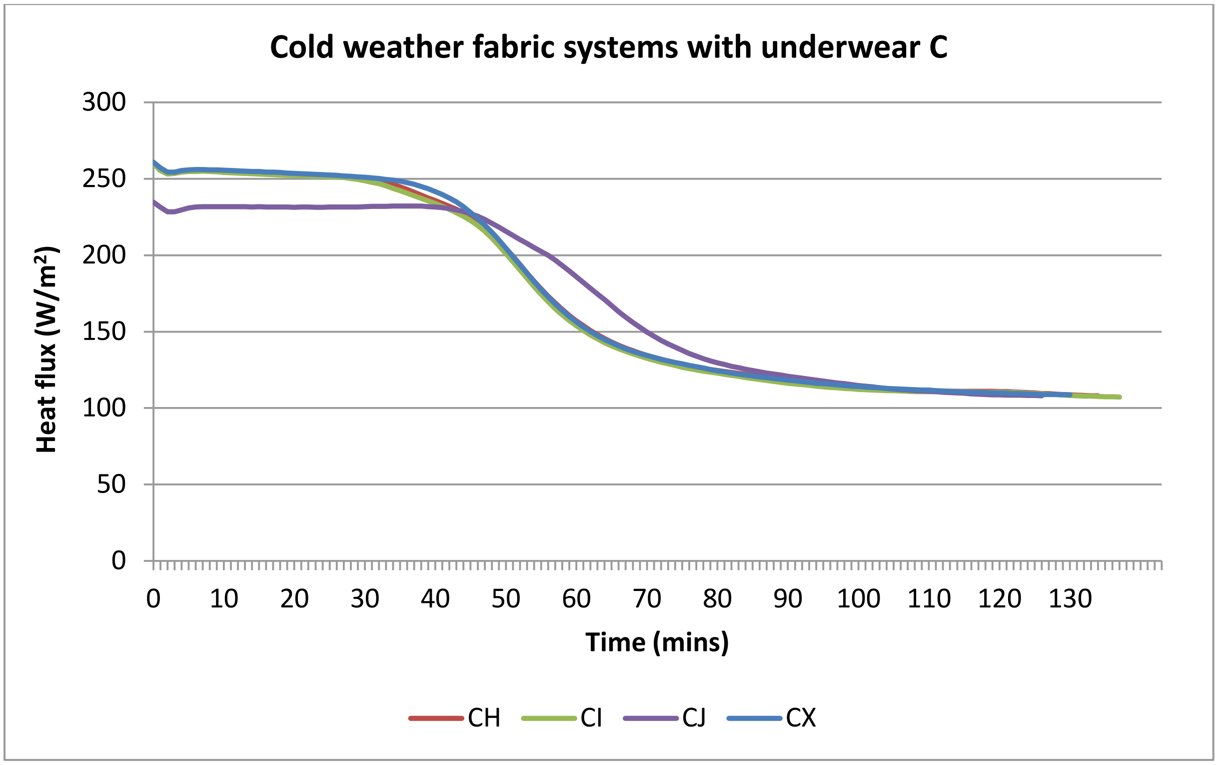

Underwear Y
Heat flux (W/m²)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Time (mins)

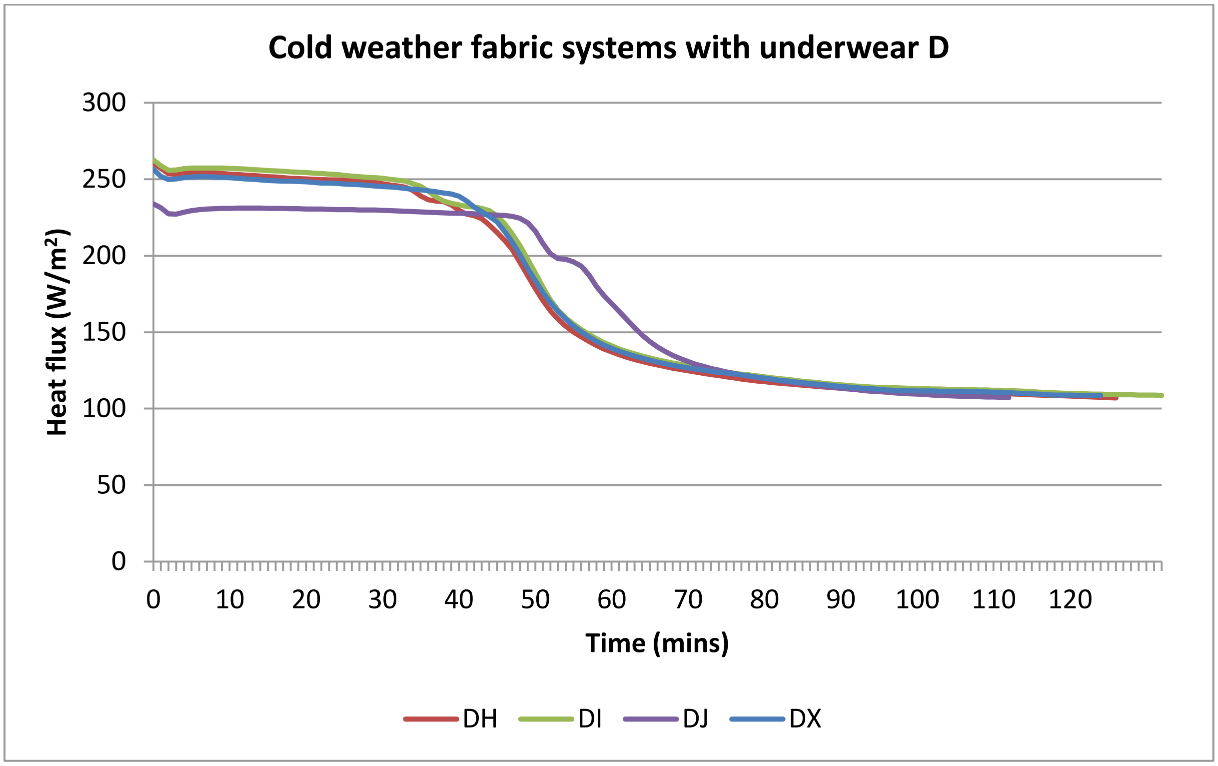
Appendix J

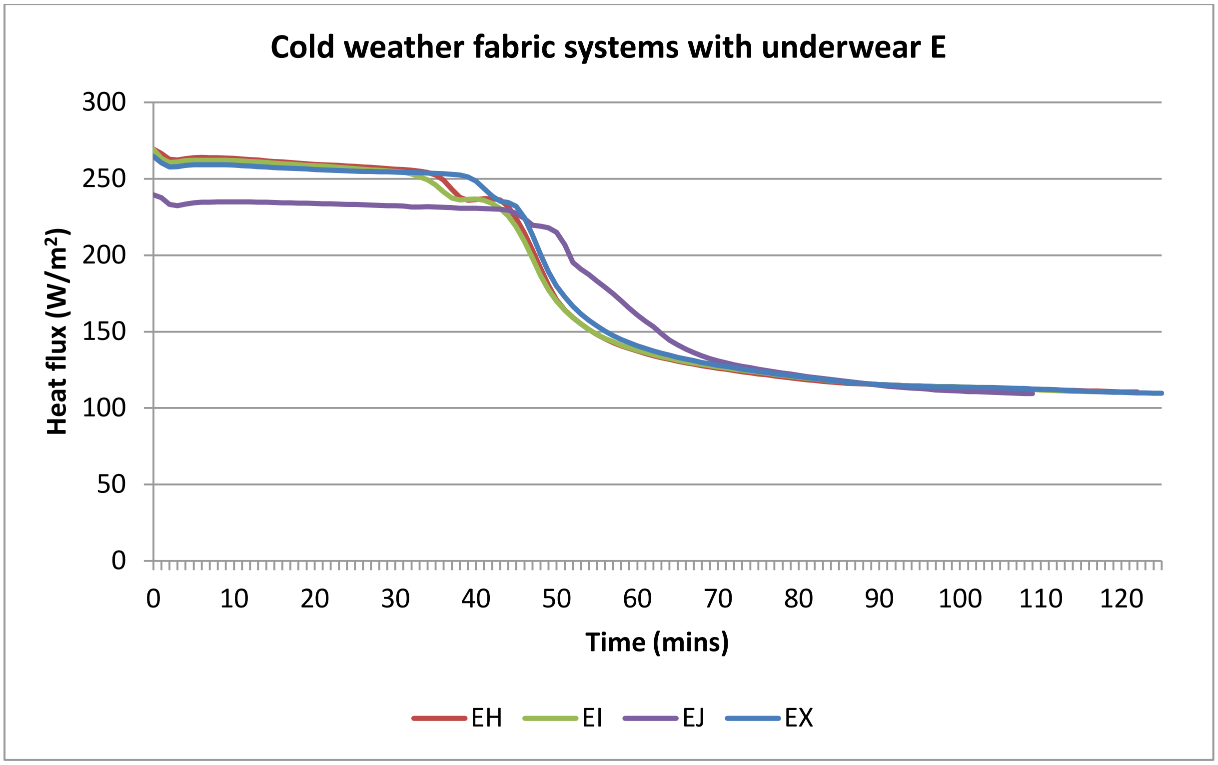
Heat flux plots of cold weather fabric systems by underwear type

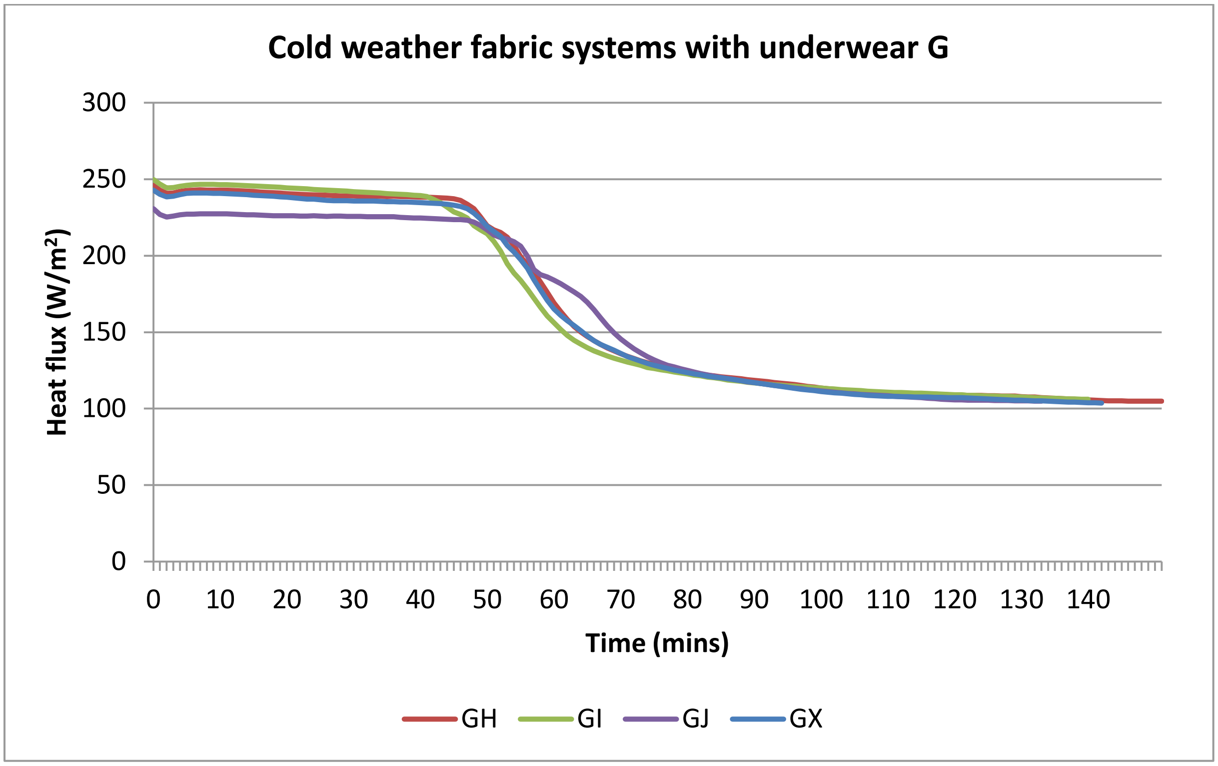

Cold weather fabric systems with underwear A
Heat flux (W/m²)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (mins)
AH
AI
AJ
AX

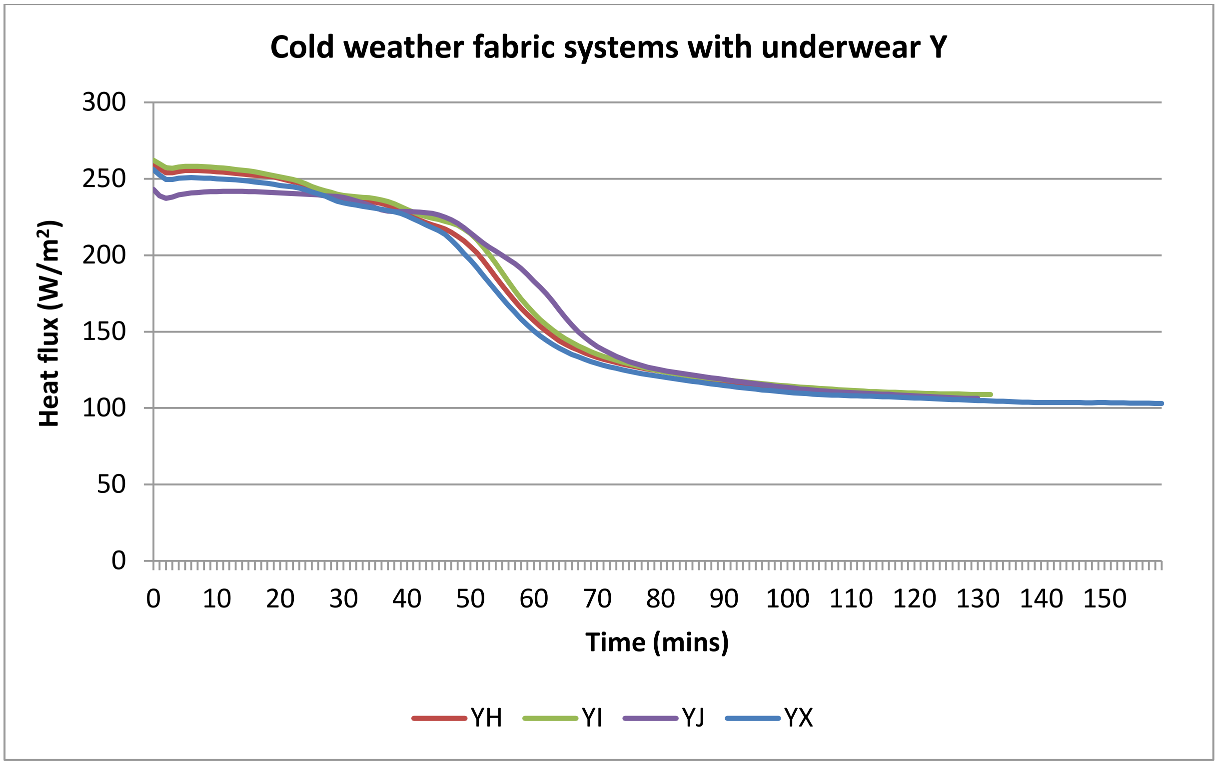

Cold weather fabric systems with underwear B
Heat flux (W/m²)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Time (mins)
BH
BI
BJ
BX


Cold weather fabric systems with underwear C
Heat flux (W/m²)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Time (mins)
CH
CI
CJ
CX


Cold weather fabric systems with underwear D
Heat flux (W/m²)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (mins)
DH
DI
DJ
DX


Cold weather fabric systems with underwear E
300
250
200
150
100
50
0
Heat flux (W/m²)
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (mins)
EH
EI
EJ
EX


Cold weather fabric systems with underwear G
300
250
200
150
100
50
0
Heat flux (W/m²)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (mins)
GH
GI
GJ
GX


Cold weather fabric systems with underwear Y
Heat flux (W/m²)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time (mins)
YH
YI
YJ
YX