University of Alberta

Effects of Moisture on Heat Transfer Through Thermal Protective Fabric Systems

by

Lelia Kathryn Lawson

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

in

Textiles and Clothing

Department of Human Ecology

Edmonton, Alberta

Fall 2002

0-612-81432-7

University of Alberta

Library Release Form

Name of Author: Lelia Kathryn Lawson

Title of Thesis: Effects of Moisture on Heat Transfer Through Thermal Protective Fabric Systems

Degree: Master of Science

Year this Degree Granted: 2002

2002.09.19

Box 26
Two Hills, Alberta
T0B 4K0

L Lawson

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Effects of Moisture on Heat Transfer Through Thermal Protective Fabric Systems submitted by Lelia Kathryn Lawson in partial fulfillment of the requirements for the degree of Master of Science in Textiles and Clothing.

Betty Crown
Dr. E. M. Crown (supervisor)

Nancy Kerr
Dr. N. Kerr

J D Dale
Dr. J. D. Dale

M. Ackerman
M. Ackerman

2002.09.16
Date of Approval

ABSTRACT

The effect of both internal and external moisture on heat transfer through four different thermal protective fabric systems was determined by exposing the fabric systems to one of five different moisture conditions prior to testing, exposing the conditioned fabric systems to either a high-heat-flux flame exposure (83 kW/m^2) or a low-heat-flux radiant exposure (10 kW/m^2), and determining peak heat flux, time at peak heat flux, total transferred energy, and time at 0.1 kJ of transferred energy.

At high-heat-flux flame exposures, external moisture tended to increase the thermal protection of the fabric systems, while internal moisture tended to decrease their thermal protection. At low-heat-flux radiant exposures, internal moisture increased the thermal performance of the fabric systems, while external moisture tended to decrease the thermal performance of the fabric systems. These differences were fabric system dependent.

ACKNOWLEDGEMENTS

There are many people (far too many to mention) whom I wish to thank for their help and support throughout my thesis work. In particular, I would like to thank Dr. Betty Crown, who provided me with much needed guidance, as well as my other committee members, Dr. Nancy Kerr, Dr. Doug Dale, and Mark Ackerman. I would also like to thank all my family, friends, and colleagues who advised and listened to me when I needed them to.

Also, I would like to thank the Workers' Compensation Board, the Faculty of Graduate Studies and Research, the Department of Human Ecology, and the Textile Analysis Service for much appreciated financial support, as well as Difco Performance Fabrics Inc., Westex Inc., and Nova Scotia Textiles, Ltd. for supplying me with fabric used in my thesis work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1
INTRODUCTION

In relatively recent years, concern for individuals working in high-risk environments, especially those with the potential of being exposed to thermal sources, has risen. As a result, extensive research has been conducted to better understand the mechanisms of heat transfer through thermal protective clothing systems and to improve upon protective clothing design and performance. New textiles have been developed, and improvements have been made to those being used for thermal protective clothing systems. These improvements have lead to a decrease in thermal injuries experienced by individuals in high-risk environments; however, even when wearing garments with these improvements, a substantial number of burn injuries occur (Stull, 2000b; Makinen, Smolander, & Vuorinen, 1988).

Many variables affect the performance of thermal protective clothing systems, including environmental conditions (temperature, humidity, wind speed), the nature of the textile used (weave structure, fiber mass and thickness, fiber type, etc.), and the mechanism of heat transfer (convection, conduction, thermal radiation). Even though extensive research has been conducted to understand the rate of heat transfer through clothing systems at high heat fluxes, moisture has not been commonly included as a variable. Moisture in a clothing system can originate from internal or external sources. Internal moisture normally comprises perspiration produced by the wearer; while external moisture consists of water spray from hoses, water produced from rain showers or dew, or swamp/lake water that the wearer walks through. The presence of moisture may increase or decrease heat transfer through a clothing system, depending on the degree of moisture sorption, location of moisture in the clothing system, where it is located on the body, its source (internal or external), the timing of the application (before, during, or after exposure to thermal energy), and duration of the heat application.

The effects of moisture on heat transfer through clothing systems at lower temperatures, such as 35°C, have been evaluated during physiological comfort assessment (Schneider, Hoschke, & Goldsmid, 1992; Yoo, Hu, & Kim, 2000; Weder, Zimmerli, & Rossi, 1996; Parsons, 1994). The evaluation of physiological comfort and/or heat stress has accounted for how moisture is absorbed into and transported through clothing systems and how this moisture interacts with environmental climates. Some mechanisms outlined by physiological comfort theory can apply to moisture and high-heat-flux interaction, but due to the significantly higher exposure temperature, different mechanisms also occur. Understanding of the mechanisms by which moisture in various textiles affects the rate of heat transfer through clothing systems at higher temperatures may potentially lead to improvements in design of thermal protective clothing.

Statement of Problem and Justification

Wildland firefighters are often exposed to high temperature environments. These individuals may experience severe and minor burn injuries, heat stress, and smoke inhalation, some of which can be fatal or health damaging. Since wildland firefighters are working in a high risk environment, and since they come in contact with moisture in many different forms, determining how moisture influences the performance of their clothing systems is of high importance, especially for the individuals wearing the clothing systems, their families, and the related industries. Moisture in a protective clothing system has been found to be a major problem for structural firefighters (Stull, 2000b), and these same problems, even though not extensively reported, may also be a problem for wildland firefighters. By examining the effects of moisture present in the materials that make up the clothing systems worn by wildland firefighters and by examining the mechanisms behind heat transfer through these clothing systems when moisture is a key factor, improved clothing systems may be developed. The ultimate goal of this research is to reduce severe burn injury experienced by individuals in this and similar occupations. In testing for significant differences in heat transfer between moistened, saturated, and control specimens, and for differences between specimens moistened externally and internally before exposure to heat, a better understanding of the mechanisms underlying the effects of moisture on heat transfer in thermal protective textiles will be developed.

Objectives

The objectives of this study were to:

1. develop a laboratory procedure to determine the combined/coupled effects of moisture and high (i.e. 83 kW/m^2) or low (i.e. 10 kW/m^2) heat flux through textiles;
2. determine effects of moisture level and location of moisture on both convective and radiative heat transfer through a thermal protective clothing system at high and low heat fluxes;
3. determine how layering of various outer and underwear materials in a clothing system affects the rate of heat transfer when moisture is a variable; and
4. determine interaction effects between moisture conditions and fabric layer compositions when exposed to both flame and radiative heat sources.

Null Hypotheses

To meet objectives 2 to 4, the following null hypotheses were tested:

Hypothesis 1 – There are no significant differences in the rate of heat transfer through thermal protective textiles under varying conditions of moisture application, including amount and location of moisture.

Hypothesis 2 – There are no significant differences found in the rate of heat transfer among various layered fabric systems when moisture is a factor.

Hypothesis 3 – There are no significant interaction effects between moisture conditions and fabric layer composition when determining their effects on heat transfer.

Limitations and Delimitations

The delimitations of this research include:

1. The fabric systems chosen for this research were limited to thermal protective outer fabrics including FR cotton and aramid, and underwear fabrics, including cotton and aramid.
2. Small-scale testing on fabric systems was conducted in this research. Garment design and garment compression were not considered as full-scale testing were not done in this study.

Limitations of this research include:

1. Testing for this research was not conducted in an environmentally controlled area. Specimens were conditioned, but specimens were removed from their controlled environments during testing. Both temperature and relative humidity of the test environment varied somewhat but were recorded during testing.

Definitions

The following terms are relevant to this research:

Wildland Firefighters: individuals who partake in "the activities of fire suppression and property conservation in woodlands, forests, grasslands, brush, prairies, and other such vegetation, or any combination of vegetation, that are involved in a fire situation but is not within buildings or structures" (NFPA, 1998, p.8).

Clothing System: Comprises all the clothing worn at the same time by an individual.

Thermal Protective Clothing: for wildland firefighters consist of a "single layer protective workwear such as, but not limited to, coveralls, trousers and shirts, designed to provide a degree of protection against the adverse effects of fire to the firefighter's body during forest firefighting. Fireline workwear covers the body from the neck to the wrists and feet and may or may not completely cover the neck. It does not include add-on accessories, such as, but not limited to, belts, backpacks, and external harnesses." (CGSB, 1997, p.3)

Moisture Regain: The total amount of moisture that a fiber absorbs and adsorbs. Moisture regain is calculated as the percent moisture in a fabric on the basis of its dry weight (Hatch, 1993).

Heat Transfer: occurs when heat energy transfers from one substance to another or within a substance when there is a temperature gradient. There are four basic mechanisms of heat transfer: conduction, convection, radiation, and coupled diffusion.

a) Conduction: heat transfer experienced by a material/substance when the heat is being transferred to the material/substance through another medium besides air or when the heat is being transferred within the material/substance. In solids, heat is conducted by means of free electrons and phonons, which are "the normal modes of lattice vibration" in a solid (Tien & Chen, 1992, p. 2). If the material has a high density, then the heat is able to conduct readily since there are larger numbers of free electrons and phonons, vice versa (Woo, Shalev, & Barker, 1994).

b) Convection: heat is transferred through the movement of a fluid medium, either a gas or a liquid, around the material/substance exposed to the heat source (Watkins, 1984, p. 4).

c) Radiation: "Thermal radiation is energy emitted by matter that is at a finite temperature… The emission may be attributed to changes in the electron configurations of the constituent atoms or molecules." Thermal radiation is heat transfer experienced by a material/substance when the heat is being transferred to the material/substance via electromagnetic waves. This transfer of energy does not require the presence of a material medium. (Incropera, 1985, p. 8-9)

d) Coupled Diffusion: heat transferred as moisture transfers, due to evaporation or diffusive vapour transport, through a material/substance (Nordon & David, 1967; Sari & Berger, 2000). This occurs as moisture changes state from a liquid to a gas phase. As described by Schneider *et al* (1992), "fiber sorption properties mainly determine the evaporation process and therefore the heat and mass transfer by evaporation of water, diffusion of water vapour, and condensation" (p. 66).

Heat Flux: "the thermal intensity indicated by the amount of energy transmitted per unit area per unit time (kW/m^2)" (CGSB, 2001, p.2).

Stoll Curve: a graphical representation of "the way in which human skin responds to a rise in temperature" and predicts "the onset of second degree burns under controlled laboratory testing conditions" (Laverty, 2001). When conducting thermal performance tests on protective clothing, the Stoll Curve is represented by "a plot of energy versus the time to cause a second-degree burn in human tissue" (ASTM, 1999, p. 170).

Thermal Protective Performance (TPP): The TPP "rating is the minimum exposure energy required to cause the accumulated energy received by the sensor to equal the energy that will cause a second-degree burn in human tissue" (CGSB, 2001, p.7).

Radiative Protective Performance (RPP): RPP is "the resistance of a material to radiant heat, measured in seconds, when exposed to a vertically oriented radiant heat source, positioned at a specific horizontal distance from the vertical placement of the protective material, sufficient to cause a second-degree burn to human tissue" (NFPA, 1998, p.7).

Chapter 2
REVIEW OF LITERATURE

Even though many textiles are available for protection against high-heat-flux exposures, many factors relating to these textiles' structures and environments affect how well they actually protect the wearer in use. In the following review, mechanisms of heat transfer through clothing systems will be discussed. Research addressing issues related to heat transfer and the effects of moisture on the thermal insulation of protective textiles will be reviewed. Although the majority of the literature relating to heat transfer through protective clothing systems pertains to the clothing systems worn by structural firefighters, it can be applied to the mechanisms of heat transfer through clothing systems worn by wildland firefighters and other workers. In this section, moisture and low-heat-flux interaction in terms of physiological comfort will also be reviewed.

Heat transfer mechanisms through clothing are different at low and at high heat fluxes. Energy in the form of heat is absorbed and transferred through clothing differently at these various fluxes, and relationships between the two can be compared. By reviewing physiological comfort theory and research, hypotheses can be made about how heat transfer at high heat fluxes may be affected by moisture in a clothing system. Current test methods for assessing the thermal protection of clothing systems will also be reviewed.

Heat Transfer Through Clothing Systems

Heat transfer through any medium may occur by one or a combination of the "three basic mechanisms of heat transfer: conduction, convection, or radiation" (Geankoplis, 1993, p. 215). Individuals who are exposed to high-heat fluxes often experience burns as heat is transferred to the skin through conduction, convection, thermal radiation, or a combination through their clothing systems (Mell & Lawson, 2000; Holmer, 1988; Backer, Tesoro, Toong, & Moussa, 1976).

Heat transfer through a clothing system is dependant on the intensity of the heat flux (Rossi & Zimmerli, 1996; Lee & Barker, 1987). For example, under a low-intensity flame exposure of 20 kW/m^2, heat is readily lost to the air layer between the skin and clothing, so the injury experienced will be minimal (Lee & Barker, 1987). Wildland firefighters are exposed to a varied intensity of flame, ranging from very low heat fluxes (e.g. 10 kW/m^2) to very high heat fluxes (e.g. 83 kW/m^2).

<u>Conduction</u>

Conduction refers to heat transfer experienced by a medium (i.e., solids, liquids, or gases) as energy is transferred by the "motion between adjacent molecules" (Geankoplis, 1993, p. 215). Heat is conducted through the medium by means of free electrons and phonons in the medium (Tien & Chen, 1992). If the material has a high density, then the heat can be conducted readily since there are larger numbers of free electrons to conduct the heat (Woo *et al*, 1994). Regarding protective clothing, conductive heat transfer occurs when the clothing is in direct contact with the wearer's skin and the heat source. When the wearer is exposed to a high heat source, the clothing conducts the energy directly to the wearer's skin. Firefighters commonly experience conductive heat transfer on their knee region and gloved hands, since these areas are often compressed while fighting a fire (e.g., kneeling on the ground and holding tools, respectively) (Stull, 2000a; Stull, 2000b; Veghte, 1986; Veghte, 1987).

<u>Convection</u>

Convection differs from conduction in that energy in the form of heat is transferred through the movement of hot or cold air or water vapour to the material/substance exposed to the heat source (Stull, 2000b). Regarding protective clothing systems, the outer layer of the clothing system might experience convective heat since the heat source is transmitting energy through the air to the garment rather than through another medium. Convective heat transfer can also occur between the layers in the clothing system and between the clothing and skin if the layers are not in direct contact with each other (i.e., if air spaces exist).

<u>Thermal Radiation</u>

Heat transfer through radiation is different from conduction and convection in that it does not require a physical medium to propagate the energy. Instead, radiative energy is transferred "through space by means of electromagnetic waves" (Geankoplis, 1993, p. 216).

Whether a textile absorbs or reflects, radiative heat transfer is directly affected by the textile's absorbance and scattering cross-section (Tien & Chen, 1992). These properties relate to the structural characteristics and properties of the textile such as orientation of fibers, fiber length, fiber cross-section, and reflectance (Yamada, Kurosaki, & Take-Uchi, 1992).

Combined Heat Transfer Mechanisms

Researchers have determined that burns experienced by firefighters are often the result of combinations of conductive, convective, and radiative heat (Stull, 2000b; Mell & Lawson, 2000; Lee & Barker, 1987; Brewster & Barker, 1983). Contact with flames results in conductive and convective heat transfer. Heat generated from the flames form wavelengths that result in radiative heat transfer.

Mechanism Of Skin Burn Injury

Skin has a normal temperature range of 31°C to 33°C (Stoll & Chianta, 1969; Umeno, Hokoi, & Takada, 2001). It experiences injury at 44°C, and "the rate at which injury proceeds increases logarithmically with a linear increase in skin temperature so that at 50°C, damage proceeds at 100 times the rate at 45°C" (Stoll & Chianta, 1969, p. 1232). Stoll and Chianta further determined that at 72°C, the skin is damaged irreparably. As a result, skin injury is experienced between the temperature range of 44°C (minimal injury) to 72°C (severe injury).

Textile Determinants of Heat Transfer

While the mechanisms of heat transfer through conduction, convection, or radiation appear to be easily determined mathematically and experimentally, numerous factors affect the rate at which heat is actually transferred through a clothing system. The thermal insulating performance of clothing systems is affected by (a) fiber properties such as wicking ability, diameter, and reflectance (Schneider *et al*, 1992); (b) fabric thickness, thermal conductivity, air permeability, and specific heat capacity (Torvi & Dale, 1998; Satsumoto, Ishikawa, &Takeeuchi, 1997; Lee & Barker, 1987); (c) clothing construction factors, such as cut, drape, design, how the garment is worn, and garment multi-layering (Satsumoto *et al*, 1997; Sun, Yoo, Zhang, & Pan, 2000; Crown, Ackerman, Dale, & Rigakis, 1993; Tan, Crown, & Capjack, 1998; Crown, Ackerman, Dale, & Tan, 1998); and (d) presence of moisture (Torvi & Dale, 1998; Stull, 2000b; Mell & Lawson, 2000).

Researchers have found that skin burns can occur after a heat exposure of 83 kW/m^2 ends (Stull, 2000b). When a textile is exposed to a heat source, energy may be absorbed and stored in the textile even after the heat source is removed. This energy absorbed by a clothing system is then transferred from the clothing to skin in the form of heat. Due to the high heat capacity of water, moisture in a thermal protective clothing system increases the amount of stored energy in the clothing system if the moisture is still present after a heat exposure (Mell & Lawson, 2000; Lee & Barker, 1986; Rossi & Zimmerli, 1996). As a result, moisture in a clothing system may increase the chance of skin burn injury after a high heat exposure ends. This may be an important mechanism to understand for low-heat-flux exposures where moisture is not driven off during the exposure. In order to decrease the amount of stored energy in thermal protective clothing, the total heat capacity of the clothing system has to be reduced (Torvi & Dale, 1998).

Physiological Comfort and Heat Transfer

The ability of excess moisture to evaporate and diffuse out of a clothing system could greatly affect thermal performance at high heat fluxes. Physiological comfort is defined as "the maintenance of thermal balance: the proper relationship between body temperature and heat production and loss" (Shivers, 1980, p. 242). Thermo-physiological comfort theory explains this heat transfer by comparing the thermal resistance and water vapour resistance of the clothing system (Weder *et al*, 1996). The heat evolved through physical exertion or exposure to elevated temperatures may lead to heat stress of the individual as internal body temperature rises above 37°C (Parsons, 1994; Bumbarger, 1999). Moisture in the clothing system affects this level of heat stress due to its ability to store energy and ability to conduct better than air. These factors are a result of water's high heat capacity, which potentially decreases the thermal insulation of the clothing system (Stull, 2000b; Lee & Barker, 1986; Rossi & Zimmerli, 1996; Krasney, 1986).

Comfort Through Evaporation

When experiencing increased physical activity or elevated external temperatures, the body needs to employ some mechanism to remove excess heat. This is attained, in part, through the evaporation of water accumulated on the skin's surface in the form of perspiration (Weder *et al*, 1996; Wang & Yasuda, 1991). Energy is required to change moisture from liquid to vapour form, so as perspiration evaporates, the liquid absorbs energy and leaves a cooling sensation on the skin (Berger & Sari, 2000; Umeno *et al,* 2001). However, clothing often restricts the movement of water vapour off the skin, and the degree of this restriction depends on the properties of the clothing system (Parsons, 1994; Schneider *et al*, 1992). Due to this restriction, a microclimate is formed in the air layer between the clothing and the body (Sun *et al*, 2000; Brownless, Anand, Holmes, & Rowe, 1996; Yoo *et al*, 2000; Parsons, 1994; Sari & Berger, 2000). If the fabric in the clothing system is able to absorb or wick moisture away from the body and if evaporation is allowed to take place, then the degree of heat stress is lessened (Sari & Berger, 2000; Wang & Yasuda, 1991; Parsons, 1994; Brownless *et al*, 1996). The opposite is true for non-permeable clothing systems.

The degree of moisture evaporation is also affected by the external relative humidity. As with any liquid or vapour, the moisture will move with the concentration gradient. If the humidity external to the clothing system is higher than the humidity within the microenvironment of, or internally within, the clothing system, moisture will not be able to evaporate out (Bumbarger, 1999).

Coupled Diffusion

The mechanism of low heat flux energy being transferred though a medium by moisture is termed coupled diffusion (Nordon & David, 1967). This relates to the mechanisms of conductive and convective heat transfer. When a moist medium is exposed to a heat source, the heat is conducted through the moisture to the medium. Likewise, if the heat source is high enough, the moisture will evaporate, and the heat will be transferred through convection by means of steam and through heat of evaporation.

When perspiration evaporates off or is wicked away from the skin, the water gains energy, due to its being a conductor, from the heat generated by the body, resulting in conductive heat loss (Brownless *et al*, 1996). Conductive heat transfer also occurs as fibers in the clothing system absorb moisture (Wang & Yasuda, 1991). The process of fibers releasing energy in the form of heat as they absorb moisture is termed the heat of absorption or heat of wetting (Li & Lu, 1999). Yasuda, Miyama, and Muramoto (1994) state that the "the temperature rise that occurs in the space between layered fabrics is mainly due to the heat absorption of water [or perspiration] vapour by the polymers" (p. 457). This rise in temperature between the layers in a clothing system greatly affects the physiological comfort of the individual (Nordon & David, 1967), and if the fibers within the clothing system do not allow for moisture vapour evaporation to the external environment, the health of the individual is at risk (Sun *et al*, 2000). As described by Schneider *et al* (1992), "fiber sorption properties mainly determine the evaporation process and therefore the heat and mass transfer by evaporation of water, diffusion of water vapour, and condensation" (p. 66). For example, even if hydrophilic fibers, such as cotton and wool, are placed next to the skin in a clothing system, if the outer material is non-absorbent and non-wicking, individuals may experience high heat stress when partaking in activities that require strenuous physical exertion since the moisture cannot evaporate out of the clothing system (Sun *et al*, 2000).

<u>Relation of Physiological Comfort Theory to Heat Transfer Through Wildland Firefighter Clothing Systems At High Heat Flux</u>

When considering thermal protective clothing worn by wildland firefighters, one has to take into account both internal sources of moisture such as perspiration and external sources of moisture such as in the air, precipitation, and water from hoses, swamps, and lakes. When an individual is exposed to a high heat source under externally dry conditions but moist internal conditions, the heat will transfer through the clothing system until it reaches a moisture layer. When heat hits a moisture layer in the clothing system, the moisture will begin to evaporate as it takes up energy. As the moisture evaporates, the moisture will move towards the outer side of the garment since the inner side is saturated. The moisture will condense on the outer garment, or it will evaporate completely out of the system, creating a cooling effect (Krasney, 1986). This mechanism is termed heat of evaporation. As a result, this situation may lead to a decrease in steam burn injury. However, if both the external environment and the microenvironment are saturated with moisture, or if a component of the clothing system such as a vapour barrier does not allow the moisture to move out, and if the individual is exposed to a high heat source, then evaporated moisture will condense on both the individual's skin and within the clothing system (Krasney, 1986; Torvi & Hadjisophocleous, 1999; Mell & Lawson, 2000; Makinen *et al*, 1988). Schneider *et al* (1992) also state, "heat transfer increases with increasing [moisture] regain" of the fibers (p. 66). As a result, the individual will experience a higher degree of heat transfer through a clothing system, and, possibly, a higher degree of steam burn injury.

Brownless *et al* (1996) investigated fabrics capable of high moisture transport properties, termed 'dynamic' fabrics, in hopes of removing excess moisture away from an individual's skin. By wicking moisture away from the skin, leaving the fabric layer closest to the skin dry, the degree of moisture evaporation and condensation on the skin's surface was decreased. Choosing materials that wick/transport moisture away from the skin in wildland firefighter clothing systems may not only improve physiological comfort, but may also reduce the risk of steam burn injury since moisture is transported and evaporated out of the clothing system rather than remaining within the system when exposed to a heat source.

Woo *et al* (1994) also considered vapour diffusivity and heat transfer through fabrics, but concentrated more on the effect of fabric structure. They discovered that moisture absorption into a textile may be affected by both fiber morphology and the structure of the textile. Fibers with a flat cross section rather than a round cross section increase the cover of the textile (decrease the porosity); as a result of increased cover, there is less space for moisture to pass through, so one mechanism of moisture transport is decreased. The same is true for thicker, more compact textiles such as twill weaves with small diameter fibers, as small fibers pack closely in a yarn and increase textile cover. Textiles with plain weave structures are more able to transport moisture due to larger porosity and larger interstices between yarns. Based on Woo *et al's* (1994) research, the moisture transport of fabrics could be partially determined by considering fabric structure characteristics.

Effects of Moisture on Protective Properties of Thermal Protective Textiles

As previously mentioned, many researchers have investigated conductive, convective, and radiative heat transfer through thermal protective textiles. Researchers have also considered coupled heat transfer in relation to intrinsic physiological comfort theory, but the mechanisms of how the textiles function under high-heat-flux were not discussed. In these studies, the area of concern was the heat stress experienced by the individual, which was due to high physical exertion, leading to high degrees of perspiration and an inability to cool the body. For example, Sun *et al* (2000) describe how textiles with high thermal resistance may lead to greater amounts of heat stress since heat generated by the body cannot escape the clothing system.

A few researchers focusing on high-heat exposures have considered moisture as a variable but most of this research simulated clothing systems worn by structural firefighters. Even though the basic mechanisms of heat transfer are the same through all media, characteristics of structural firefighting clothing systems, such as inclusion of a vapour barrier, differ from those of wildland firefighting clothing systems. These characteristics alter the rate and the method by which energy is transferred, so the heat transfer trends identified in structural firefighting clothing systems may not be reflected in those of wildland firefighting clothing systems. Regardless, research conducted on structural firefighting clothing systems may aid in understanding mechanisms of heat transfer through clothing systems worn by wildland firefighters, and will be included in this section.

Regarding the effects of moisture on the thermal insulation of protective clothing systems, both low-heat-flux (e.g., less than 20 kW/m^2) and high-heat-flux exposures (e.g., 80-83 kW/m^2) have been investigated. Firefighters are exposed to numerous conditions and environments, so it is important to study how clothing systems react under the various heat exposures (Torvi & Hadjisophocleous, 1999). A summary of research on the performance of thermal protective materials used in firefighter clothing when moisture is a factor is provided in Table 1. Findings are discussed in more detail in the section that follows.

Table 1. Summary of Literature: Moisture Effects on Heat Transfer Through Garment or Fabric Systems

a) Structural Fire Fighter Clothing Systems

Author(s)	Garment or Fabric Layering	Moisture Application		Heat Transfer	
		Level/Location	Method of Application	Test Method	Result
Stull (2000a)	Knee reinforcement configurations: permeable outer layer or impermeable moisture barrier, and liner	Saturated and dry	-immersed in water for 2 min -removed, drip-dried for 5 min -placed between 2 sheets of blotting paper under 3.5kPa weight for 20 min	ASTM RPP[1] ASTM Contact heat[2]	High radiant – wet specimens higher threshold Low radiant – dry specimens higher threshold
Veghte (1987)	Glove configurations with and without Gore-tex™ moisture barrier	Saturated (external and inner), partial saturated (external and inner), and dry	-completely or partially immersed in water for 3 min -removed & drip-dried for 60 sec	NFPA 1971 Conductive heat[3] NFPA 1971 RPP[3]	Wet specimens containing a moisture barrier have a lower threshold than those without
Rossi & Zimmerli (1996)	Multilayered specimens – FR outer layer, moisture barrier layer, thermal insulator, and underwear	Conditioned in standard atmosphere, outer layer humid, and inner layer humid	Humid – specimens placed in water vacuum for 80 sec and then spun-dried for 5 minutes	ISO RPP[4] ISO Contact heat[5] ISO TPP[6] Contact	Specimens containing a wet inner layer exhibited decreased thermal protection
"Advisory Committee at URTAC", cited in Stull (2000b)	Turnout coat specimens – shell and liner with a permeable or impermeable moisture barrier	Shell wet, liner wet, both wet, or both dry	Wet with 250g of water/m2	TPP Contact	Low Radiant – all specimens with a wet liner exhibited decreased thermal protection
Stull (2000c)	Hydroweave™ inner liner with either Kevlar® or Nomex® outer layer	Dry, Wet #1, and Wet #2	Wet #1 – specimens machine washed and spun Wet #2 – same method as in Stull (2000a)	ASTM RPP[1]	Thermal insulation was not affected by moisture

Con't…

Table 1. (Con't).

b) Single-Layered Clothing Systems

Author(s)	Garment or Fabric Layering	Moisture Application		Heat Transfer	
		Level/Location	Method of Application	Test Method	Result
Torvi & Dale (1998)	Nomex IIIA® and Kevlar®/PBI® for turnout coats	Moisture from 0% (dry) to 100% (saturated)	N/A	Modified Contact ASTM TPP[7]	Moisture improved thermal protection; however, when saturation reached, thermal protection decreased
Chen (1959)	Single-layer materials	Moist and dry	Moist specimens conditioned at 80% relative humidity	RPP	Moisture decreased thermal protection
Morse, cited in Lee & Barker (1986)	Single-layer material	Moist and dry	N/A	TPP	Moisture increased thermal protection
Perkins, cited in Lee & Barker (1986)	FR cotton	Wet and dry	N/A	Spaced TPP	Moisture increased thermal protection
Lee & Barker (1986)	materials composed of PBI®, Kevlar®, and FR rayon blends	Oven-dried, standard atmosphere conditioned, or saturated	Saturated – soaked in water for 5 min and squeezed to remove excess moisture	RPP ISO TPP[6]	High radiant – moisture decreased thermal protection Low radiant – moisture increased thermal protection TPP – moisture increased thermal protection

Con't…

Table 1. (Con't).

c) Two-Layered Clothing Systems

Author(s)	Garment or Fabric Layering	Moisture Application		Heat Transfer	
		Level/Location	Method of Application	Test Method	Result
Makinen *et al* (1988)	outer layer (FR cotton or Karvin®) and inner underwear (cotton, wool, or aramid knit)	Inner layer subjected to moisture regain of 0% (dry), 20%, 60%, or 80%	N/A	ISO RPP[4]	Low radiant – moisture decreased thermal protection

[1]ASTM F 1939 (1999b), [2]ASTM 1060 (1999a), [3]NFPA 1971 (1986), [4]ISO 6942 (1993), [5]ISO/DIS 12127 (1996), [6]ISO/DIS 9151 (1995), [7]ASTM D 4108 (1989 – modified: now CAN/CGSB no. 4.2-78.1, 2001)

Structural Firefighting Clothing Systems

Even though structural firefighter clothing systems involve many more layers than those worn by wildland firefighters, both outer fabrics and underwear fabrics are often made of the same or similar materials. One of the layers found in structural firefighter clothing systems often comprises a moisture barrier. The moisture barrier "prevents [liquid] moisture and many corrosive liquids from penetrating to the inside" of the clothing system (Krasney, 1986, p. 464). Even though both vapour permeable and impermeable moisture barriers have been found to decrease the number of steam burns from external moisture in structural firefighters, there is a larger problem of increased sweat accumulation resulting in steam burns and an increased incidence of heat stress (Rossi & Zimmerli, 1996; Krasney, 1986; Makinen *et al*, 1988).

Stull (2000a) investigated the effects of moisture and compression in several knee reinforcement configurations of structural firefighter protective clothing consisting of outer layer, vapour permeable or impermeable moisture barrier, and liner. Due to the high compression that this area of the garment experiences during use as a result of kneeling and bending, the knee area is exposed to higher levels of conductive heat transfer. Also, this area is likely to become wet from water on the ground or floor. Stull employed both radiative and contact heat sources following ASTM F1939 (ASTM, 1999a) and ASTM F1060 (ASTM, 1999b) respectively, on both dry and saturated specimens. Only one level of moisture application was tested, following Section 6-1.8 of NFPA 1971 Standard on Protective Clothing for Structural Firefighting (NFPA, 1997). Composite specimens were immersed in water for 2 minutes, removed and drip-dried for 5 minutes, and then placed between sheets of blotting paper under a 3.5kPa weight for 20 minutes. Percent moisture regain was then calculated. Stull found that wetted composite specimens exposed to a high radiant heat flux of 83 kW/m^2 exhibited longer threshold times before second-degree burn criteria were reached. However, when exposed to a low radiant heat flux of 8.4 kW/m^2, the dry specimens displayed a longer threshold.

Veghte (1987) investigated the effect of moisture on the thermal insulation of gloves worn by structural fire fighters. Like the knee region of a thermal protective garment, the gloves are exposed to high amounts of manipulation and compression. As Veghte states, "the hands are a fire fighter's most important and most exposed extremity" (p.313). In fire fighting, gloves are continually being exposed to high amounts of moisture. In his research, following NFPA 1973 Gloves for Structural Fire Fighting (1983), Veghte examined the conductive and radiative protective performance of compressed gloves constructed from a silicone-treated leather outer, wool liner, and either a vapour permeable moisture barrier (Gore-tex™) or no moisture barrier. The purpose of his research was to determine whether the vapour permeable moisture barrier under compression deters or accelerates burn injury. Specimens were tested under complete moisture saturation, partial moisture uptake, and dry state. Wet specimens were either completely or partially immersed in water for 3 minutes. The specimens were then removed from the water bath and allowed to drip-dry for 60 seconds. Percentage water gain was calculated on the basis of the specimen's saturated weight. Veghte concluded that gloves containing a vapour permeable moisture barrier were less effective against heat transfer to the skin when internal moisture was a factor than were gloves containing no moisture barrier. Even though moisture barriers prevent external moisture from entering the clothing system, internal moisture cannot as easily evaporate out since the barriers are only semi-permeable. As a result, when moisture internal to the moisture barrier is heated and evaporates, it is forced to condense on the skin, resulting in a higher degree of steam burn injury.

Rossi & Zimmerli (1996) investigated the effects of simulated external and internal moisture on multi-layered clothing specimens consisting of an FR layer (outer), vapour permeable moisture barrier layer, thermal insulator (100% wool), and underwear (100% cotton). Specimens were tested under radiant heat, combined convective and radiant heat (i.e., flame), and contact heat following ISO 6942 (ISO, 1993), ISO/DIS 9151 (ISO, 1995), and ISO/DIS 12127 (ISO, 1996) respectively, for three conditions: conditioned in a standard atmosphere (65% RH, 21°C), outer layer humid, and inner layers humid. For humid-conditioned specimens, the specimens were placed in water under a vacuum for 80 seconds and then spun-dried for 5 minutes. When the inner layers were humid, thermal performance was decreased regardless of the external heat source. This was explained by the multi-layered system since moisture could not vaporize and evaporate out of the system easily. When the outer layer was wet, thermal performance was not affected. This can be attributed to the vapour barrier preventing moisture from vaporizing and condensing on the sensor.

Stull (2000b) reviewed numerous earlier studies in which moisture was a variable when examining the thermal performance of structural firefighter's clothing systems. In research by the "Advisory Committee at URTAC", the performance of turnout coats was evaluated. Specimens representing materials used in turnout coats consisted of a shell and a liner with either an impermeable or a permeable moisture barrier between. Performance was evaluated under a combined radiant and convective heat flux of 21 kW/m^2 for specimens with the shell wet and liner dry, shell dry and liner wet, or both being wet with $250g/m^2$ of water. In all four cases where the liner was wet (liner wet and shell/liner wet for both impermeable and permeable moisture barriers), the thermal performance was reduced. Hoechst-Celanese's research regarding the same specimen composition as that for URTAC was also reviewed by Stull. The findings were the same. Stull concluded that the effect of moisture on thermal performance is more "a function of the material layer composition" than the amount of moisture in the system or the type of thermal exposure (p. 569). In Stull's review, however, the "NFPA task group" found that placing a wet T-shirt material against the liner during heat exposure to simulate perspiration actually improved the thermal performance as compared to tests where the liner was saturated with water through immersion.

Stull (2000c) tested the thermal performance of Hydroweave™, an inner liner material for structural firefighters' ensembles, consisting of an "outer woven fabric shell, a fibrous batt containing a water-absorbent polymer, and a moisture conductive, microporous film on a lighter fabric substrate" (p. 1). Two compositions of Hydroweave™, one with a 60/40 Kevlar®/PBI® outer shell and one with a Nomex® outer shell, were evaluated for thermal performance against radiative heat following ASTM F 1939 (ASTM, 1999a) under three conditions: dry, wet (machine washed and spun), and wet following Section 6-1.8 of NFPA 1971 Standard on Protective Clothing for Structural Firefighting (NFPA, 1997). In all cases, no detrimental effects of the moisture were observed. Stull explained this by stating, "the relatively high and evenly distributed water-absorbing capacity of Hydroweave™ prevents rapid temperature rises in the material and contributes to longer protection times" (p. 12).

Single Layer Clothing Systems

Several studies investigating heat transfer through moist and/or wet structural firefighting clothing composites have considered only the outer shell of these clothing systems. Since the outer shell of these clothing systems is normally composed of similar textiles to those used in the clothing systems worn by wildland firefighters, the results of these studies should reflect heat transfer experienced by wildland firefighters.

Torvi and Dale (1998) investigated the thermal protective performance of Nomex IIIA® and Kevlar®/PBI® fabrics with a moisture regain varying from 0% to 100% following a modified ASTM D 4108-87 (ASTM, 1989), with pins (modification used is now published as CAN/CGSB-4.2 no. 78.1-2001). In general, as the amount of moisture in the fabrics increased, the thermal protection increased. However, when the moisture regain was close to saturation, the thermal performance was reduced. By increasing moisture regain, the thermal conductivity through the fabric was increased, resulting in a decrease in thermal protection. Torvi and Dale suggested that the thermal properties during and after heat exposure should be evaluated because steam burns can still occur as the fabric cools, since the fabric "transfers large quantities of energy to the skin behind it" (p. 795).

Chen (1959) examined the effects of high-intensity thermal radiation, using a solar furnace, on thermal injury to the skin. "The range of intensity of the incident radiation covered in these tests was 0.5 to 4.5 cal/cm^2-s" (21 to 189 kW/m^2) (p. 3). In a short radiant exposure period, he observed a high rate of heat transfer through moist fabrics, conditioned at 80% relative humidity, resulting in a lower thermal protective performance and higher degree of steam burn injury. The moisture was evaporating and moving inwards toward the skin simulant used to measure the heat transfer. However, as exposure time increased, the temperature of the skin simulant slowly decreased as recondensation and dissipation of heat out of the fabric occurred.

Lee and Barker (1986) reviewed several studies that examined heat transfer through moist/wet outer layer fabrics of structural firefighting clothing systems. As cited by Lee and Barker, Morse found that moist-conditioned specimens exhibited a higher thermal protective performance than dry specimens when exposed to combined radiant and convective heat from a JP-4 fuel fire. As reviewed by Lee and Barker, Perkins found that fire retardant (FR) cotton specimens exposed to a flame source with a 6.4 mm spacer showed a higher thermal protective performance when wet than when dry.

Lee and Barker (1986) examined the effects of moisture on thermal performance of fabrics "made with polybenzimidazole (PBI®), aromatic polyamide (aramid), and blends of PBI® with aramid or with flame retardant rayon fibers" (P. 315) under both pure radiant heat and combined 50% radiant and 50% convective heat sources. Three moisture conditions were tested for each: oven-dried, standard atmosphere conditioned (65% RH, 21°C), and saturated (soaked in water for 5 minutes and squeezed to remove excess moisture). For a pure radiant exposure of 83 kW/m^2, both standard atmosphere and saturated moisture in the single layer fabric decreased thermal protective performance. In this situation, "radiant energy and heated vapour are transported directly from the fabric to the thermal sensor" (p. 329). As a result, the moisture cannot escape the system quickly, and is forced to condense on the surface within the system (representing the wearer's skin), leading to a higher rate of burn injury. On the other hand, moisture increased thermal protection under a radiant exposure of 20 kW/m^2. Since moisture has a high heat capacity, it absorbs thermal energy. At a low radiant heat flux, thermal energy is absorbed by moisture, slowing heat transfer through the fabric. As a result, moisture is able to evaporate and slowly move out of the fabric into the external environment. For the combined 50/50 radiative/convective heat exposure of 83 kW/m^2 with 6.4 mm spacer following NFPA 1971 (NFPA, 1986), moisture increased the thermal protective performance. In this situation, "flames impinging on the surface of the test fabric generate a convective flow in a direction parallel to the fabric surface" (p. 326). In other words, the "convective action of the flames has an ablative effect and acts to carry the thermal energy away from the side of the fabric exposed to the flames" (p. 329). As a result, vapour is not transported directly to the sensor, but rather is "transported away from the interior of the fabric" (p. 326).

Two-Layer Clothing Systems

Other than studies on turnout gear worn by structural firefighters, few researchers have investigated the effects of high heat and moisture through two-layered clothing systems simulating an outer FR fabric and an underwear fabric worn by both structural and wildland firefighters. Makinen *et al* (1988), while focusing on structural firefighting ensembles, chose materials for their research that resembled those used for wildland firefighting clothing systems. The outer layer was composed of either FR cotton twill or Karvin® (65/30/5 FR viscose/Nomex®/Kevlar®) and the inner underwear layer was composed of cotton, wool, or aramid knit. Specimens were exposed to a low radiant heat flux of 20 kW/m^2 following ISO 6942 (ISO, 1993) where the inner underwear layer was subjected to a moisture regain of 0% (dry), 20%, 60% or 80% prior to heat exposure. Thermal protection was decreased in all specimens where inner underwear layer was moistened.

Thermal Protective Clothing Systems

When conducting research on thermal protective clothing, researchers often focus on the outer layer of the clothing system – the layer that provides the thermal insulative protective properties. However, other layers of the clothing system play an important role in determining the rate of heat transfer and the rate of burn injury to the exposed individual. A clothing system comprises everything the individual is wearing. Regarding wildland firefighters, this would consist of the protective coveralls or jacket/pants ensemble, gloves, boots, socks, hats, and under garments, including a T-shirt and/or pants. Whereas wildland firefighters tend to wear single layer protective garments (Dale, Ackerman, Crown, Hess, Tucker, & Bitner, 2000), Sun *et al* (2000) have reported that "the California Department of Forestry and Fire Protection currently requires wildland firefighters to wear two layers of clothing during fire fighting operations" due to evidence "that extra clothing layers provide additional protection against burn injuries" (p. 567). These two layers consist of the outer layer (coveralls or jacket/pants ensemble) and underwear (T-shirt and briefs).

The outer garment of the clothing system worn by a wildland firefighter is composed of a textile that is flame resistant (FR). These garments studied in research projects have been reported to be constructed from numerous textiles such as aramid and aramid blends (e.g., Kevlar®/PBI [polybenzimidazole]®, Nomex IIIA®, Kermel [aramid and FR rayon]®), FR cottons (e.g., Proban®, Indura®), FR wools, or modacrylics (e.g., Firewear®) (Budd, Brotherhood, Hendrie, Jeffery, Beasley, Costin, Zhien, Baker, Cheney, & Dawson, 1997; Yoo, Sun, & Pan, 2000; Sun *et al*, 2000). Makinen *et al*

(1988) have reported that the most common underwear garments are made from cotton, wool, or aramid fabrics.

Characteristics of Thermal Protective Textiles

Fiber characteristics, in terms of both micro and macro structure, determine their inherent properties. When the fibers are made into yarns, and consequently, fabrics, the properties relating to the yarn and textile formation affect the performance of the overall system. Properties relating to and affecting thermal protective performance are fiber porosity, moisture absorption and transport capabilities, length such as staple or filament, ignition and melting temperatures, heat transfer, and heat reflectance (Backer, Tesoro, Toong, & Moussa, 1976). Aramids, PBI®/aramid blends, viscose/aramid blends, and FR cottons are textiles used for thermal protective garments for wildland firefighters.

FR Cotton

Cotton is a natural cellulosic fiber. It is composed of cellulose polymers, with an amorphous phase of 35-30% and a crystalline phase of 65-70%. The larger crystalline phase contributes to this fiber having medium tensile strength. Due to a large number of hydrogen bonds and numerous hydroxyl groups in this fiber's polymer structure, it is hydrophilic. It is able to absorb large amounts of water, and its moisture regain capabilities are high. As a result of this ability to absorb moisture, and also due to the convolutions along the fiber length and kidney-shaped cross section, cotton is considered to be a comfortable fiber to wear. (Hatch, 1993, p. 165-169)

Unfortunately, due to cotton's low Limiting Oxygen Index (LOI)[1], cotton will burn quickly and readily once it ignites (Hatch, 1993). In order to increase the LOI of cotton fibers, cotton fabrics are chemically treated with flame-retardant finishes (Hatch, 1993, p. 169). These finishes increase the flame resistance of cotton fabrics dramatically, and, as a result, thermal protective garments can be produced. However, when such garments are exposed to a high heat source, they tend to produce large amounts of smoke and noxious off-gassing.

[1] The Limiting Oxygen Index (LOI) is the lowest oxygen concentration in an oxygen-nitrogen mixture at which a substance will continue to burn by itself (AFP Inc., 1987). The earth's atmosphere has an oxygen content of 21%, so any material with a LOI index above this percentage normally will not burn after a flame source is removed. Note that this is only true while the exposed material is in the earth's ambient atmosphere.

Numerous finishes are available for producing FR cottons, but Indura® and Proban® seem to be the most common on the market in North America. Many individuals requiring overall thermal protection find cotton coveralls the most comfortable since they are considerably cooler to wear in high-heat-stress conditions (Budd *et al,* 1997). However, since these finishes are applied after the fibers/textiles are produced, the finish may be uneven, and applying FR finishes to cotton often reduces its durability and may reduce comfort. Variation in the amount of protection a FR cotton garment provides may be significant if high quality is not assured. For some FR cottons (e.g., Indura® and Proban®) the finish is guaranteed throughout the life of the garment.

Nomex IIIA®

Nomex® was first developed by EI DuPont du Numours (DuPont) in 1967. The polymer structure of this aramid fiber is similar to that of nylon, except that the amide group is meta-bonded to a benzene ring. As a result of the aromatic structure, this fiber has superior mechanical properties compared to nylon. Also due to the aromatic structure, Nomex® has a high degree of thermal stability. High amounts of energy are required to break the sigma bonds in the aromatic structure. As a result, high temperatures (> 200°C) are required to decompose this fiber.

Nomex® does not drip or melt, so body burn due to molten polymer will not happen with this fiber. Nomex® has a LOI of around 28%, which means that at room temperature, "Nomex® will not continue to burn when a flame is removed" (DuPont, 1999, p. 11). There are many different types of Nomex® developed by DuPont, but Nomex IIIA® is the composition most commonly used for individuals requiring thermal protection. This material is a mixture of meta and para aramid fibers, which increase its thermal properties, and carbon-based fibers, which improves static dissipation. (DuPont, 1999)

When exposed to high temperatures (e.g. greater than 150°C), Nomex® fibers tend to shrink, causing the garment worn by an individual to conform more closely to the body. As a result of decreased air space, areas where the fabric shrinks and conforms to the body may continue to experience increased rates of heat transfer, resulting in higher degrees of burn injury.

60/40 Kevlar®/PBI®

Kevlar®, like Nomex®, was also developed by DuPont, but PBI® (polybenzimidazole) was developed by Hoechst Celanese. As a result, this blend has not received the same publicity that Nomex® has. This fiber blend can be superior to Nomex® in numerous ways related to thermal protective performance. The costs of producing this blend are higher, however.

Kevlar® is identical to the polymeric structure of Nomex®, except the benzene ring is para-bonded instead of meta-bonded (Hatch, 1993). As a result, the structure of Kevlar® is more rigid and stable. Very high temperatures (> 500°C) are required to break the sigma bonds (Xin-Gui & Mei-Rong, 1999). Like Nomex®, Kevlar® does not melt or drip when exposed to high heat sources. It also has a high LOI (higher than Nomex®), so it does not continue to burn when the flame source is removed. Instead, Kevlar® tends to char. The overall structure of the textile remains intact. Unlike Nomex®, Kevlar® blends do not shrink, so there is no incidence of body burn occurring due to the garment shrinking to the body.

PBI® is composed of a long-chain aromatic polymer with recurring imidazole groups. This polymer exhibits a thermal stability at higher temperatures and a high LOI due to its stable structure. The inclusion of this polymer in a blend reinforces the thermal resistance of the overall polymer. Also, due to its kidney-shaped cross section, similar to that of cotton, and low stiffness, PBI® increases the tactile comfort of the fiber, and it has a higher moisture regain than Kevlar® or Nomex®. (Hatch, 1993)

Review of Bench-Scale Test Methods for High-Heat-Flux Thermal Performance

For this research, two approaches, one involving a combined radiative and convective flame source (thermal protective performance) and the other a pure radiative heat source (radiative protective performance), will be referenced.

Thermal Protective Performance (TPP)

There are at least four different test methods used to evaluate thermal protective textiles subjected to a high-heat-flux open flame: (i) American Society for Testing and Materials Method D 4108-87 Standard Test Method for Thermal Protective Performance of Materials for Clothing by Open-Flame Method[2] (ASTM, 1989), (ii) ISO 9151: International Standard for Protective Clothing Against Heat and Flame – Determination of Heat Transmission on Exposure to Flame (ISO, 1995), (iii) NFPA 1977 Standard on Protective Clothing and Equipment for Wildland Firefighters – Standard on Protective Clothing for Proximity Fire Fighting, section 6-22 Thermal Protective Performance (TPP) Test (NFPA, 1998), (iv) and CAN/CGSB-4.2 No 78.1-2001: Thermal Protective Performance of Materials for Clothing (CGSB, 2001).

ASTM (American Society for Testing and Materials) D 4108 was first developed to measure the TPP of a specimen exposed to a high heat flame exposure (Day, 1988; Torvi *et al*, 1997). In this method, an open-flame single Mekker gas burner with a heat flux of 84 ± 2 kW/m^2 is placed horizontally beneath a specimen. The open flame is a combination of approximately 30% radiative and 70% convective heat flux. A copper calorimeter sensor is placed behind the specimen to measure the rate at which the specimen allows heat to pass through to the sensor until second-degree burn criterion, measured as a function of time-to-burn using the Stoll curve, is reached (Stull, 2000b). Multilayer specimens are tested while in direct contact with the copper sensor, while single layer specimens are tested 6.4 mm away from the copper sensor. Specimens are 100 mm by 100 mm square. This method has one major limitation: the specimen is not firmly secured in the holder, so a specimen can shrink. If the specimen shrinks, the cover of the textile increases, since the textile is becoming more compact, and more air space is developed due to deformations in the textile's surface. The shrinkage may therefore improve the TPP results obtained, leading to the collection of invalid results.

CGSB (Canadian General Standards Board) 78.1 is similar to the ASTM D4108 except that the specimen in the CGSB method is held in place by pins on the specimen holder. The pins in the CGSB method are in place to prevent excessive shrinkage of the test specimen (Day, 1988; Crown *et al*, 1998). This modification was first made to the ASTM specimen holder in 1982 (Day, 1988). It was first accepted in CAN/CGSB-155.1-88: Firefighters' Protective Clothing for Protection against Heat and Flame in 1988 (CGSB, 1988).

---

[2] ASTM D 4108-87 is currently CAN/CGSB-4.2 No. 78.1:Thermal Protective Performance of Materials for Clothing.

ISO (International Organization for Standardization) 9151 is similar to the ASTM method except that specimens are "held in position by an aluminum retaining plate that has a central hole to position the calorimeter in its insulating mounting block" (Day, 1988, p. 113), the heat flux is reduced to 80 kW/m^2, and "the ISO standard uses the time it takes for a 24°C temperature rise to occur in the sensor" rather than basing "the end point on the time it takes for the heat transferred through the fabric to cause the onset of a second degree burn" based on the Stoll Curve (Dale *et al*, 2000, p. 394). The retaining plate restricts movement of the specimen due to thermal shrinkage.

In the 1977 NFPA (National Fire Protection Association) method, the single burner is replaced with "two gas burners and a bank of nine quartz tubes so that the radiative component can be held at 50% of the total heat flux to the fabric surface" (Crown *et al*, 1998, p. 80), and a shutter between the specimen and the heat source is removed, initiating the test. Also, the size of the mounting frame, specimen, and exposure opening are larger in the NFPA method, and a 1000g weight is utilized to prevent movement from thermal shrinkage (Day, 1988).

In this research the CGSB method will be followed. As Day (1998) concluded, "the use of a pin restraining frame appears to offer the advantage of preventing thermal shrinkage without deforming the assembly" (p. 119).

Radiant Protective Performance (RPP)

In terms of RPP, three different test methods used to evaluate thermal protective textiles subjected to a high-heat flux radiant source will be reviewed: NFPA 1977 Standard on Protective Clothing and Equipment for Wildland Firefighters – Standard on Protective Clothing for Proximity Fire Fighting, section 6-2 Radiant Protective Performance (RPP) Test (NFPA, 1998); ASTM 1939-99: Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials (ASTM, 1999b); and ISO 6942 – Evaluation of the Thermal Behaviour of Materials and Material Assemblies When Exposed to a Source of Radiant Heat (ISO, 1993).

In the NFPA 1977 method, a bank of quartz tubes, oriented vertically, provide the necessary heat flux. The heat flux is controlled through the use of a power controller, which is set to approximately 83 kW/m^2 (the same as for TPP). The specimen is mounted in the holder, and the holder is held in place on the lamp source by magnets. A shutter between the specimen and the lamps is removed, initiating the test. A copper calorimeter sensor is placed on the interior of the specimen in order to measure the rate of heat transfer through the specimen. As with TPP, the skin threshold level to reach second-degree burn criterion is measured using a Stoll curve (Stull, 2000b). The ASTM method uses the same equipment and test procedure as outlined in the NFPA method. The ISO method also uses similar equipment and test procedure as in the NFPA method except that a panel of silicon carbide rods, instead of a bank of quartz tubes, provides the required heat flux (Holcombe & Hoschke, 1986).

For this research, the NFPA method will be followed.

Summary

According to the research reviewed, moisture in a clothing system may either increase or decrease thermal insulation. As concluded by Stull (2000b), "the effect of moisture on thermal insulation has been shown to vary with: the type of heat transfer; the amount of water added; the location of moisture in the clothing material system; the type of materials used in the construction of the clothing; the condition of the materials in the clothing (laundered versus non-laundered); the intensity of thermal exposure; and the duration of the thermal exposure". Considering all of the literature reviewed, no researcher considered the effects of both internal and external moisture on the thermal protective performance (TPP) and radiative protective performance (RPP) of two-layered protective clothing systems worn by wildland firefighters; nor was the effect of moisture on thermal performance measured during or after the heat exposure. Rossi and Zimmerli (1996) investigated the effects of both internal and external moisture on the RPP and convective heat performance through clothing systems containing a moisture barrier, but the effects of this heat transfer are inconclusive when the moisture barrier is not included in the specimen composite. In this research, the effects of both internal and external moisture on the thermal performance through specimens simulating clothing systems worn by wildland firefighters will be investigated.

Chapter 3
PRELIMINARY RESEARCH

Preliminary experiments were conducted to (a) become familiar with methods of moisture application to thermal protective textiles; (b) observe the effects of moisture on thermal protective performance (TPP); and (c) gain context for future laboratory experiments. This study investigated only one degree of moisture sorption (saturation) and only one type of high-heat-flux flame application (combined convective and radiative heat following CAN/CGSB-4.2 No. 78.1-2001: Thermal Protective Performance of Materials for Clothing).

A focus group interview involving an intact group of wildland firefighters was conducted to learn more about the environment to which wildland firefighters are exposed. By understanding this environment, the laboratory experiments evaluating thermal performance of clothing systems could be conducted in such a manner to simulate, or control, influential factors that may affect results. Conducting experiments that simulate situations experienced by wildland firefighters may lead to improvements in the design of the clothing systems these individuals wear. These improvements will ideally lead to reduction in severe burn injury.

Experimental Design

An experimental research design was used to determine the effects of moisture saturation within a clothing system on thermal protection. The dependent variable was TPP. The independent variables were the thermal protective fabric systems and amount and location of moisture in the system.

Fabric Sampling and Preparation

Three thermal protective outer fabrics and two underwear fabrics were combined to produce six different systems. The outer fabrics were Nomex IIIA®, 60% Kevlar®/40% PBI®, and Indura® FR cotton; the underwear fabrics were 100% cotton rib knit and Nomex® waffle knit. The fabric combinations are outlined in Table 2. Specimens were cut from the individual fabrics so that each specimen contained a separate set of warp and filling yarns.

Specimens were tested for thermal performance under four conditions: (i) conditioned in a standard atmosphere following CAN/CGSB-4.2 No.2-M88 (CGSB, 1993) (20°C ± 1°C and 65% ± 2% relative humidity) for 24 hours prior to testing, (ii) outer layer saturated, (iii) inner layer saturated, and (iv) both outer and inner layers saturated. Saturated specimens were prepared following Section 6-1.8 of NFPA 1971 Standard on Protective Clothing for Structural Firefighters. This method involved immersing specimens in water for 2 minutes, drip-drying for 5 minutes, and then placing between sheets of blotting paper under a 3.5kPa weight for 20 minutes. Percent moisture content was calculated from Equation 1:

$$\text{Moisture Content (\%)} = [(\text{Wet Weight} - \text{Dry Weight})/\text{Wet Weight}] * 100 \qquad (1)$$

Table 2. Percent Moisture Content of Outer and Inner Fabrics

Fabric	Fiber Content	Moisture content (%)
Outer		
1	Nomex IIIA®	8
2	Kevlar®/ PBI®	8
3	Indura® FR cotton	9
Inner		
a	100% Cotton rib knit	22
b	Nomex® waffle knit	9

Fabric Systems:
1a: Nomex IIIA® aramid with 100% Cotton rib knit
1b: Nomex IIIA® aramid with Nomex® waffle knit
2a: Kevlar®/PBI® with 100% Cotton rib knit
2b: Kevlar®/PBI® with Nomex® waffle knit
3a: Indura® FR cotton with 100% Cotton rib knit
3b: Indura® FR cotton with Nomex® waffle knit

Measurement of Thermal Protective Performance

TPP was measured following CAN/CGSB-4.2 No. 78.1-2001: Thermal Protective Performance of Materials for Clothing (CGSB, 2001) in the spaced configuration as per paragraph 8.2(b). Heat flux was calibrated to 83 kW/m^2.

Experimental Results

A two-way analysis of variance (fabric by moisture condition) using the SPSS statistical program showed that main effects for both fabric and condition, and interaction effects (fabric by condition) were significant ($p<0.05$) in the model corrected for lack of homogeneity. One-way analyses of the effects of moisture condition were also conducted separately for each of the six fabric systems (Table 3). In general, for each of the six fabric systems, the TPP values for the outer wet/underwear wet condition and the outer dry/underwear wet condition were significantly lower than the values for the outer dry/underwear dry system and the outer wet/underwear dry TPP system. Generally, TPP

Table 3. The effects of moisture on contact thermal protective performance (TPP) of six different fabric systems

Outer Layer and Underwear Combination	Outer Dry/ Underwear Dry	Outer Wet/ Underwear Dry	Outer Dry/ Underwear Wet	Outer Wet/ Underwear Wet
1a Kevlar®/PBI® with Nomex®	25.5^{a}	25.5^{a}	$24.7^{a,b}$	24.3^{b}
1b Kevlar®/PBI® with 100% cotton	11.7^{a}	11.8^{a}	9.3^{b}	9.7^{b}
2a Nomex IIIA® with Nomex®	25.3^{a}	24.8^{a}	16.3^{c}	19.4^{b}
2b Nomex IIIA® with 100% Cotton	12.0^{a}	11.6^{a}	9.4^{c}	10.3^{b}
3a Indura® with Nomex®	9.8^{c}	10.9^{b}	10.0^{c}	11.5^{a}
3b Indura® with 100% Cotton	8.2^{b}	9.5^{a}	8.3^{b}	9.6^{a}

[a,b,c] For each fabric system (rows), TPP values with the same superscript letter do not differ significantly from each other.

increased slightly with the outer wet/underwear wet systems compared to the outer dry/underwear wet system. TPP was highest when both the outer and underwear layers were dry, except for fabric systems with an Indura® outer layer. The significant interaction effects, however, indicate that the direction and magnitude of such differences among moisture conditions were different for each clothing system/fabric combination, as indicated in Table 3.

Tentative Conclusions

Although only one level of moisture in the clothing system was evaluated, and only one type of heat source was used, for each of six different fabric combinations (3 outer fabrics and 2 underwear fabrics), moisture did affect the rate of heat transfer through the fabric systems. This suggested that further investigations of heat transfer through these clothing systems when moisture is a factor was justified.

Focus Group Interview

A focus group interview was conducted involving an intact group of wildland firefighters. A Moderator's Guide for the interview is attached as Appendix A (Moderator Guide). Participants in this study included seven full-time wildland firefighters employed by Alberta Land and Forest Service in Whitecourt, Alberta.

Interview Results

The results of this interview indicate that moisture is an important issue for wildland firefighters. All seven participants responded that they were often exposed to both internal and external moisture. Common sources of moisture mentioned were perspiration, water spray from hoses, water produced from rain showers or dew, and lake/swamp water. Participant responses stressed perspiration as being a substantial problem when working long hours. As a result of heat stress and excess perspiration, participants often did not wear their protective apparel properly, such as leaving zippers open, rolling up sleeves, or tying sleeves around the waist, in order to reduce heat stress.

Even though participants did not explicitly state that moisture causes the risk of increased steam burn injury, they did state that moisture increases the rate of heat transfer through their protective clothing systems when they are exposed to a high temperature heat source. They also reported that they feel more heat stress if their garments are wet.

This is due to the increased weight of their clothing, as well as perspiration moisture not being able to evaporate out of the clothing system. A full summary of results is attached in Appendix B (Participant Responses).

Chapter 4
METHODS

Experimental Design

A laboratory experiment with two independent variables (fabric system and moisture condition) and eight dependent variables was conducted to determine the effects of several moisture application parameters within a clothing system. Dependent variables calculated were:

1. (a) peak heat flux through the fabric systems and (b) time to reach peak heat flux transferred through the fabric systems when:
   - i. exposed to a purely radiant heat source of a relatively low heat flux (10 kW/m^2)
   - ii. exposed to a flame heat source of a relatively high heat flux (83 kW/m^2)
2. (a) energy transferred through the fabric systems and (b) time to reach 0.1 kJ of energy transferred through the fabric systems when:
   - i. exposed to a purely radiant heat source of a relatively low heat flux (10 kW/m^2)
   - ii. exposed to a flame heat source of a relatively high heat flux (83 kW/m^2).

Four different fabric systems were evaluated for thermal performance when moisture was and was not a factor. Each of the four fabric systems was tested under five different moisture conditions when exposed to a flame heat source and under five different moisture conditions when exposed to a radiant heat source. Moisture conditions included: (i) both layers oven-dried at 105°C for 1 hour, (ii) both layers conditioned in a standard atmosphere (65% RH, 21°C), (iii) outer layer saturated prior to exposure, (iv) underwear layer saturated prior to exposure, and (v) both outer and underwear layer saturated prior to exposure. Three replications of the experiment were conducted.

Materials

The four fabric systems comprised combinations of two different thermal protective outerwear materials and two different underwear materials. Fabric characteristics are outlined in Table 4. The outerwear materials chosen are typical of what is used for thermal protective clothing worn by wildland firefighters, and the underwear materials chosen are typical of underwear materials worn. Each outer material was combined with each underwear material to form four fabric systems.

Table 4. Description of Single Layer Materials Used in Fabric Systems

	Fiber Content	Fabric Construction	Fabric Count (yarns/cm)	Standard Conditioned Mass (g/m²)	Saturated Moisture Content (%)
Outer					
A	Indura® FR cotton	3/1 Twill Weave	Warp: 36 Filling: 18	337.5	35
B	Nomex IIIA® aramid	Plain Weave	Warp: 17 Filling: 27	211.5	40
			(Wales or Courses/cm)		
Inner					
1	100% Cotton	Jersey Knit	Wales: 17 Courses: 13	176.5	50
2	Nomex®	Rib Knit	Wales: 14 Courses: 13	164.0	45

Fabric Systems:
A1: Indura® FR cotton outer with 100% Cotton jersey knit inner
A2: Indura® FR cotton outer with Nomex® rib knit inner
B1: Nomex IIIA® aramid outer with 100% Cotton jersey knit inner
B2: Nomex IIIA® aramid outer with Nomex® rib knit inner

Specimens for each replication of the experiment were randomly cut from the materials, and then these specimens were randomly allocated to an experimental treatment prior to testing.

Moisture Application

Following CAN/CGSB-4.2 No.2-M88 (CGSB, 1993), specimens were conditioned from the dry side at 20 ± 1°C and 65 ± 2% relative humidity for 24 hours prior to moisture application and testing. As outlined above, specimens were tested according to five conditions:

(i) both layers oven-dried at 105°C for 1 hour:

After oven-drying, specimens were placed in a desiccator for a maximum of 4 hours prior to testing. Specimens were tested within 40 seconds of removal from the desiccator. These specimens were considered control specimens. No further moisture was applied.

(ii) both layers conditioned in a standard atmosphere (65% RH, 21°C):

Specimens were placed in a plastic bag to prevent moisture loss when being removed from the standard atmosphere. Specimens were tested within 40 seconds of removal from the plastic bag. These specimens were control specimens and were only conditioned according to CAN/CGSB-4.2 No.2-M88 (CGSB, 1993). No further moisture was applied.

(iii) outer layer saturated prior to exposure and inner layer conditioned in a standard atmosphere,

(iv) underwear layer saturated prior to exposure and outer layer conditioned in a standard atmosphere, and

(v) both outer and underwear layer saturated prior to exposure.

To saturate specimens, appropriate layers of multi-layer specimens were saturated with moisture following ASTM D-461: Standard Test Method for Felts, Section 17 (ASTM, 1999). Specimens were immersed in water for a minimum of 5 minutes and a maximum of 60 minutes. Moisture content of the specimens did not vary between these time periods. They were then removed from the water, placed between sheets of commercial blotting paper, and rolled over with a 2000g metal roller to remove excess moisture. Percent moisture content was calculated using Equation 1 (p. 30). Results are shown in Table 4. Nomex IIIA® aramid outer had a higher saturated moisture content than the Indura® FR cotton outer, while the 100% cotton jersey knit inner had a higher saturated moisture content than the Nomex® rib knit inner.

Measurement and Determination of Dependent Variables

The dependent variables were peak heat flux transferred through the fabric systems, time to reach peak flux transferred through the fabric systems, total energy transferred through the fabric systems, and time to reach 0.1 kJ of energy transferred through the fabric systems for both pure radiant and flame exposures.

Flame Exposure (FE)

After appropriate moisture application, specimens were tested following CAN/CGSB-4.2 No. 78.1, Thermal Protective Performance of Materials for Clothing, with a 6.4 mm spacer, according to paragraph 8.2(b), with a calibrated heat flux of 83 kW/m^2 (CGSB, 2001). The equipment used is shown in Figure 1. The procedure and data acquisition program were modified in order to measure the heat flux and energy transferred through the fabric systems as a function of exposure time. The flame was not removed from the specimen when the second-degree burn criterion was reached. Rather, the flame remained under the specimen for a total of 10 ± 0.5 seconds in order to drive off excess moisture. Heat flux and transferred energy were measured for 60 seconds.

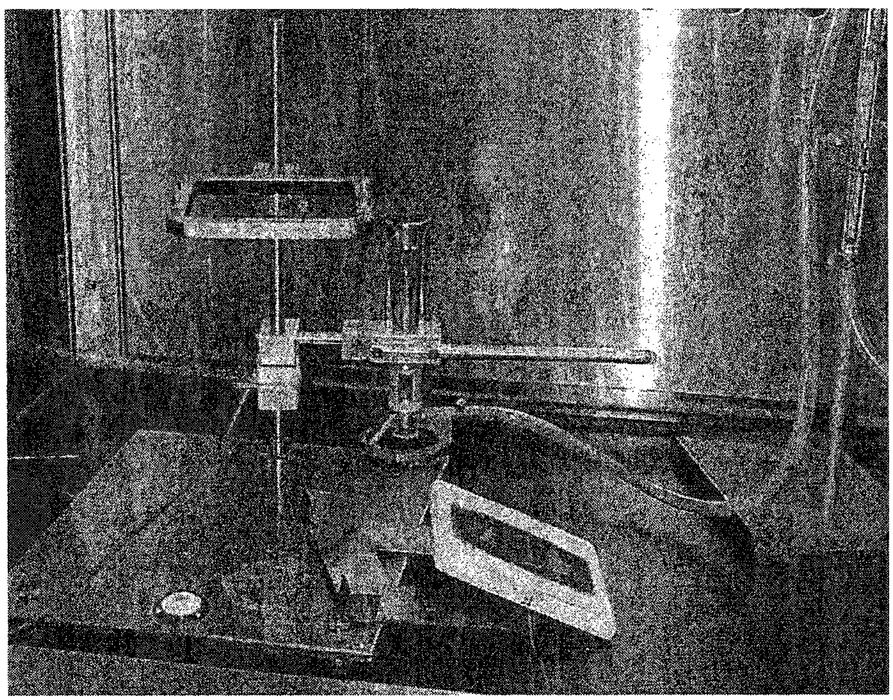


Figure 1. High-Heat-Flux Flame Exposure Equipment.

Radiant Exposure (RE)

After appropriate moisture application, specimens were tested using equipment for NFPA 1977 Standard on Protective Clothing and Equipment for Wildland Firefighters – Standard on Protective Clothing for Proximity Fire Fighting, section 6-2 Radiant Protective Performance (RPP) Test, with a 6.4 mm spacer and a calibrated heat flux of 10 kW/m^2 (NFPA, 1998). The equipment used is shown in Figure 2, which illustrates the vertical orientation of the heat source. The procedure and data acquisition program were modified in order to measure the heat flux and energy transferred through the fabric system as a function of exposure time. The quartz tubes were not turned off and the specimen was not removed from the test apparatus when the second-degree burn criterion was reached. Rather, the specimen remained exposed to the heat flux for a total of 100 seconds. Heat flux and total transferred energy were measured during this time.

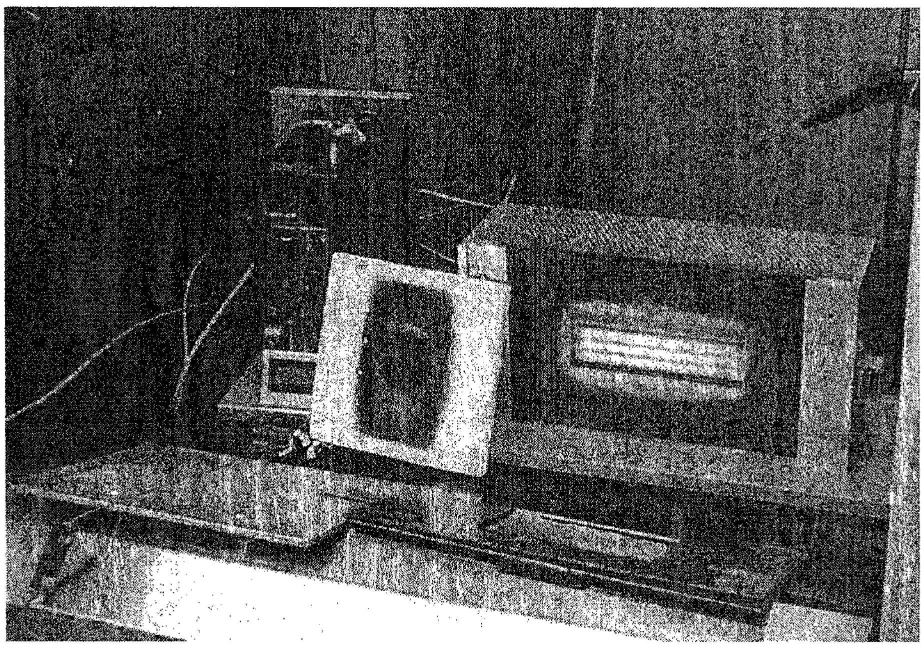


Figure 2. Radiant Exposure Equipment.

Calculation of Energy Losses

In order to determine the total heat flux and total energy received by the copper calorimeter for both flame exposure (FE) and radiant exposure (RE) tests, the heat losses during exposure were calculated. These losses result from a) heat transferring, via conduction, to the ceramic block in which the calorimeter is embedded, b) heat transferring, via convection, to the cavity at the back of the calorimeter, and c) heat re-radiating off the calorimeter.

Disregarding heat losses during exposure, the total energy absorbed by the calorimeter is determined with the formula:

$$Q_{calorimeter} = MC_p(T - T_o) \quad (2)$$

where:

M = mass of calorimeter (assumed constant)

C_p = specific heat capacity of the calorimeter (assumed constant)

T = temperature of calorimeter after exposure (°C)

T_o = initial temperature of calorimeter (°C)

In this formula, the function of time is ignored. Energy absorbed by the calorimeter is only determined as a function of temperature. As a result, the end point of total absorbed energy may be the same for different materials even though the slope of the curves may not be the same (see Figure 3).

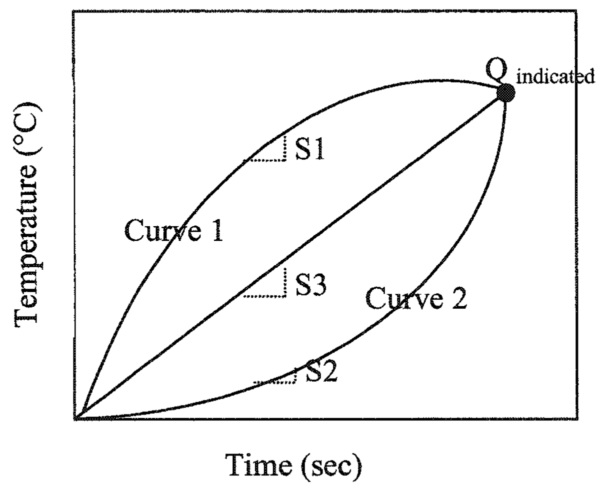


Figure 3. Total energy (Q) absorbed by the calorimeter.

In order to compensate for losses, the total heat flux was determined with the formula:

$$Q''_{total} = (Q''_{indicated} + Q''_{Lost})/\text{calorimeter area} \quad (3)$$

$$= \left\{MC_p \frac{dT}{dt} + f(T - T_o)\right\}/\text{calorimeter area}$$

where:

Q" = represents heat flux (kW/m^2)

$Q''_{indicated}$ = actual heat flux recorded from testing (kW/m^2)

Q''_{Lost} = (actual temperature recorded from testing - ambient temperature)*(calculated loss) dT = Change in temperature (°C)

dt = Change in time (sec)

Ambient temperature (T_o) = 20°C

Calorimeter Area: The area of the calorimeter was determined to be 0.001257m^2.

To calculate loss for heat flux for both RE and FE, the estimated slope of a decay curve was determined as a function of temperature change (Temperature – Ambient Temperature). This slope was then plotted against temperature change (Temperature – Ambient Temperature) to obtain the calculated loss as a function of temperature rise. The calculated loss for FE was determined to be (0.0282 * ΔT) + 0.0086°C, and the calculated loss for RE was determined to be (0.0176 * ΔT) + 0.0155°C. Energy absorbed by the calorimeter in kJ is converted to a heat flux (J/s-m^2) in Equation 3 since absorbed energy is divided by dt (sec) and the calorimeter area (m^2).

Total energy was determined with the formula:

$$E\ total = (E_{indicated} + E_{Lost})*Time \quad (4)$$

where:

E = represents energy (kJ)

E indicated = actual total energy recorded from testing (kJ)

E Lost = (actual temperature recorded from testing - ambient temperature)*(calculated loss)

Ambient temperature = 20°C

Time = actual time recorded from testing (sec)

To calculate loss for absorbed energy for both RE and FE, the estimated slope of a decay curve was determined as a function of temperature change (Temperature – Ambient Temperature). This slope was then plotted against temperature change (Temperature – Ambient Temperature) to obtain the calculated loss as a function of temperature rise. For FE, the calculated loss for absorbed energy was determined to be (0.0282 * ΔT) + 0.0086°C, and the calculated loss for RE was determined to be (0.0176 * ΔT) + 0.0155°C.

Determination of Dependent Measures

After accounting for energy loss, the revised data for heat flux and transferred energy were plotted. From these plots, peak heat flux and total transferred energy data were collected by taking these data points from plots of heat flux and energy versus time. Plots of heat flux and total transferred energy as a function of time were performed using Microsoft® Excel, version 2000. Time to reach peak heat flux and time to reach 0.1 kJ of energy were also measured from the plots. The energy quantity 0.1 kJ was determined as a data collection point since some of the RPP energy curves show a total energy slightly over 0.1 kJ. To remain consistent, this data collection point was kept for TPP, even though the total energy in these curves is higher.

Statistical Analysis

The following statistical analyses were performed using the Statistical Package for Social Sciences (SPSS), version 11.0, with a significance level of $p<0.05$ for hypothesis testing.

1. Descriptive statistics were used to obtain means and standard deviations for each dependent variable for each combination of fabric system and moisture condition.
2. For each dependent variable: a) a three-way ANOVA was performed to determine interaction effects among fabric system, moisture condition, and replication. Results were taken from the model corrected for heterogeneity of variance; b) two-way ANOVAs were performed to determine interaction effects between fabric system and replication, fabric system and moisture condition, and moisture condition and replication. Results were taken from the corrected model; c) Levene's statistic for homogeneity of variance was performed for each fabric system for each dependent variable.
3. a) Because interaction effects were found, one-way ANOVA's were performed separately for each fabric system to determine which moisture conditions significantly differed from each other for each dependent variable. Results were taken from the corrected model; b) Duncan's and Tamhane's post hoc tests were conducted to determine how the effects of moisture condition differed. Tamhane's post hoc test was performed when there was no homogeneity of variance among treatments. Duncan's post hoc test was performed when there was homogeneity of variance among treatments.

Chapter 5
RESULTS AND DISCUSSION

For each of the fabric systems at all five moisture conditions for both radiant exposure (RE) and flame exposure (FE), data were collected for the peak heat flux, time at peak heat flux, total energy, and time at 0.1 kJ. Analyses of variance (ANOVA) were conducted to determine significant differences among the fabric systems and among moisture conditions. Three-way ANOVAs showed that main effects (fabric, replication, and moisture condition) were significant ($p<0.05$) in the corrected model. Three-way interaction effects (fabric by condition by replication) were significant in the corrected model for all dependent variables except FE peak heat flux. Two-way interaction effects (fabric by condition, fabric by replication, condition by replication) were significant except for fabric by replication for FE peak heat flux, time at peak heat flux, time at 0.1 kJ, and RE time at 0.1 kJ. Details of the three-way ANOVAs for each dependent variable for both FE and RE are in Appendices C and D respectively.

One-way ANOVAs of the effects of moisture condition were conducted separately for each of the four fabric systems. Homogeneity of variance tests indicated differences in results among replications for some of the dependent variables. When variances were unequal, Tamhane's T2 post hoc tests were used to determine significant differences among conditions. For homogenous variances, Duncan's post hoc tests were used to determine significant differences among conditions. Descriptives for each fabric system and Levene's homogeneity of variance tests for each fabric system are also in Appendices C and D.

Statistical analyses indicate some significant differences in the dependent variables among the moisture conditions for each fabric system. However, those analyses do not take into account the shape of the heat flux or transferred energy curves. These curves (Figures 4-7, 9-17, and 19-23) illustrate dramatic and/or gradual changes in heat flux and transferred energy through the fabric systems. The discussion that follows first reviews differences among the moisture conditions and visible trends for each fabric system for both FE and RE. Then, differences among fabric systems for each moisture condition for both FE and RE are reviewed.

Differences Among Moisture Conditions at 83 kW/m² Flame Exposure (FE)

Results of one-way ANOVAs showing differences in each of the dependent variables among moisture conditions are given in Table 5 for each fabric system. Plots of heat flux and transferred energy versus time for each moisture condition are displayed separately for each fabric system in Figures 4 to 7. Due to unequal variances between and within replications, the graphs represent an average of 5 specimens for one typical replication for each fabric system. The replication selected had the lowest within-treatment variance. Other replications show similar patterns. Results in Table 5 and Figures 4 to 7 are discussed below by dependent variable.

Peak Heat Flux

For all four fabric systems, the peak heat flux for the wet/conditioned specimens was the lowest. This moisture combination is significantly different from most other moisture combinations (Table 5). The peak heat flux for the wet/wet specimens was the second lowest for all four fabric systems. These two conditions are always significantly different from the other moisture combinations. They have heat transfer curves (Figures 4-7) that more gradually reach peak heat flux, at which time the heat flux gradually decreases. Statistical and graphical analyses suggest, therefore, that external moisture decreases the rate of heat transfer through the clothing system at high heat fluxes (83 kW/m^2). When exposed to a high-heat-flux flame exposure, flames produce a convective air flow that carries the thermal energy away from the surface of the exposed fabric. Water vapour is carried away from the fabric system by means of this convective airflow, resulting in an increase in thermal protection (Figure 8a).

The other three fabric moisture conditions, dry/dry, conditioned/conditioned, and wet/conditioned, generally have high peak heat flux values. These three moisture combinations generally have heat flux curves that rapidly reach peak heat flux and then drop rapidly. The Nomex®/ Nomex® (B2) fabric system has the largest deviation from these generalizations (Figure 7), but still follows a similar trend. This suggests that having a garment that is completely dry, slightly humidified, or wet internally increases the initial rate of heat transfer through a clothing system at high heat fluxes. Dry, or slightly humidified, garments allow heat to transfer through to the skin more readily than

Table 5. The effects of moisture on heat transfer and transferred energy through four different fabric systems: 83 kW/m^2 Flame Exposure

Fabric System	Moisture Condition	Mean Peak Heat Flux (kW/m^2) (std. dev.)	Mean Time at Peak Heat Flux (sec) (std. dev.)	Mean Total Energy (kJ) (std. dev.)	Mean Time at 0.1 kJ (sec) (std. dev.)
A1	Dry/Dry	47.28^{b} (6.04)	4.05^{c} (0.37)	0.355^{a} (0.01)	5.07^{e} (0.28)
Indura® with	Cond/Cond	49.33^{b} (6.33)	5.37^{b} (0.28)	0.349^{a} (0.01)	5.64^{d} (0.16)
100% Cotton	Wet/Cond	14.55^{c} (1.32)	9.31^{a} (1.28)	0.237^{c} (0.02)	9.68^{b} (0.56)
	Cond/Wet	57.69^{a} (7.52)	5.26^{b} (0.36)	0.300^{b} (0.01)	5.87^{c} (0.17)
	Wet/Wet	14.97^{c} (0.99)	9.44^{a} (1.08)	0.239^{c} (0.01)	10.83^{a} (0.48)
A2	Dry/Dry	59.35^{a} (6.72)	3.87^{c} (0.48)	0.426^{a} (0.02)*	4.52^{d} (0.22)
Indura® with	Cond/Cond	59.18^{a} (8.00)	5.04^{b} (0.46)	0.405^{b} (0.01)*	5.22^{c} (0.15)
Nomex®	Wet/Cond	15.18^{b} (1.52)	8.78^{a} (0.49)	0.228^{d} (0.02)*	9.53^{b} (0.56)
	Cond/Wet	59.55^{a} (4.78)	5.17^{b} (0.30)	0.313^{c} (0.01)*	5.38^{c} (0.21)
	Wet/Wet	15.83^{b} (1.00)	9.00^{a} (0.64)	0.232^{d} (0.01)*	10.42^{a} (0.55)
B1	Dry/Dry	35.74^{a} (2.19)	8.98^{b} (0.93)*	0.371^{a} (0.02)*	7.75^{d} (0.33)
Nomex IIIA®	Cond/Cond	35.54^{a} (1.46)	9.53^{ab} (0.69)*	0.341^{b} (0.01)*	8.31^{c} (0.25)
with 100%	Wet/Cond	10.90^{d} (0.79)	7.23^{c} (1.34)*	0.225^{d} (0.01)*	10.17^{b} (0.66)
Cotton	Cond/Wet	28.19^{b} (1.87)	9.19^{b} (0.90)*	0.313^{c} (0.01)*	7.46^{d} (0.23)
	Wet/Wet	13.09^{c} (0.81)	10.10^{a} (1.45)*	0.233^{d} (0.01)*	10.79^{a} (0.33)
B2	Dry/Dry	18.18^{b} (0.79)	10.22^{a} (0.66)*	0.362^{a} (0.01)*	8.99^{c} (0.33)
Nomex IIIA®	Cond/Cond	17.11^{c} (0.52)	10.44^{a} (0.56)*	0.326^{b} (0.01)*	9.15^{bc} (0.31)
with Nomex®	Wet/Cond	11.46^{e} (0.97)	6.51^{c} (0.87)*	0.232^{c} (0.02)*	9.68^{ab} (0.68)
	Cond/Wet	29.48^{a} (2.16)	7.60^{b} (0.85)*	0.318^{b} (0.01)*	6.57^{d} (0.35)
	Wet/Wet	13.57^{d} (1.39)	9.85^{a} (1.18)*	0.228^{c} (0.02)*	10.32^{a} (0.75)

[a,b,c,d,e] For each fabric system, means with the same superscript letter do not differ significantly from each other (columns).

* Asterisk indicates significant differences determined using Duncan's, rather than Tamhane's, post hoc tests.

externally saturated garments since the convective airflow produced by the flames is able to flow and transfer thermal energy towards the sensor. Due to water's high heat capacity, internal moisture in the fabric system absorbs the thermal energy and becomes water vapour. This water vapour is unable to exit the fabric system quickly and condenses on the sensor, resulting in a decease in thermal protection (Figure 8b).

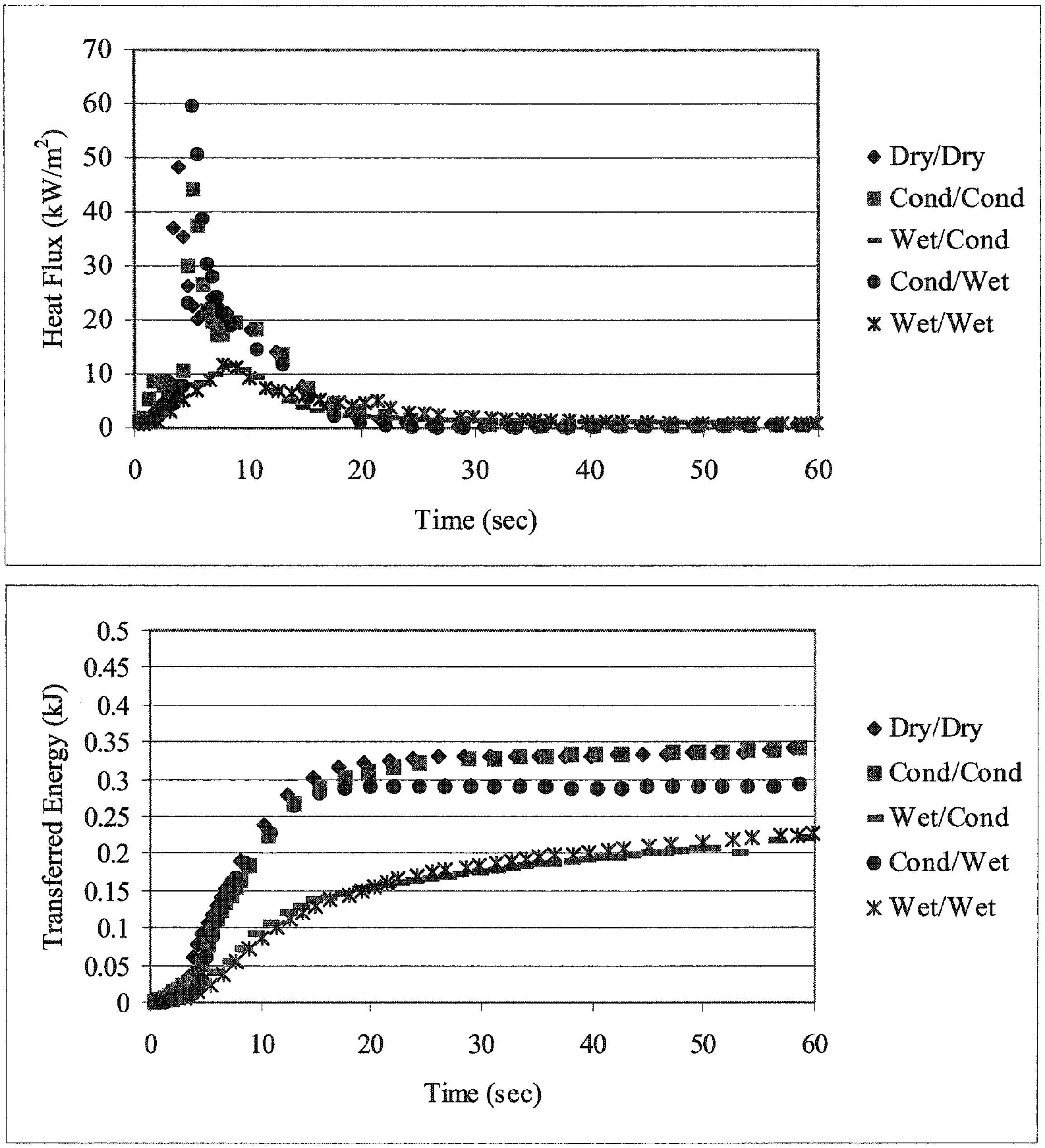


Figure 4. The effects of moisture on heat flux and transferred energy through fabric system A1 (Indura®/Cotton): Flame Exposure.

The significance of the differences and the order among conditions varies, however, depending on the fabric system, as confirmed by the interaction effects. For example, the magnitude of the differences among conditions are notably less for systems B1 and B2 (Figures 6 and 7) than for A1 and A2 (Figures 4 and 5).

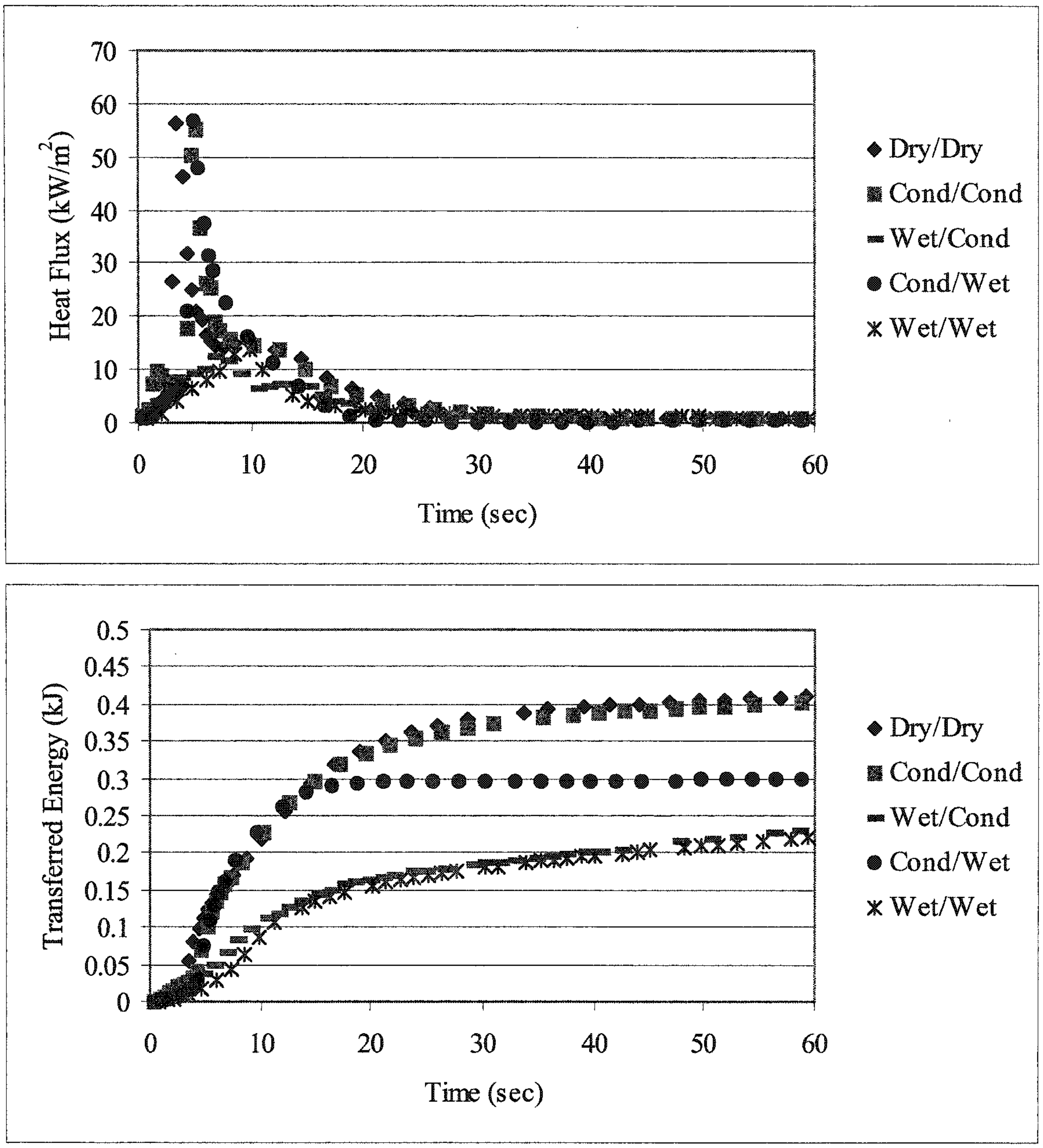
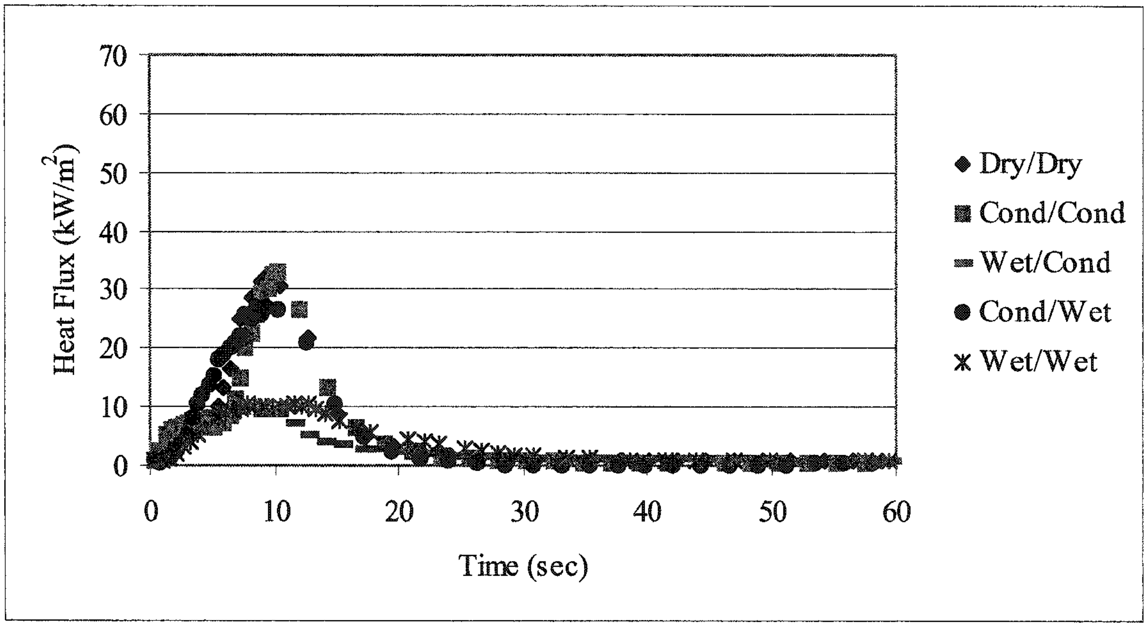


Figure 5. The effects of moisture on heat flux and transferred energy through fabric system A2 (Indura®/Nomex®): Flame Exposure.

Time to Peak Heat Flux

For the Indura® fabric systems (A1 & A2), moisture combinations of wet/conditioned and wet/wet have the longest time before peak heat flux is reached, reflecting results of peak heat flux. The other three combinations have a significantly



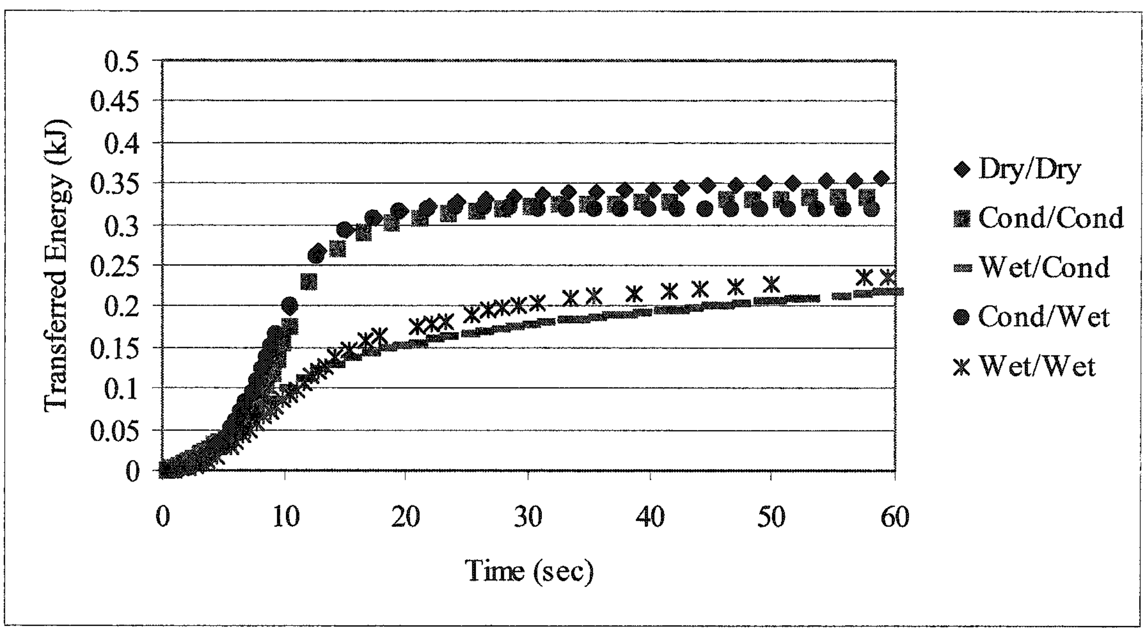


Figure 6. The effects of moisture on heat flux and transferred energy through fabric system B1 (Nomex®/Cotton): Flame Exposure.

shorter time period before peak heat flux is reached, with dry/dry having the shortest (Table 5).

These results suggest that for Indura® fabric systems, external moisture decreases

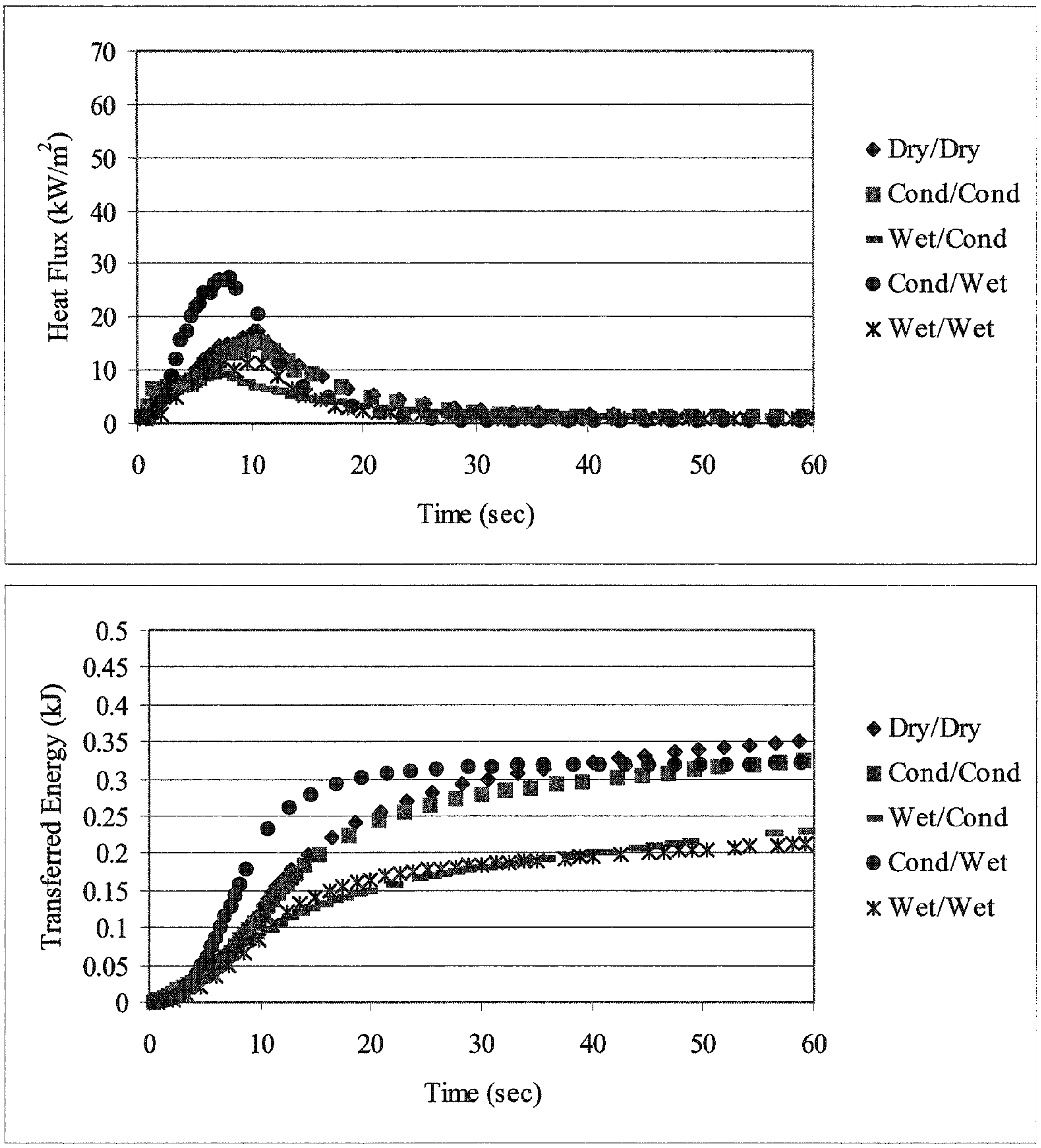
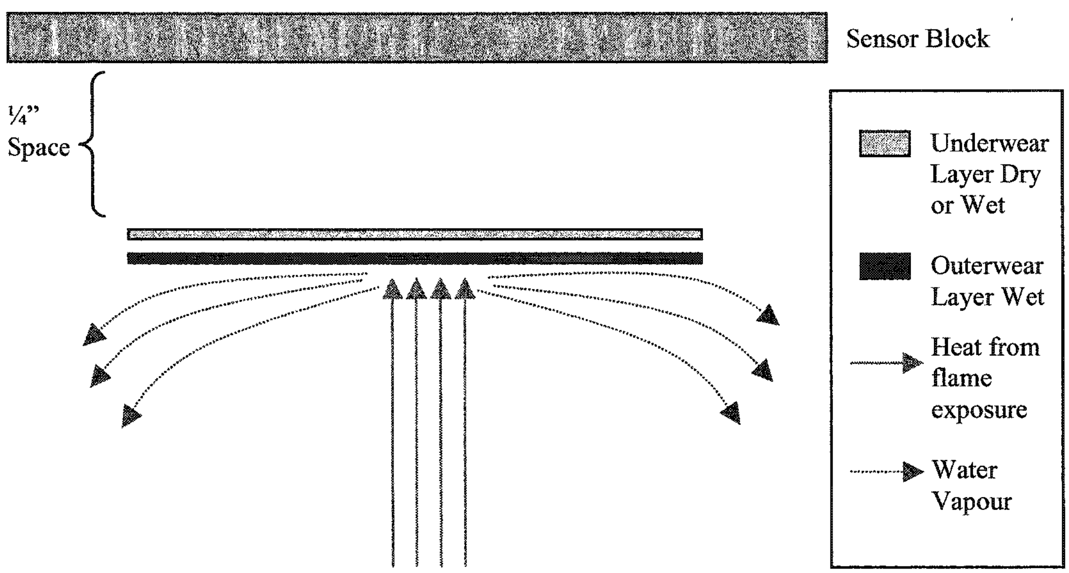
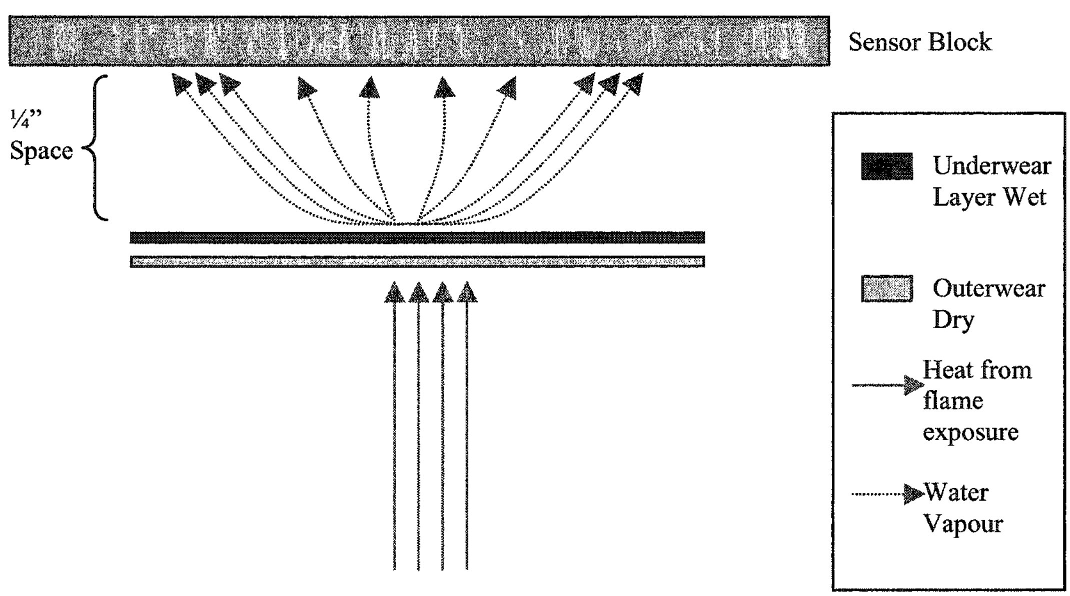


Figure 7. The effects of moisture on heat flux and transferred energy through fabric system B2 (Nomex®/Nomex®): Flame Exposure.

the rate of the heat transfer, while internal moisture with no or little external moisture increases heat transfer through the clothing system at high heat fluxes (83 kW/m^2) (Figure 8).



a) External moisture increases thermal protection.



b) Internal moisture decreases thermal protection.

Figure 8. High-Heat-Flux Flame Exposure.

For Nomex® fabric systems (B1 & B2), the time before peak heat flux is reached and the differences among moisture conditions vary depending on fiber content of the underwear (Table 5). For the cotton underwear, conditioned/conditioned, conditioned/wet, and wet/wet have the longest time before peak heat flux is reached. For Nomex® underwear, dry/dry, conditioned/conditioned, and wet/wet have the longest time before peak heat flux is reached. The wet/conditioned specimens have the shortest time to reach peak heat flux for Nomex® fabric systems. These results generally suggest that any moisture condition, except for wet/conditioned, will have a time at peak heat flux that is similar. However, the results for the two Nomex® fabric systems are so different that such a conclusion is not always valid.

Total Transferred Energy

For all four fabric systems, the total transferred energy was lowest for both the wet/conditioned and wet/wet moisture combinations (Table 5). These two combinations were not significantly different from each other. The transferred energy curves for these two combinations are more gradual before they reach a plateau.

The other three fabric moisture combinations, dry/dry, conditioned/conditioned, and wet/conditioned, generally have higher total transferred energy values. These three moisture combinations generally have transferred energy curves that rapidly reach a plateau. Statistical and graphical analyses suggest that having external moisture decreases the total amount of energy that is transferred through a clothing system at high heat fluxes (Figure 8b).

As for peak heat flux, the significance of the differences and the order among conditions varies depending on the fabric system, as confirmed by the interaction effects.

Time at 0.1 kJ

For all four fabric systems, the time at 0.1 kJ of transferred energy was highest for both the wet/conditioned and wet/wet moisture combinations, and in this case, wet/wet was significantly higher than wet/conditioned except for system B2. The other three fabric moisture combinations, dry/dry, conditioned/conditioned, and wet/conditioned, have lower time values. This suggests that having external moisture increases the time for 0.1 kJ of energy to be transferred through a clothing system at high heat fluxes (Figure 8a).

Differences Among Fabric Systems at 83 kW/m^2 Flame Exposure (FE)

Plots comparing heat flux and transferred energy versus time for all fabric systems are displayed separately for each moisture condition in Figures 9 to13. Due to unequal variances between and within replications, the graphs are an average of 5

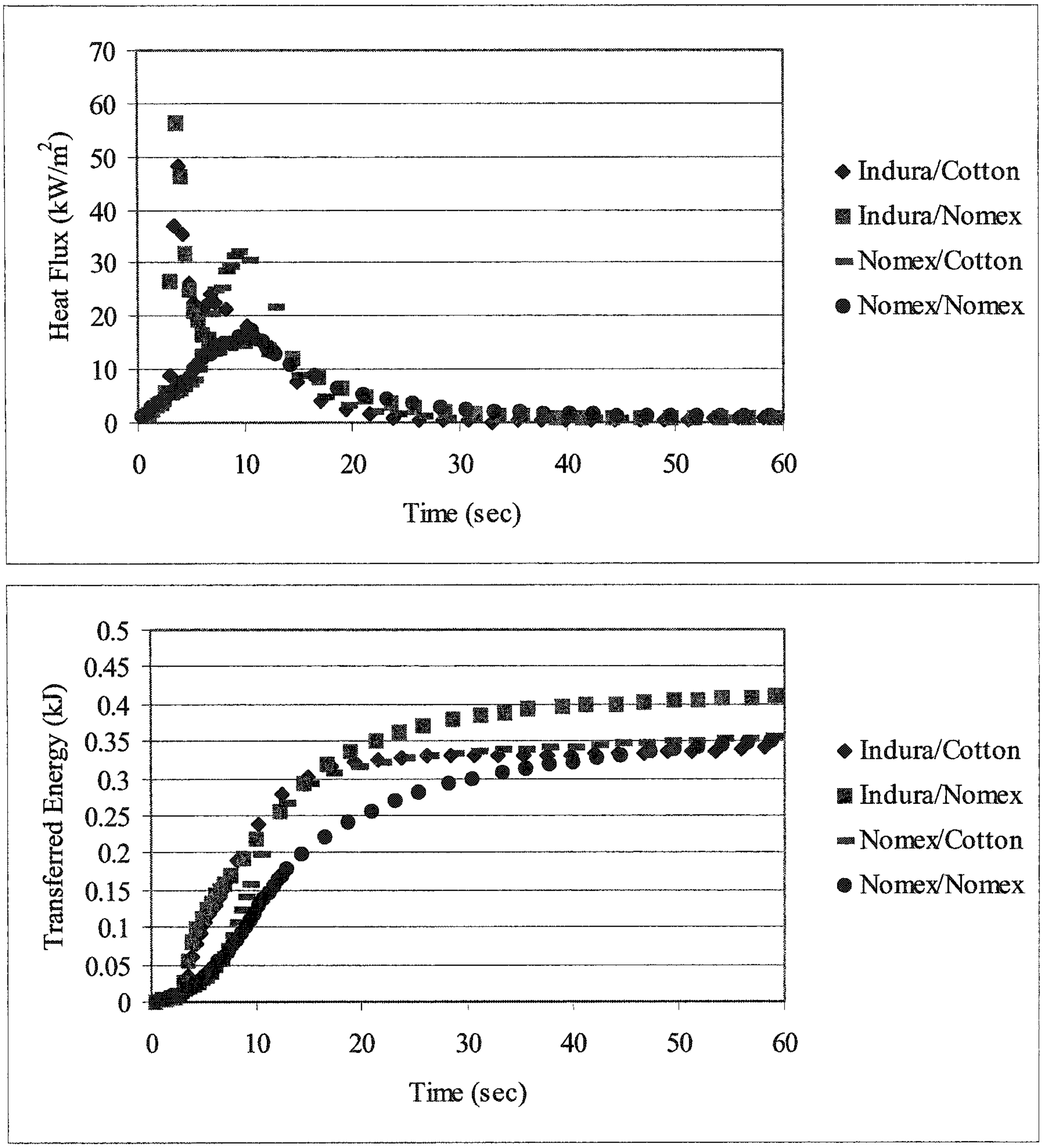
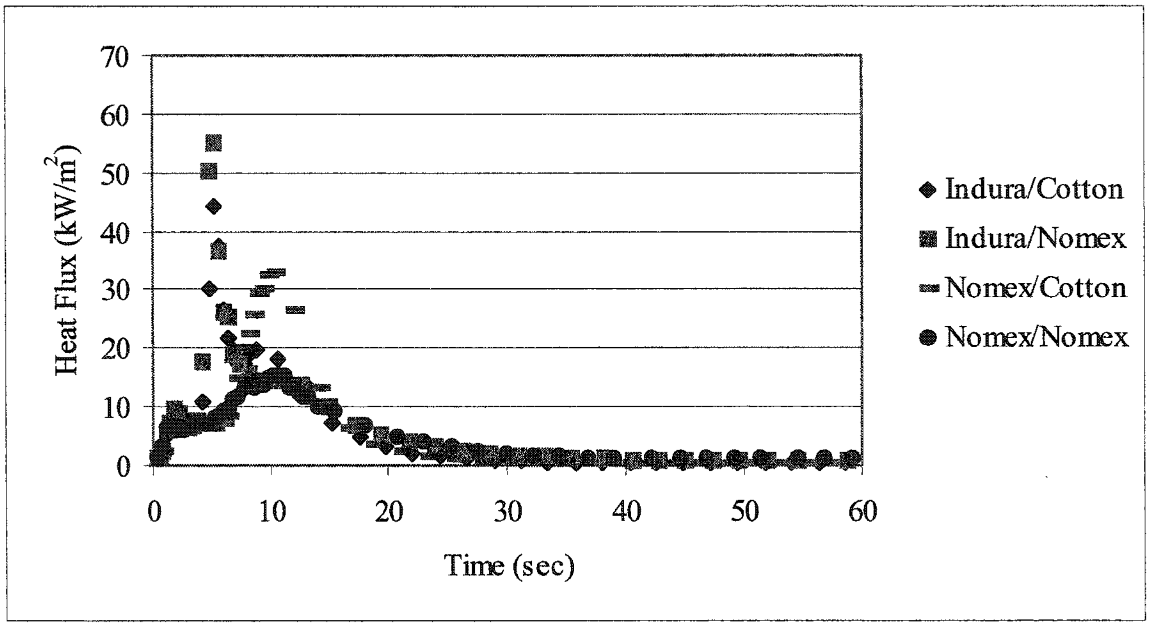


Figure 9. The effects of fabric system on heat flux and transferred energy: Dry/Dry Specimens, Flame Exposure.

specimens for one replication for each fabric system. The replication chosen had the lowest within-treatment variance. Other replications for each fabric system show similar patterns.

Heat Flux

For each condition, Nomex® fabric systems (B1 & B2) have similar heat flux



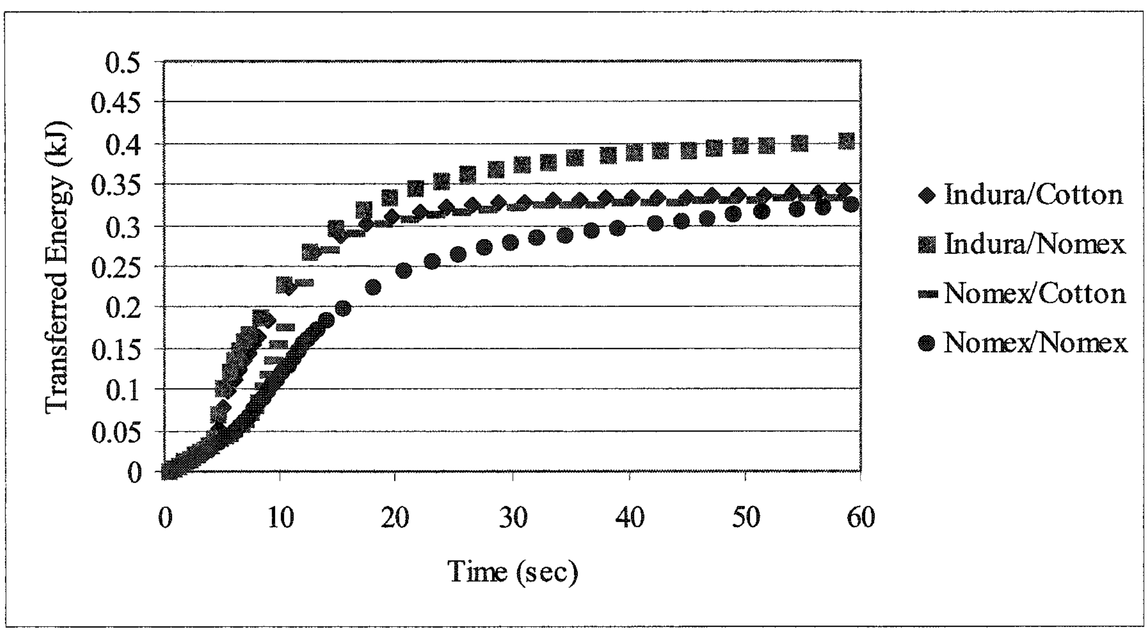


Figure 10. The effects of fabric system on heat flux and transferred energy: Conditioned/Conditioned Specimens, Flame Exposure.

curves, and Indura® fabric systems (A1 & A2) have similar heat flux curves. In general, fabric systems with Nomex® outer layers have a lower peak heat flux. Differences between fabric systems with the two different outer fabrics are much more pronounced for dry/dry, conditioned/conditioned, and conditioned/wet specimens than they are for the other two moisture combinations, wet/wet and wet/conditioned. This indicates that the

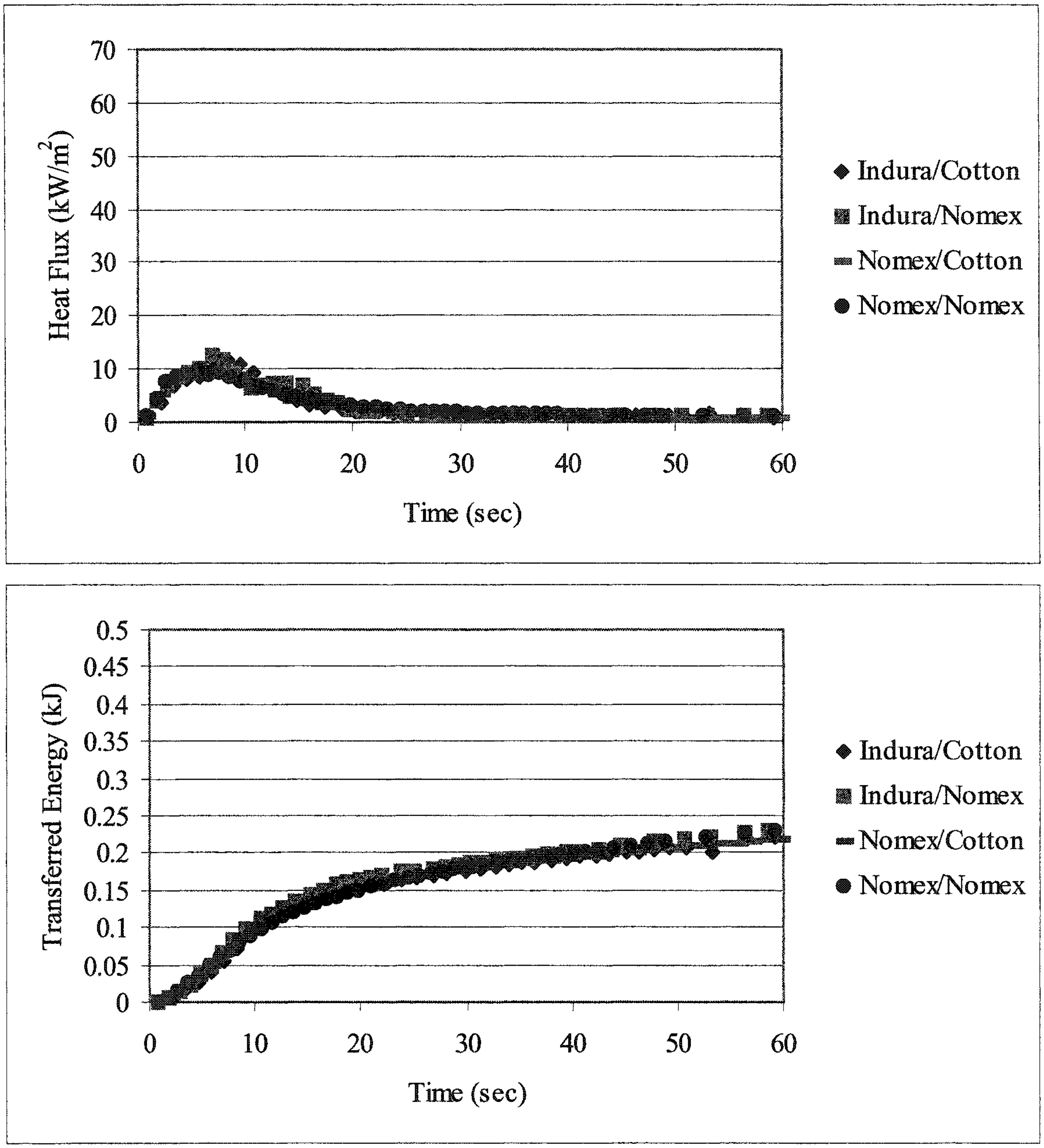
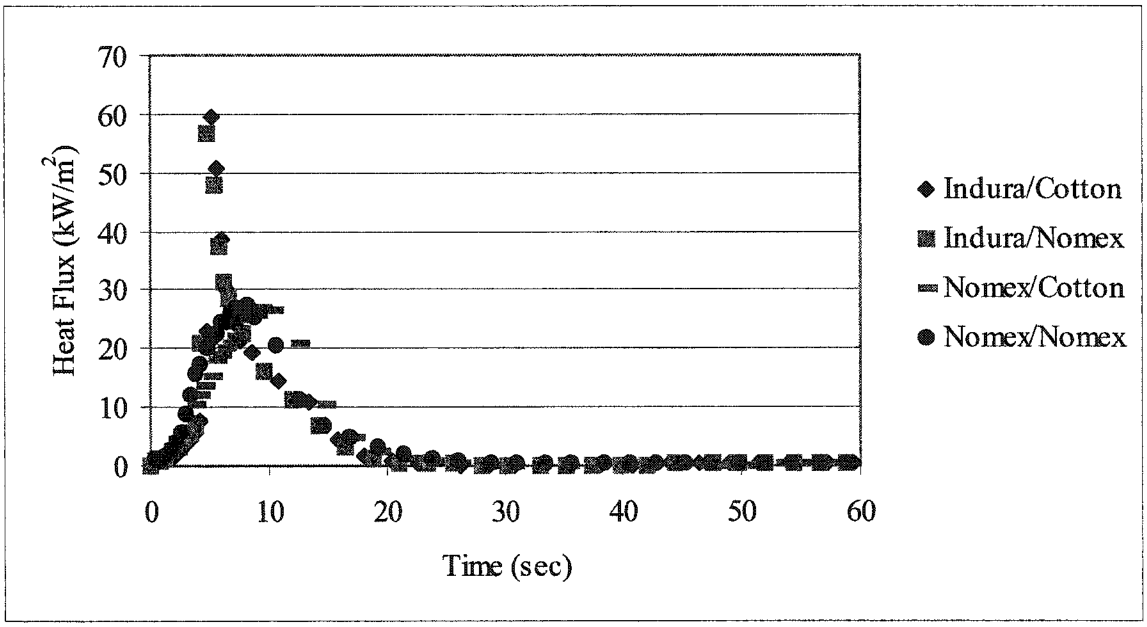


Figure 11. The effects of fabric system on heat flux and transferred energy: Wet/Conditioned Specimens, Flame Exposure.

fabric systems behave similarly when they are externally wet; however, fabric systems that are either dry, or slightly humidified, or have wet or humidified inner layer behave differently.

Transferred Energy

The four fabric systems have similar transferred energy curves for all moisture



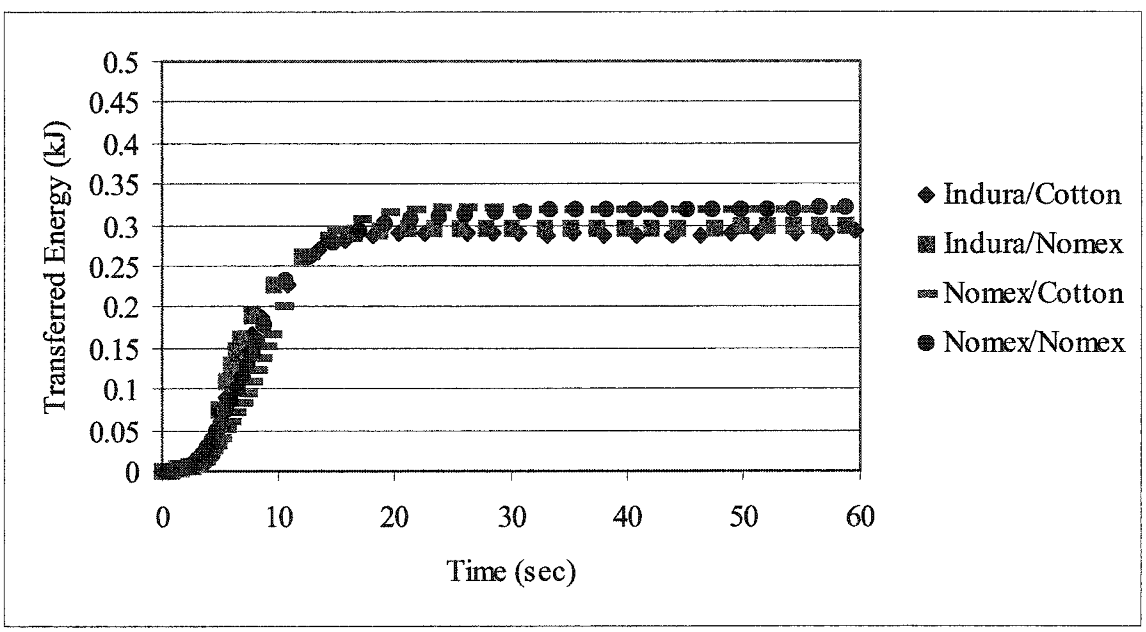
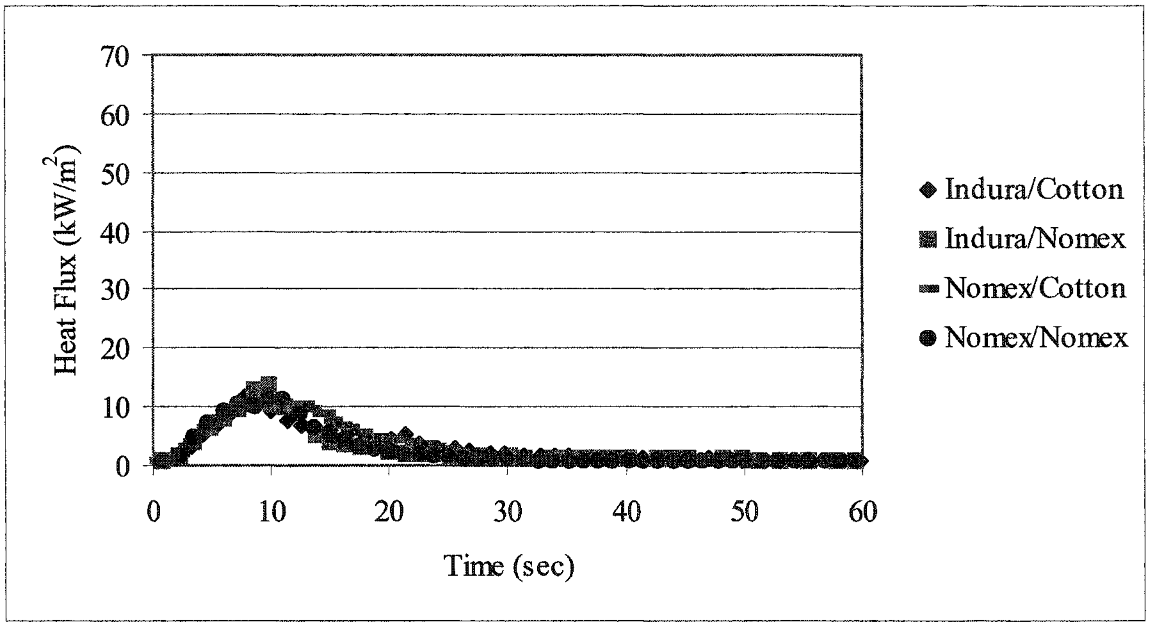


Figure 12. The effects of fabric system on heat flux and transferred energy: Conditioned/Wet Specimens, Flame Exposure.

conditions except dry/dry and conditioned/conditioned. For the latter two moisture conditions, the curve for each fabric is slightly different. For most of the curve, the Nomex®/Nomex® fabric system (B2) has the lowest transferred energy for these two moisture conditions. These graphs illustrate that the differences in energy transferred through various fabric systems may vary by moisture condition.



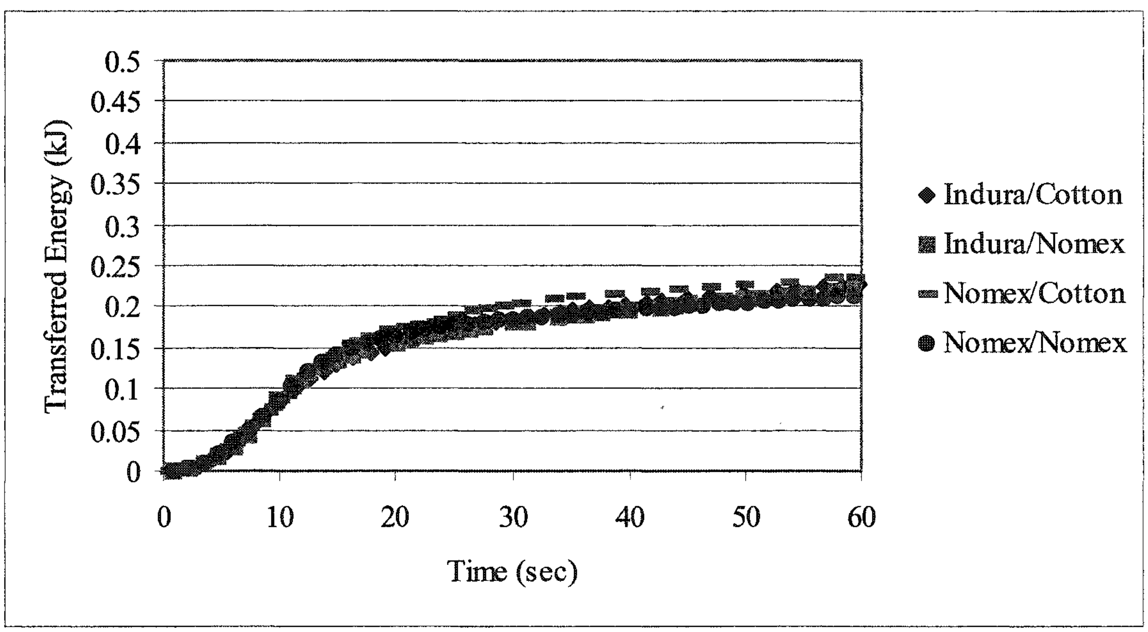


Figure 13. The effects of fabric system on heat flux and transferred energy: Wet/Wet Specimens, Flame Exposure.

Differences Among Moisture Conditions at 10 kW/m^2 Radiant Exposure (RE)

Results of one-way ANOVAs showing differences in each of the dependent variables among moisture conditions are given in Table 6 for each fabric system. Plots of heat flux and transferred energy versus time for each moisture condition are displayed separately for each fabric system in Figures 14 to 17. Due to unequal variances between and within replications, the graphs represent an average of 5 specimens for one typical replication for each fabric system. The replication selected had the lowest within-treatment variance. Other replications show similar patterns. Results in Table 6 and Figures 14 to 17 are discussed below by dependent variable.

Peak Heat Flux

For all four fabric systems, the peak heat flux for the conditioned/wet moisture combinations was the lowest. This moisture combination is significantly different from the other moisture combinations except for wet/wet in the Nomex® fabric systems (B1 & B2). The peak heat fluxes for the other moisture conditions are higher. Some of these results are significantly different from one another (Table 6). In terms of the heat flux plots, it appears as if wet/conditioned, conditioned/wet, and wet/wet moisture combinations have similar curves. These three moisture combinations generally have heat flux curves that rapidly reach peak heat flux and then drop gradually. The other two moisture conditions have curves that are significantly different from those curves and from each other.

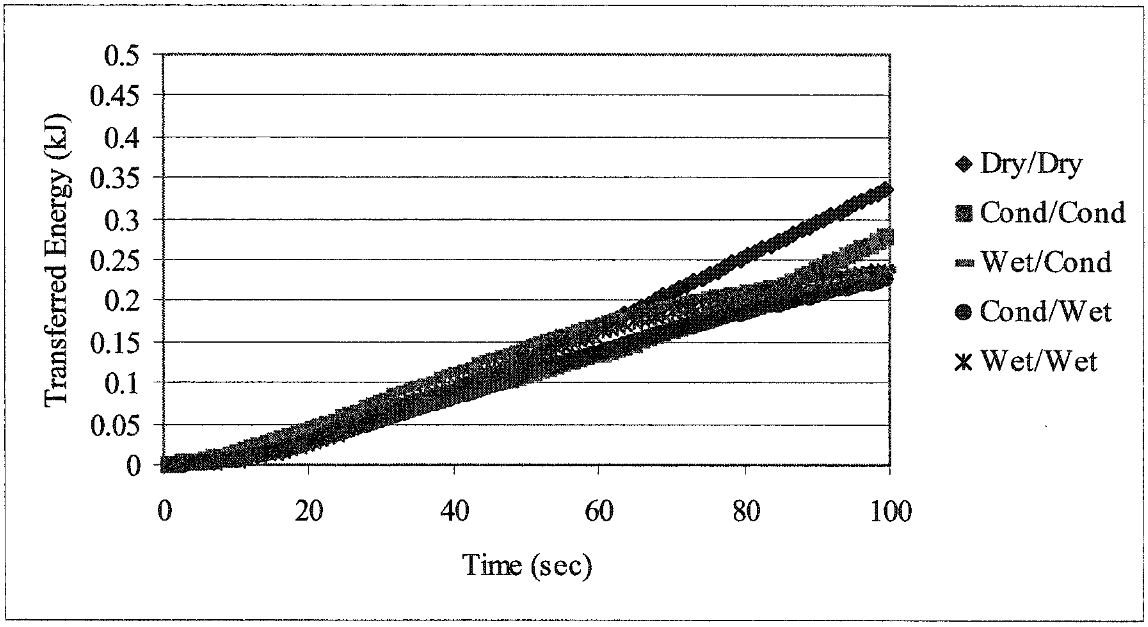
These data suggest that internal moisture decreases the peak heat transfer through the clothing system at low heat fluxes (10 kW/m^2). Wearing a garment that is internally moistened by perspiration decreases the peak heat transfer through a clothing system at low heat fluxes (Figure 18). When exposed to a low-heat-flux radiant exposure, moisture in the fabric system absorbs thermal energy, decreasing the rate of heat transfer through the fabric system. Moisture is able to evaporate and move slowly out of the system rather than towards the sensor.

Table 6. The effects of moisture on heat transfer and transferred energy through four different fabric systems: 10 kW/m^2 Radiant Exposure

Fabric System	Moisture Condition	Mean Peak Heat Flux (kW/m^2) (std. dev.)	Mean Time at Peak Heat Flux (sec) (std. dev.)	Mean Total Energy (kJ) (std. dev.)	Mean Time at 0.1 kJ (sec) (std. dev.)
A1	Dry/Dry	3.34^{a} (0.21)*	61.08^{b} (9.80)	0.356^{a} (0.02)*	41.90^{b} (1.77)
Indura® with	Cond/Cond	3.13^{b} (0.23)*	83.64^{a} (5.43)	0.313^{b} (0.02)*	44.34^{ab} (4.20)
100% Cotton	Wet/Cond	3.41^{a} (0.32)*	20.23^{d} (2.77)	0.259^{c} (0.01)*	33.77^{d} (1.77)
	Cond/Wet	2.49^{c} (0.18)*	31.65^{c} (9.23)	0.239^{d} (0.02)*	45.74^{a} (3.35)
	Wet/Wet	3.23^{ab} (0.23)*	28.30^{c} (9.20)	0.263^{c} (0.02)*	38.81^{c} (2.75)
A2	Dry/Dry	3.48^{a} (0.17)	55.61^{b} (9.99)	0.375^{a} (0.01)	39.93^{b} (2.01)*
Indura® with	Cond/Cond	3.16^{b} (0.15)	80.49^{a} (3.12)	0.328^{b} (0.02)	42.93^{a} (2.82)*
Nomex®	Wet/Cond	3.62^{a} (2.68)	21.07^{c} (2.35)	0.268^{c} (0.02)	31.80^{d} (3.29)*
	Cond/Wet	2.68^{c} (0.14)	29.27^{c} (13.0)	0.244^{d} (0.01)	42.81^{a} (2.93)*
	Wet/Wet	3.37^{ab} (0.32)	25.21^{c} (5.83)	0.273^{c} (0.01)	37.26^{c} (2.47)*
B1	Dry/Dry	3.70^{a} (0.24)	55.55^{b} (3.76)	0.411^{a} (0.01)	35.32^{bc} (1.20)
Nomex IIIA®	Cond/Cond	3.38^{b} (0.27)	67.80^{a} (10.74)	0.354^{b} (0.03)	42.50^{a} (4.01)
with 100%	Wet/Cond	3.37^{ab} (0.49)	22.27^{c} (2.09)	0.254^{c} (0.02)	33.70^{c} (3.15)
Cotton	Cond/Wet	2.75^{c} (0.34)	26.39^{c} (7.35)	0.238^{c} (0.02)	42.23^{a} (1.85)
	Wet/Wet	3.18^{bc} (0.46)	26.11^{c} (8.47)	0.266^{c} (0.03)	39.07^{ab} (4.56)
B2	Dry/Dry	3.94^{a} (0.22)	51.13^{a} (7.94)*	0.438^{a} (0.01)	32.93^{c} (1.78)*
Nomex IIIA®	Cond/Cond	3.62^{b} (0.32)	55.47^{d} (6.28)*	0.382^{b} (0.03)	39.92^{a} (3.29)*
with Nomex®	Wet/Cond	3.60^{ab} (0.46)	20.73^{c} (2.95)*	0.268^{de} (0.02)	32.15^{c} (2.71)*
	Cond/Wet	2.96^{c} (0.25)	27.38^{b} (8.55)*	0.246^{e} (0.02)	41.18^{a} (3.60)*
	Wet/Wet	3.25^{bc} (0.47)	24.01^{bc} (5.75)*	0.272^{cd} (0.02)	36.56^{b} (3.49)*

[a,b,c,d,e] For each fabric system, means with the same superscript letter do not differ significantly from each other (columns).
* Asterisk indicates significant differences determined using Duncan's, rather than Tamhane's, post hoc tests.

The dry/dry moisture condition follows a heat flux curve that increases and then plateaus. The conditioned/conditioned follows a heat flux that increases rapidly to a low peak heat flux, at which time the curve gradually decreases. This heat flux curve then increases and eventually plateaus. The second portion of this curve is similar to the dry/dry moisture condition heat flux curve but occurs later. This indicates that at initial



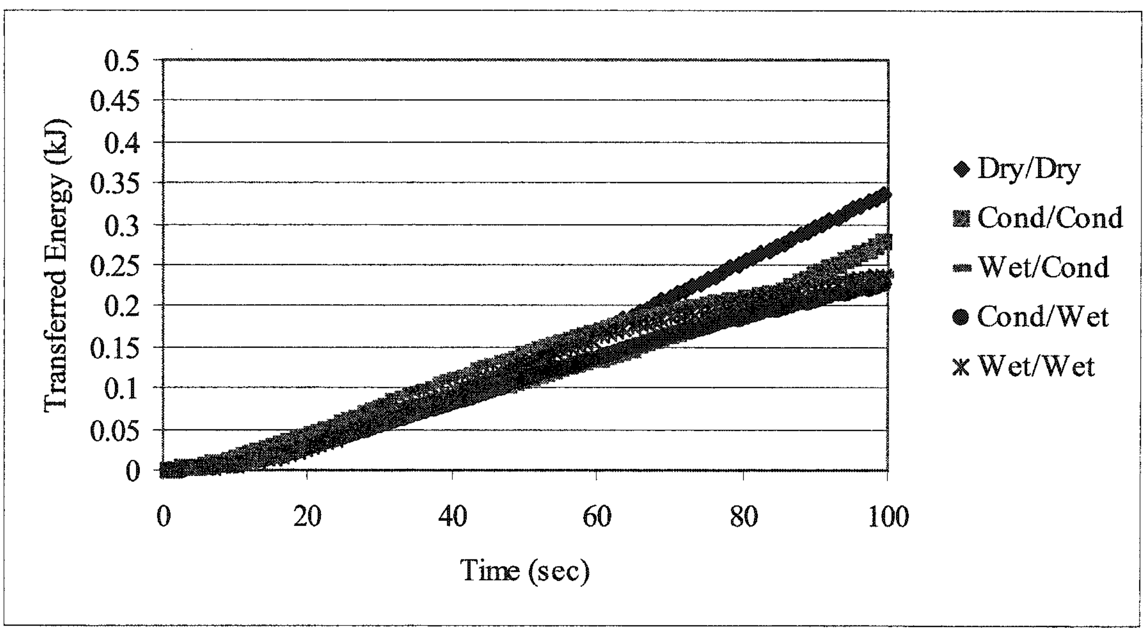


Figure 14. The effects of moisture on heat flux and transferred energy through fabric system A1 (Indura®/Cotton): Radiant Exposure.

heat exposure, the small amount of moisture present in the material is driven off and escapes from the fabric system. Once the moisture is driven off, the fabric is now dry, so the heat flux curve parallels the curve for the dry/dry moisture condition as the curve increases rapidly and then plateaus. Initially, the slight amount of moisture present in the conditioned/conditioned specimens improves the thermal performance, but heat flux and

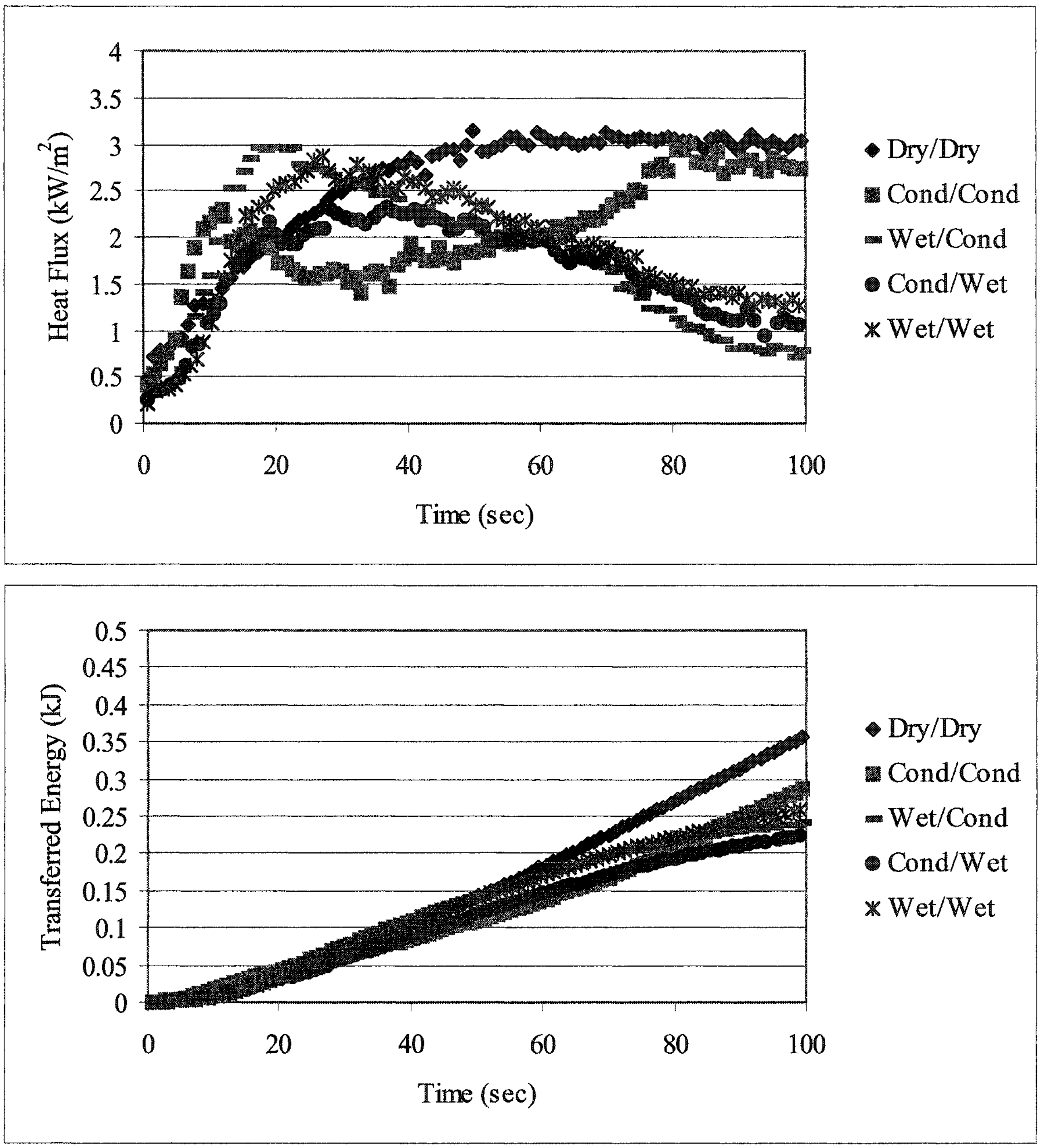


Figure 15. The effects of moisture on heat flux and transferred energy through fabric system A2 (Indura®/ Nomex®): Radiant Exposure.

transferred energy increase after this moisture dissipates.

Time to Peak Heat Flux

Fabric systems with both inner and outer layers conditioned took the greatest length of time to reach peak heat flux, followed by dry/dry moisture combination. The other three moisture combinations displayed significantly shorter times before peak heat

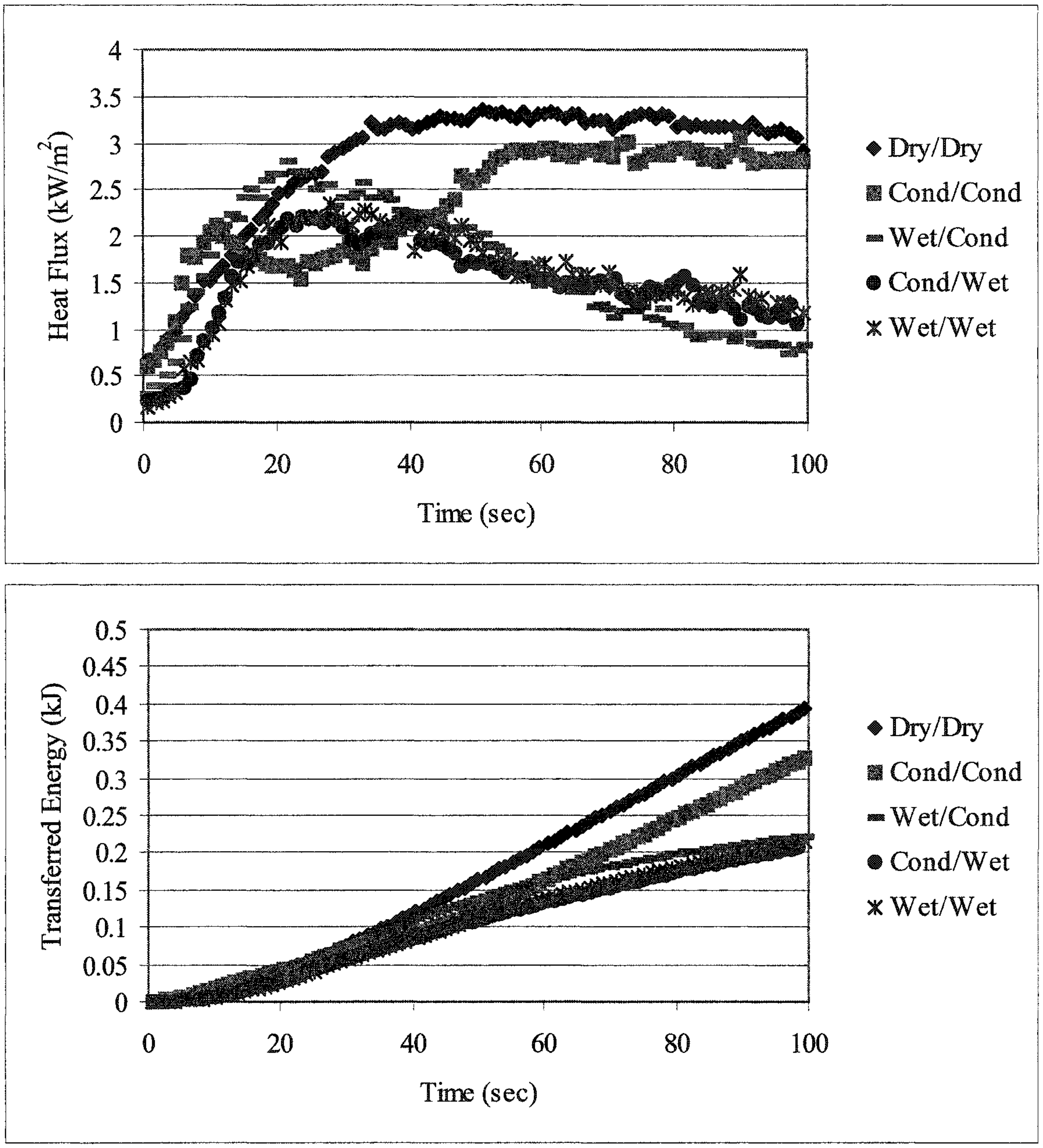


Figure 16. The effects of moisture on heat flux and transferred energy through fabric system B1 (Nomex®/ Cotton): Radiant Exposure.

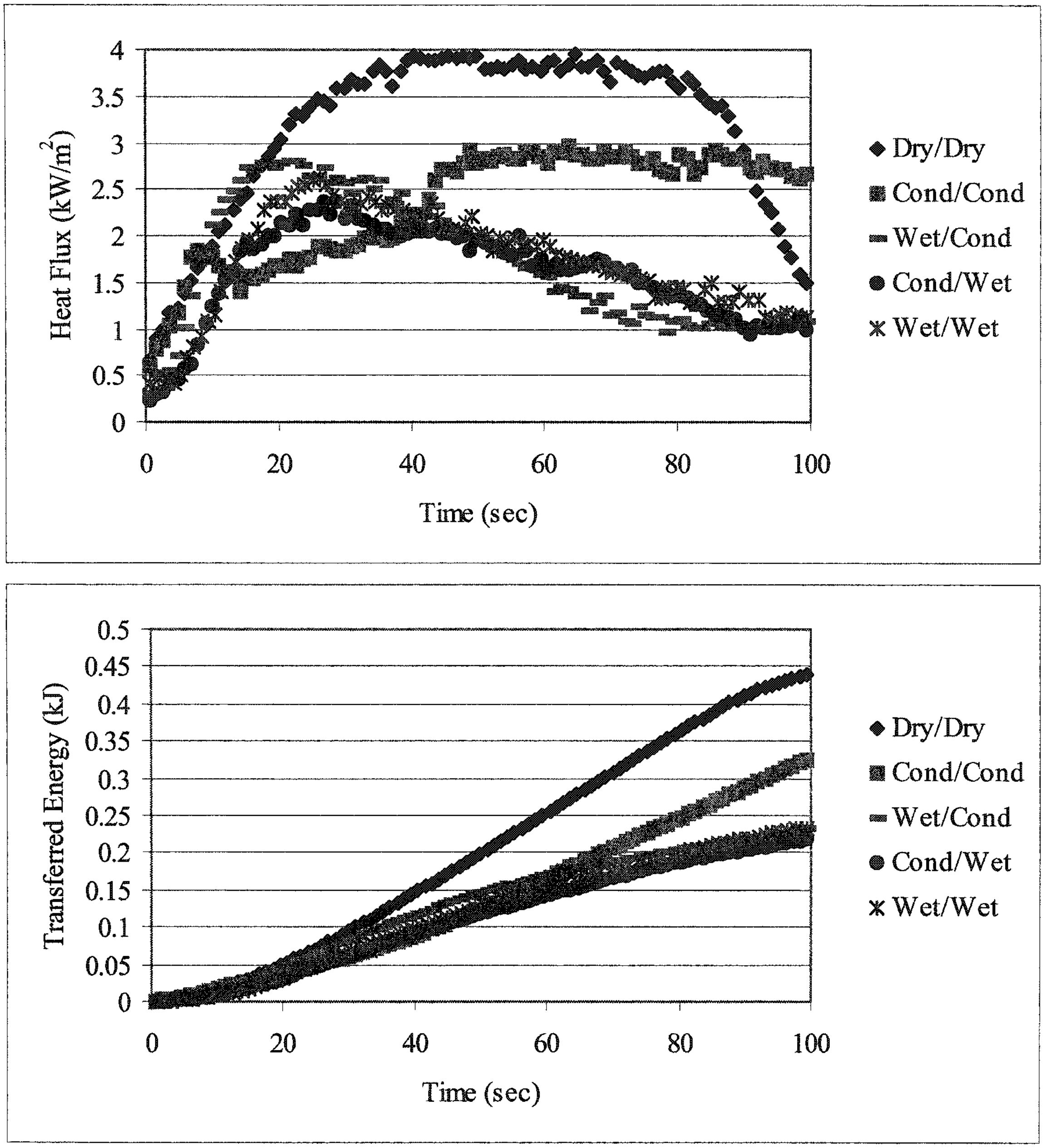


Figure 17. The effects of moisture on heat flux and transferred energy through fabric system B2 (Nomex®/ Nomex®): Radiant Exposure.

flux was reached. This suggests that excessive moisture in inner or outer layers of a clothing system increases the rate at which heat is transferred through a clothing system at low heat fluxes, but small amounts of moisture (standard regain) decrease the rate at which heat is transferred.

Total Transferred Energy

For all four fabric systems, the total transferred energy was lowest for the conditioned/wet moisture combination. Wet/conditioned and wet/wet also show lower values for total transferred energy and are not significantly different from conditioned/wet for Nomex® fabric systems (B1 & B2) (Table 6). Fabric systems with outer, inner, or both outer and inner layers wet have similar transfer energy curves. These curves show lower amounts of energy transferred through the fabric systems.

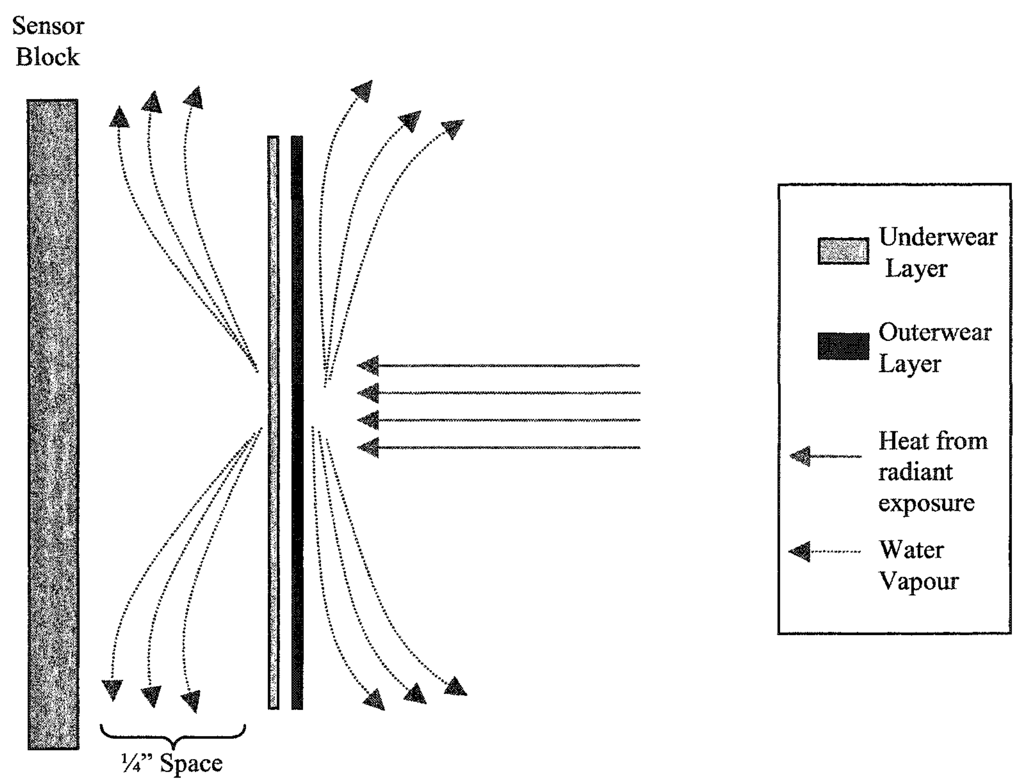


Figure 18. Low-Heat-Flux Radiant Exposure. External and/or internal moisture increase thermal protection.

Fabric systems with both inner and outer layers conditioned or dry have significantly higher total transferred energy than the other three moisture conditions. The transferred energy curves for these two moisture conditions are similar in shape, but the dry/dry moisture condition always has a higher total energy transfer than the conditioned/conditioned moisture condition. These curves, illustrated in Figures 14-17, reflect the delay described above for heat flux. The curves for conditioned/conditioned and dry/dry moisture conditions are significantly different from the other three curves, and they show larger amounts of energy are transferred through the fabric systems.

Statistical and graphical analyses suggest that moisture in a clothing system decreases the total transferred energy through a clothing system at low heat fluxes. Due to the high heat capacity of water, moisture in a clothing system absorbs thermal energy, slowing the transfer of heat through the fabric. As a result, moisture is able to evaporate and slowly move out of the clothing system to the external environment (Figure 18).

Time at 0.1 kJ

For all four fabric systems, the time at 0.1 kJ of transferred energy was highest for the conditioned/conditioned and conditioned/wet moisture combinations. The other three fabric moisture combinations, dry/dry, wet/wet, and wet/conditioned, generally have lower times (Table 6). These results suggest that having a garment that is externally wet or completely dry decreases the amount of time for 0.1 kJ of energy to be transferred through a clothing system. Slightly humidified, or garments that are internally wet, reach 0.1 kJ of transferred energy slower than garments that are completely dry or are externally wet and internally dry.

Differences Among Fabric Systems at 10 kW/m^2 Radiant Exposure (RE)

Plots comparing heat flux and transferred energy versus time for all fabric systems are displayed separately for each moisture condition in Figures 19 to 23. Due to unequal variances between and within replications, the graphs represent an average of 5 specimens for one replication for each fabric system. The replication chosen had the

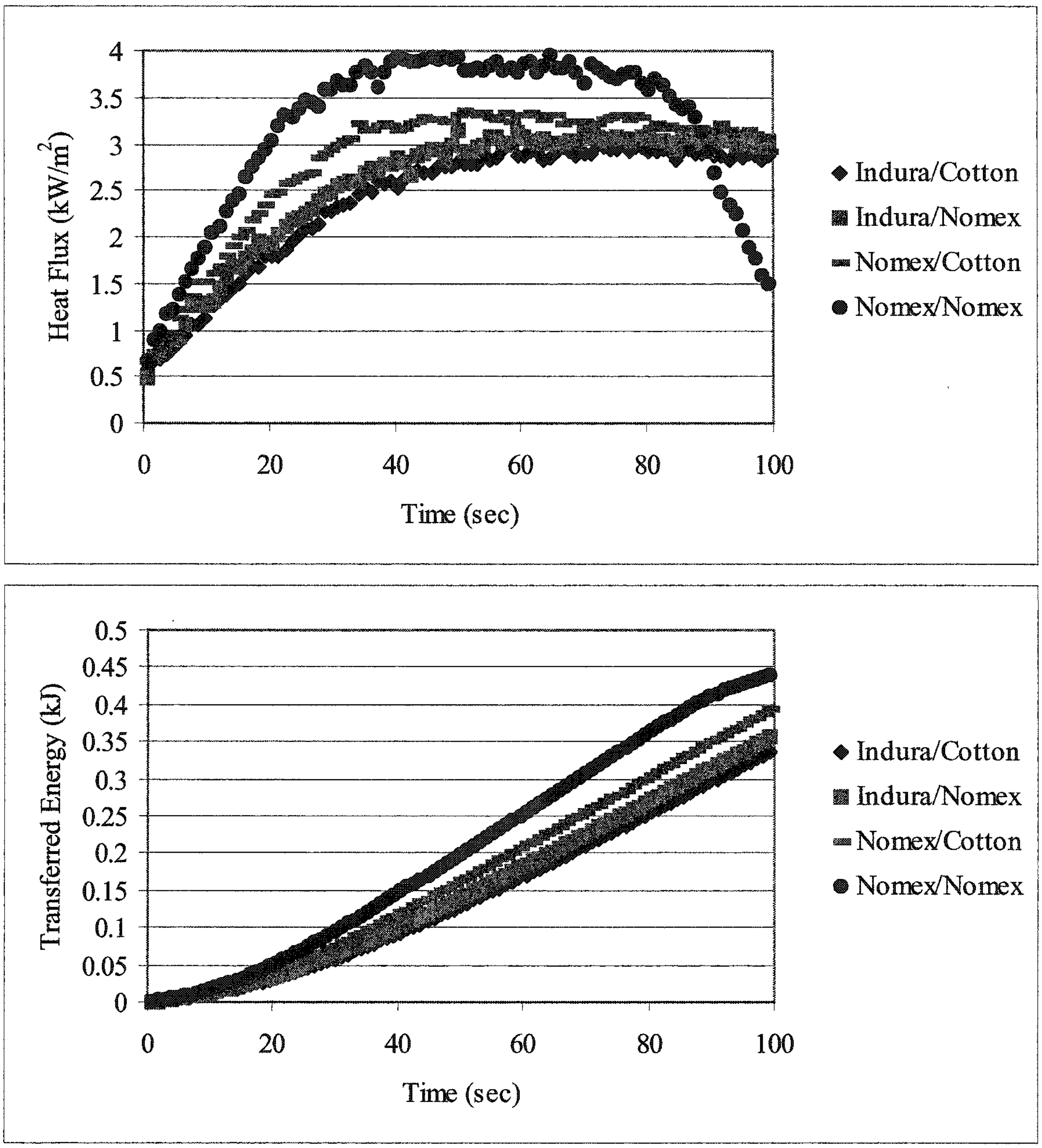
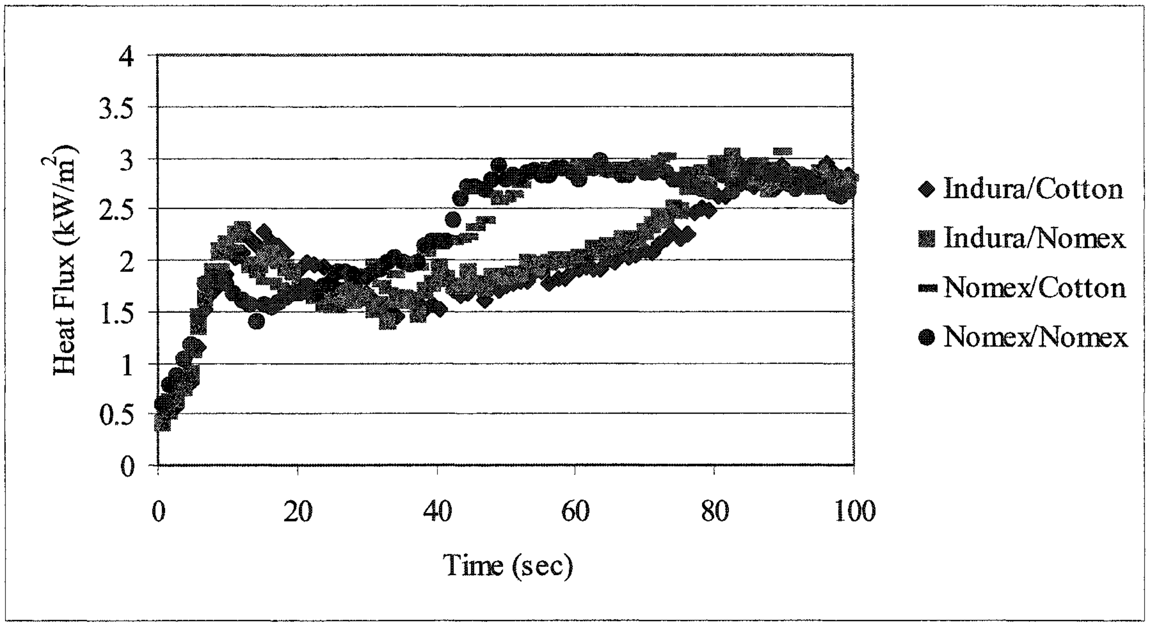


Figure 19. The effects of fabric systems on heat flux and transferred energy: Dry/Dry Specimens, Radiant Exposure.

lowest within-treatment variance. Other replications for each fabric system show similar patterns.

For dry/dry (Figure 19) and conditioned/conditioned (Figure 20), Indura® fabric systems (A1 & A2) tend to have lower peak heat flux and total transferred energy than the Nomex® fabric systems, indicating that these fabric systems are slightly more



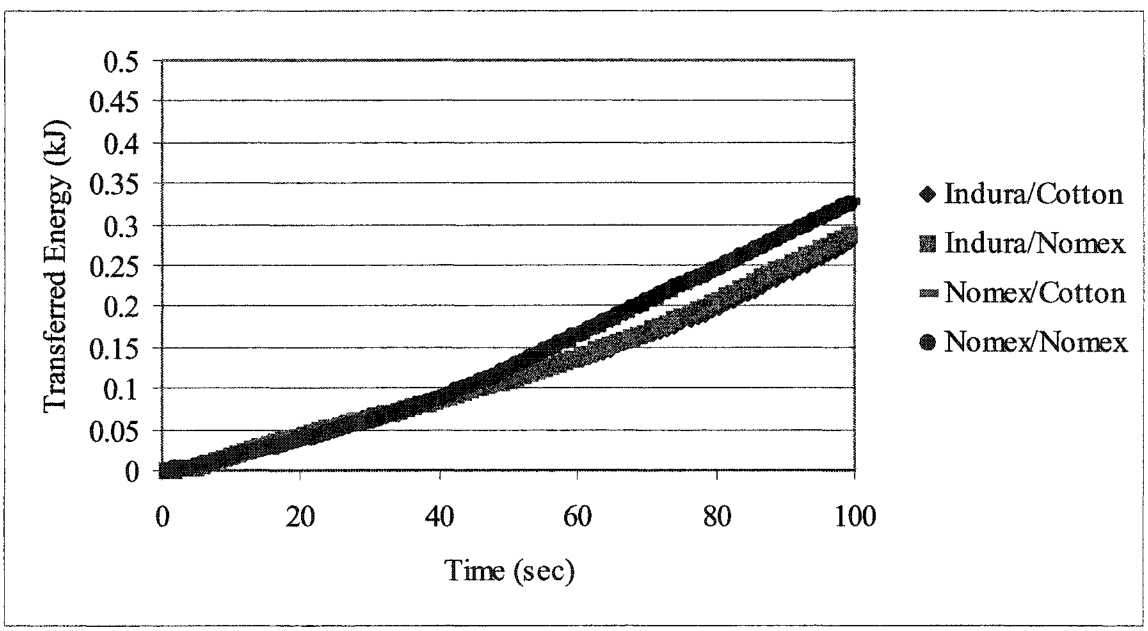
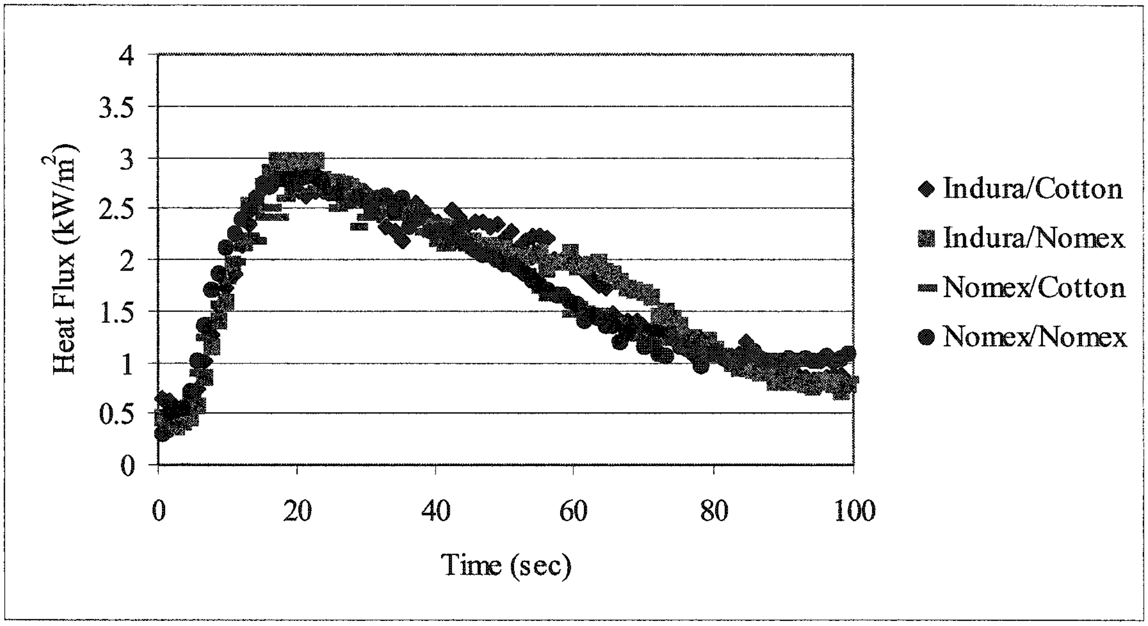


Figure 20. The effects of fabric systems on heat flux and transferred energy: Conditioned/Conditioned Specimens, Radiant Exposure.

protective when both outer and inner layers are either dry or conditioned and the heat flux is low. For wet/conditioned (Figure 21) and conditioned/wet (Figure 22) moisture conditions, the four fabric systems follow similar heat flux and transferred energy curves, with A1 and A2 tending to be slightly higher. For wet/wet (Figure 23) moisture condition, fabric systems B1 and B2 have a lower peak heat flux and total transferred



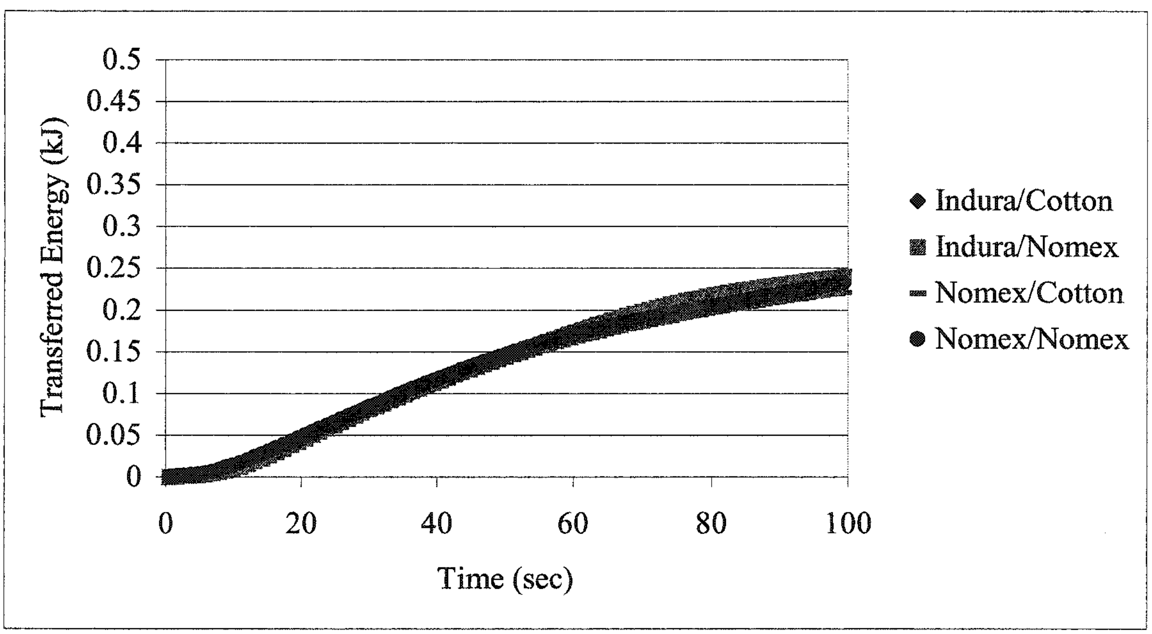
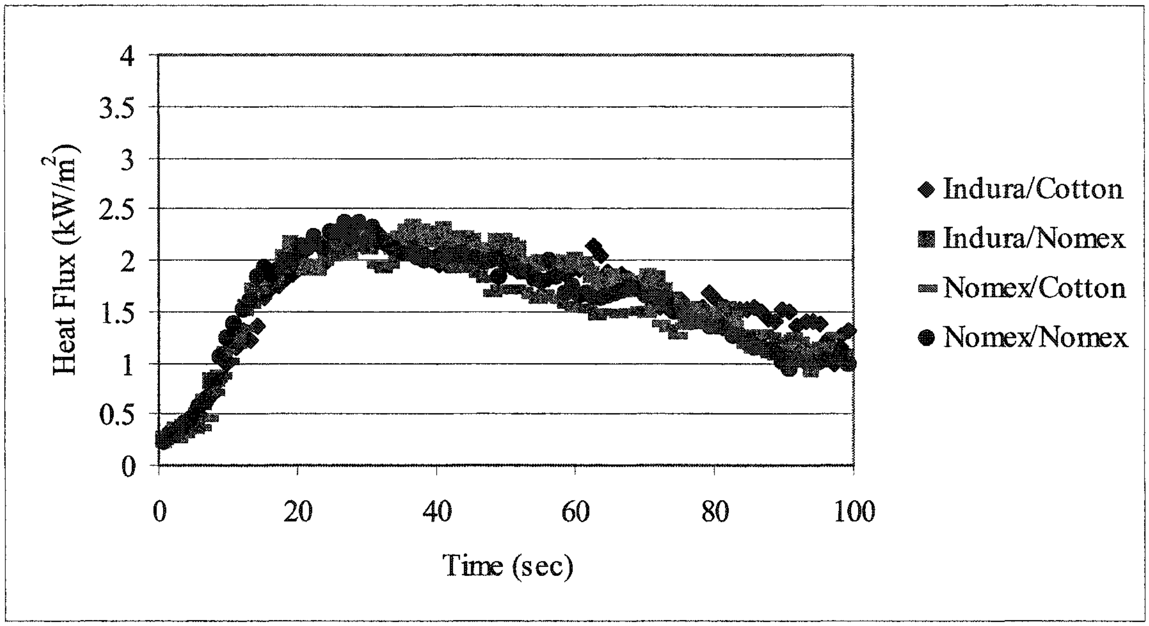


Figure 21. The effects of fabric systems on heat flux and transferred energy: Wet/Conditioned Specimens, Radiant Exposure.

energy than the Indura® fabric systems, making these fabric systems slightly more protective when both layers are wet and the heat flux is low.

These graphs indicate that moisture may significantly affect the peak heat flux or total energy transferred through a clothing system depending on the moisture condition.



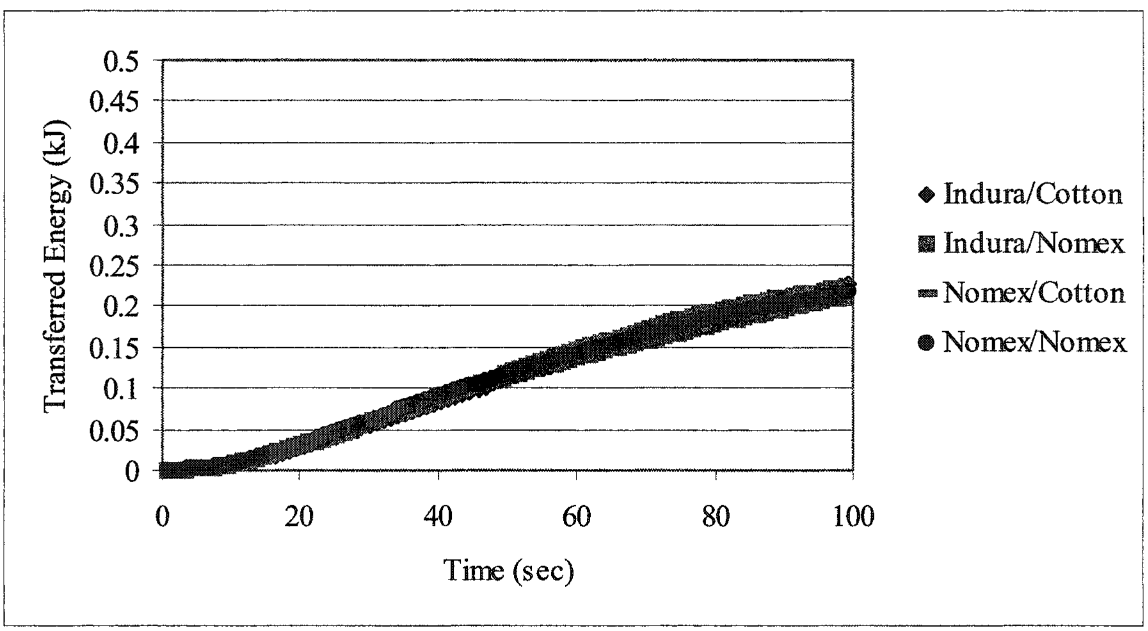


Figure 22. The effects of fabric systems on heat flux and transferred energy: Conditioned/Wet Specimens, Radiant Exposure.

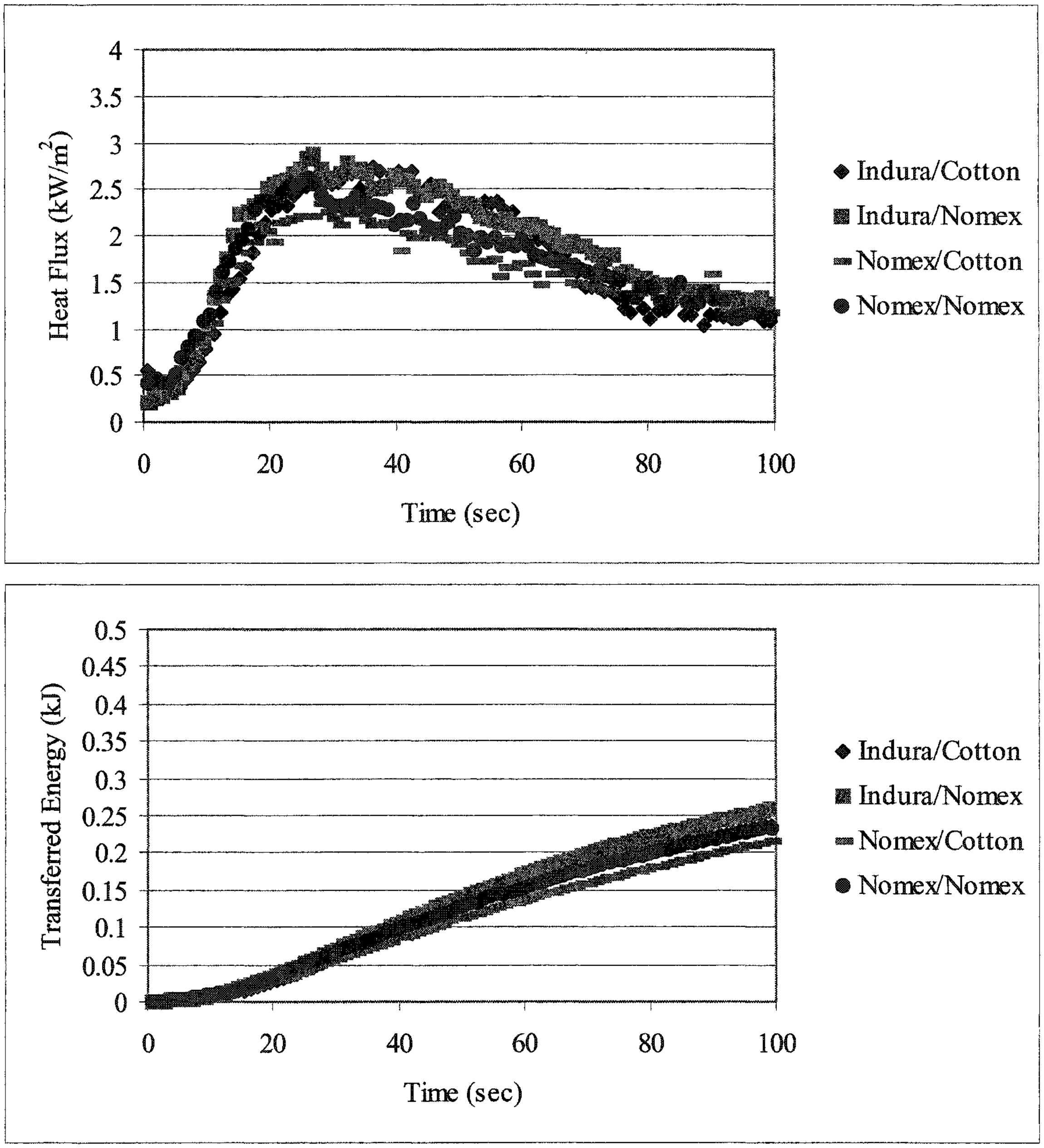


Figure 23. The effects of fabric systems on heat flux and transferred energy: Wet/Wet Condition, Radiant Exposure.

Discussion of Objectives and Hypotheses

Objective 1

The first objective of this research was to develop a laboratory procedure to determine the combined/coupled effects of moisture and high (i.e. 83 kW/m^2) or low (i.e. 10 kW/m^2) heat transfer through textiles. This objective was only partially met. When the experimental design for this research study was first contemplated, two additional moisture conditions were to be included. One involved exposing the underwear of the fabric system specimens to moisture during the heat exposure, simulating perspiration development during heat exposure. To conduct this experiment, an ultrasonic humidifier attached to the sensor block for both TPP (thermal protective performance) and RPP (radiant protective performance) test method equipment was used to moisten specimens. The humidifier formed droplets 10 μm in size. The droplets traveled from the humidifier through a hose to the sensor housing. The sensor housing, constructed from aluminum metal, fit snuggly on the sensor block to reduce moisture loss. The sensor block had holes, approximately 5 mm in diameter, drilled along all four sides to allow water droplets to reach the fabric system being tested. More work is required, however, to achieve the proper distribution of water droplets in order to simulate perspiration development due to heat exposure.

Another anticipated moisture condition involved exposing the outer material of the fabric system to moisture after heat exposure. This condition was meant to simulate the effect that water spray from hoses would have on heat transfer and total energy transfer after a heat source is removed. To attempt to create this condition, specimens were sprayed with a fine mist after the heat source was removed. More work is also required, however, to obtain reliable results for this treatment. Thus, these two moisture conditions, moistened during and after heat exposure, were eliminated as part of the current research.

Although modifications to existing equipment were not successful, this objective was met for the five moisture conditions examined in this study. The dependent variables were measured using standard test method equipment for TPP and RPP using a 6.4 mm spacer. When measuring TPP and RPP in standard tests, layered systems are tested without a spacer, since there is the assumption that a layered system incorporates air spaces. However, the effects of high and low heat fluxes on layered fabric systems with a spacer have not been examined. As a result, this research study incorporates the effect of space between the skin and fabric system when exposed to a heat source. The results obtained in this study differ slightly from results of other research discussed in Chapter 2. These differences will be discussed in a subsequent section.

Objective 2

The second objective of this research was to determine effects of moisture level and location of moisture in clothing layers on both flame and radiative heat transfer through thermal protective clothing systems at high heat fluxes. This objective was successfully met for the five moisture conditions tested. Hypothesis 1 is rejected since there are significant differences in heat transfer through each of the thermal protective systems studied under varying conditions of moisture application, including amount and source/location of moisture.

Objective 3

The third objective of this research was to determine how layering of various outer and underwear materials in a clothing system affects the rate of flame and radiative heat transfer when moisture is a variable. As with Objective 2, differences were found among fabric systems for each moisture condition. Differences between Nomex® and Indura® fabric systems are greater than differences between fabric systems with the same outer fabrics (i.e. A1 vs. A2, B1 vs. B2). Hypothesis 2 is rejected since there are differences in heat transfer among various layered fabric systems when moisture is a factor.

Objective 4

The fourth objective of this research was to determine interaction effects between moisture conditions and fabric layer compositions when exposed to both flame and radiative heat transfer. In two-way and three-way ANOVAs, interaction effects between fabric system and moisture condition were significant for most dependent variables.

Comparison to Previous Research

The main purpose of this research was to examine the effects of moisture present in the materials that make up the clothing systems worn by wildland firefighters and to examine the mechanisms behind heat transfer through these clothing systems when moisture is a key factor. Reviewing literature in this area led to the conclusion that little research has been conducted examining how clothing systems worn by wildland firefighters would perform under the conditions typically experienced while fighting a fire.

No research reviewed (see Chapter 2) examined the effects of combined radiative and convective heat transfer (flame heat source) through two-layered clothing systems worn by wildland firefighters. Most of the reviewed research examined the effects of heat transfer through single-layer clothing and structural firefighter clothing systems containing moisture barriers when moisture was a factor. In some situations, moisture increased thermal protection, where in others, moisture decreased thermal protection, depending on the saturation level. For single-layer fabric systems, moisture typically increased thermal protection. Results obtained in this research demonstrated that, when exposed to high-heat sources, external moisture increases thermal protection even if the fabric system was internally wet. Internal moisture, alone, decreased thermal protection. The results from this research are not directly comparable to previous research results due to the different fabric system combinations and the inclusion of a 6.4 mm spacer. The spacer may have influenced how heat was transferred through the fabric systems.

As previously reviewed, Makinen *et al* (1988) examined effects of internal moisture on heat transfer through outer (FR cotton, Karvin®) and underwear (cotton, wool, aramid knit) fabric combinations at a low radiant heat flux of 20 kW/m^2. They discovered a decrease in thermal protection for all specimens that were internally moistened. Other researchers examining the effect of heat transfer through single layer fabric systems (Chen, 1959; Lee & Barker, 1986) and structural firefighter clothing systems (Stull, 2000a; Rossi & Zimmerli, 1996) using radiant energy also concluded that internal moisture decreased thermal protection. In this research, the opposite was found. Internally moistened specimens exposed to a heat flux of 10 kW/m^2 increased thermal protection. These differences may be due to the inclusion of the 6.4 mm spacer and the lower heat flux.

As discussed in Chapter 2, moisture in a thermal protective clothing system increases the amount of stored energy in the clothing system if moisture is still present after the heat exposure, due to the high heat capacity of water. This mechanism is visible in both the FE (flame exposure) and RE (radiant exposure) experiments of this research. For high heat fluxes (83 kW/m^2), external moisture increased thermal protection, whereas internal moisture decreased thermal protection. When exposed to a high heat flux, external moisture in a clothing system will store energy and evaporate out of the system. If the clothing system is both externally and internally wet, the external moisture will still store energy and evaporate out of the system. If the clothing system is internally wet only, when exposed to a high heat flux, the moisture cannot escape the clothing system. It will evaporate towards the skin, which may result in a steam burn. This mechanism was opposite for the low radiant heat flux exposure of 10 kW/m^2. When internally wet only, moisture has time to escape out of the clothing system, creating a cooling effect. When externally wet, moisture vapour may tend to enter the clothing system and re-condense on the skin, causing increased fatigue and heat stress.

Chapter 6
SUMMARY, CONCLUSIONS, RECOMMENDATIONS, AND IMPLICATIONS

Summary

Wildland firefighters work in environments that are not always favourable for maintaining heat equilibrium in the human body. Constant exposure to low heat fluxes around the range of 10-20 kW/m^2 may lead to increased heat stress and fatigue and even steam burn injury if conditions satisfy such a situation. Occasional exposure to high heat fluxes around 83 kW/m^2, either by conduction, convection, or thermal radiation, may lead to increased burn injury. Wildland firefighters are exposed to many sources of external moisture, such as water spray from hoses, water from lakes and swamps, morning dew, and internal moisture, such as perspiration, therefore potentially increasing the risk of coupled heat transfer.

Moisture in the clothing systems worn by wildland firefighters may increase or decrease heat transfer through the clothing systems depending on factors such as: degree of moisture sorption; location in the clothing system; where it is located on the body; its source; and its timing of application. Fabric layering/combinations may also affect how heat transfers through the clothing system when moisture is a factor.

In this research, four fabric systems (Indura®/cotton, Indura®/Nomex®, Nomex®/cotton, Nomex®/Nomex®) were exposed to five different moisture conditions in the outer/inner layers (dry/dry, conditioned/conditioned, wet/conditioned, conditioned/wet, wet/wet). Wet specimens were saturated with water prior to heat exposure.

The fabric systems were exposed to both a combined convective and radiative high-heat-flux flame source of 83 kW/m^2 and a radiative low-heat-flux source of 10 kW/m^2 using a 6.4 mm spacer. Four dependent variables for each type of exposure were calculated: peak heat flux; time to reach peak heat flux; total transferred energy; and time to reach 0.1 kJ of transferred energy.

Differences were found in the rate of heat transfer through thermal protective textiles under varying conditions of moisture application (rejection of Hypothesis 1) and in the rate of heat transfer among various layered fabric systems when moisture was a factor (rejection of Hypothesis 2). There were also significant interaction effects between moisture conditions and fabric layer compositions when determining their effects on heat transfer (rejection of Hypothesis 3). In general, external moisture increased heat transfer through fabric systems exposed to a low heat flux (10 kW/m^2), while internal moisture increased heat transfer through fabric systems exposed to a high heat flux (83 kW/m^2).

Conclusions

The conclusions obtained from this research are as follows:

1. Moisture level and location of moisture in a clothing system do affect how energy is transferred through the clothing system. There are more differences among moisture conditions for each type of fabric system then there are differences among fabric systems for each type of moisture condition. At high heat fluxes, external moisture generally increased the thermal protection of the fabric systems. Outer wet/underwear conditioned and outer wet/underwear wet specimens tended to have the best thermal protection. Dry/dry, conditioned/conditioned, and conditioned/wet specimens had the lowest thermal protection. At low heat fluxes, internal moisture generally increased the thermal protection of the fabric system. Conditioned/wet and wet/wet specimens tended to have the best thermal protection.
2. Layering of outer and underwear materials in a clothing system does affect the rate of convective and radiative heat transfer when moisture is a variable. Fabric systems with a Nomex® outer layer behave differently from fabric systems with an Indura® outer layer. At high heat fluxes, fabric systems with a Nomex® outer layer generally had a better thermal protection than fabric systems with an Indura® outer layer. At low heat fluxes, Indura® fabric systems showed a better thermal protection than the Nomex® fabric systems when completely dry or conditioned in a standard atmosphere. Nomex® fabric systems showed better thermal protection than the Indura® fabric systems when both outer and underwear layers were wet. There does not appear to be a difference between the two outer fabrics for wet/conditioned and conditioned/wet specimens. Differences between fabric systems may be due to the different mass and saturated moisture content of the Indura® and Nomex® outer fabrics (Table 4).

Implications and Recommendations

Implications for Standard Test Method Development

When conducting standard TPP and RPP tests, the endpoint is reached when the curve representing the temperature of the calorimeter crosses the Stoll Curve. Using only this endpoint, the shapes of the heat flux and transferred energy curves are disregarded. In this research, the four dependent variables measured accounted for the shape of the heat flux and transferred energy curves. By examining the test results in this manner, more information may be collected as to the actual behaviour and mechanism of the heat transfer through the clothing systems. In the future, using these types of endpoints for TPP and RPP may lead to a more comprehensive understanding of thermal protective clothing systems.

When conducting standard TPP and RPP tests, specimens are conditioned in a standard atmosphere of 21°C and 65% RH prior to testing. No other moisture condition is evaluated. This allows for a standard test procedure to which all testing facilities comply for ease of comparison of results. This research has demonstrated how moisture level and location of moisture in the fabric layers can alter the rate of heat transfer though the fabric system. In the future, the end use and working environment for the materials should be considered when conducting TPP and RPP tests on materials. Other moisture conditions could be added to the standard protocols.

Implications For Industry/Use of Protective Clothing

This research has shown that moisture can negatively, as well as positively, affect the thermal protection of a clothing system. In different moisture settings, some outer fabrics may perform better than others, depending on the end use of the clothing system. Considerations for wildland firefighters as to which clothing system would be best in a certain moisture condition at a specific heat exposure temperature may eventually arise. For example, wildland firefighters experience clothing conditions ranging from being completely dry to completely wet. Due to the extreme complexity of these considerations, there may be merit in developing clothing systems that will accommodate all moisture conditions and environments.

Further Research

Further examination of moisture conditions is required to fully understand how moisture affects the rate of heat transfer through clothing systems. Two moisture conditions that should be considered in the future are specimens moistened internally during heat exposure and specimens moistened externally after heat exposure for both low- and high-heat fluxes.

In this research, specimens were tested using a 6.4 mm spacer to simulate air space between the fabric and the skin. Conducting this experiment without the spacer may provide interesting results which will further our understanding of the mechanisms by which moisture in various textiles affects the rate of heat transfer through clothing systems.

REFERENCES

AFP Associates Inc. (1987). Glossary of Technical Terms. Retrieved October 20, 2000 from http://members.aol.com/afp1fire/terms.htm

ASTM (1989). ASTM D 4108-87 Standard Test Method for Thermal Protective Performance of Materials for Clothing by Open-Flame Method. Annual Book for ASTM Standards, 07.01. Philadelphia: American Society for Testing and Materials.

ASTM (1999a). ASTM F1060 Standard Test Method for Thermal Protective Performance of Materials for Protective Clothing for Hot Surface Contact. Annual Book for ASTM Standards, 07.01. Philadelphia: American Society for Testing and Materials.

ASTM (1999b). ASTM F1939 Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials. Annual Book for ASTM Standards, 07.01. Philadelphia: American Society for Testing and Materials.

Backer, S., Tesoro, C., Toong, T., & Moussa, N. (1976). Textile Fabric Flammability. USA: The Massachusetts Institute of Technology.

Berger, X. & Sari, H. (2000). A new dynamic clothing model, Part I: Heat and mass transfers. International Journal of Thermal Science, 39, 673-683.

Brewster, E.P. & Barker, R.L. (1983). A summary of research on heat resistant fabrics for protective clothing. American Industrial Hygiene Association Journal, 44(2), 123-130.

Brownless, N., Anand, S., Holmes, D., & Rowe, T. (1996). The dynamics of moisture transportation, part I: The effect of 'wicking' on the thermal resistance of single and multi-layer fabric systems. Journal of Textile Institute, 87(1), 172-182.

Budd, G., Brotherhood, J., Hendrie, A., Jeffrey, S., Beasley, F., Costin, B., Zhien, W., Baker, M., Cheney, N., & Dawson, M. (1997). Project aquarius 12: Effect of style, fabric, and flame-retardant treatment on the effectiveness and acceptability of wildland firefighters' clothing. International Journal of Wildland Fire, 7(2), 201-206.

Bumbarger, S. (1999). Reducing the hazards of high heat. Occupational Health and

Safety.

CGSB (1993). CAN/CGSB-4.2 No 2-M88: Conditioning Textile Materials For Testing. Ottawa, ON: Canadian General Standards Board.

CGSB (2001). CAN/CGSB-4.2 No 78.1-2001: Thermal Protective Performance of Materials for Clothing. Ottawa, ON: Canadian General Standards Board.

CGSB (1988). CAN/CGSB-155.1-88: Firefighters' Protective Clothing for Protection against Heat and Flame. Ottawa, ON: Canadian General Standards Board.

CGSB (1997). CAN/CGSB-155.23-97: Recommended Practices for the Provision and Use of Fireline Workwear for Forest Firefighters. Ottawa, ON: Canadian General Standards Board.

Chen, N.Y. (1959). Transient Heat and Moisture Transfer Through Thermally Irradiated Cloth. Ph.D. Thesis in Chemical Engineering, MIT, Cambridge, MA. Retrieved October 14, 2001 from http://theses.mit.edu:80/Dienst/UI/2.0/Describe/0018.mit.theses/1959-2

Crown, E.M., Ackerman, M.Y., Dale, J.D., & Rigakis, K.B. (1993). Thermal protective performance and instrumented mannequin evaluation of multi-layer garment systems. In AGARD Conference Proceedings 540. Aerospace Medical Panel Symposium: The Support of Air Operations Under Extreme Hot and Cold Conditions. Nealy Sur Seine, France: NATO Advisory Group for Aerospace Research and Development, 14.1-14.8.

Crown, E.M., Ackerman, M.Y., Dale, J.D., & Tan, Y. (1998). Design and evaluation of thermal protective flightsuits, Part II: Instrumented mannequin evaluation. Clothing and Textiles Research Journal, 16(2), 79-87.

Dale, J., Ackerman, M., Crown, B., Hess, D., Tucker, R., & Bitner, E. (2000). A study of geometry effects on testing single layer fabrics for thermal protection. C. Nelson & N. Henry, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386. West Conshohocken, PA: American Society for Testing and Materials, 393-408.

Day, M. (1988). A comparative evaluation of test methods for thermal protective performance. S.Z. Mansdorf, R. Sager, & A.P. Nielsen, (Eds.), Performance of

Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 989. Philadelphia, PA: American Society for Testing and Materials, 108-120.

DuPont. (1999). Technical Guide for Nomex® Brand Fiber. USA: EI DuPont du Numours.

Geankoplis, C.J. (1993). Transport Processes and Unit Operations, Third Edition. Englewood Cliffs, NJ: Prentice-Hall Inc.

Hatch, K. (1993). Textile Science. USA: West Publishing.

Holcombe, B.V. & Hoschke, B.N. (1986). Do test methods yield meaningful performance specifications? R.L. Barker & G.C. Coletta, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 900. Philadelphia, PA: American Society for Testing and Materials, 327-339.

Holmer, I. (1988). Thermal properties of protective clothing and prediction of physiological strain. S.Z. Mansdorf, R. Sager, & A.P. Nielsen, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 989. Philadelphia, PA: American Society for Testing and Materials, 82-86.

Incropera, F.P. (1985). Fundamentals of Heat and Mass Transfer, Second Edition. USA: John Wiley & Sons, Inc.

ISO (1993). ISO 6942 Evaluation of the Thermal Behaviour of Materials and Material Assemblies When Exposed to a Source of Radiant Heat. Geneva, Switzerland: International Organization of Standardization.

ISO (1995). ISO/DIS 9151 International Standard for Protective Clothing Against Heat and Flame: Determination of Heat Transmission on Exposure to Flame. Geneva, Switzerland: International Organization of Standardization.

ISO (1996). ISO/DIS 12127 Clothing for Protection Against Heat and Flame: Determination of Contact Heat Transmission Through Protective Clothing or Constituent Materials. Geneva, Switzerland: International Organization of Standardization.

Krasney, J.F. (1986). Some characteristics of fabrics for heat protective garments. R.L. Barker & G.C. Coletta, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 900. Philadelphia, PA: American

Society for Testing and Materials, 463-474.

Laverty, G. (Jan.3, 2001). Measuring the performance of fabric systems to protect against the thermal effects of electric arc. New Textiles. Retrieved March 16 from http://www.technica.net/NT/ewelcome.html

Lee, Y.M. & Barker, R.L. (1986). Effect of moisture on the thermal protective performance of heat-resistant fabrics. Journal of Fire Sciences, 4, 315-331.

Lee, Y.M. & Barker, R.L. (1987). Thermal protective performance of heat-resistant fabrics in various high intensity heat exposures. Textile Research Journal, 123-132.

Li, Y. & Lu, Z. (1999). An improved mathematical simulation of the coupled diffusion of moisture and heat in wool fabric. Textile Research Journal, 69(10), 760-768.

Makinen, H., Smolander, J., & Vuorinen, H. (1988). Simulation of the effect of moisture content in underwear and on the skin surface on steam burns of fire fighters. S.Z. Mansdorf, R. Sager, & A.P. Nielsen, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 989. Philadelphia, PA: American Society for Testing and Materials, 415-421.

Mell, W.E. & Lawson, J.R. (2000). A heat transfer model for firefighters' protective clothing. Fire Technology, 36(1), 39-68.

NFPA (1986). NFPA 1971 Standard on Protective Clothing for Structural Firefighting. Quincy, MA: National Fire Protection Association, Inc.

NFPA (1997). NFPA 1971 Standard on Protective Clothing for Structural Firefighting. Quincy, MA: National Fire Protection Association, Inc.

NFPA (1983). NFPA 1973 Gloves for Structural Fire Fighting Quincy, MA: National Fire Protection Association, Inc.

NFPA (1997). NFPA 1977 Standard on Protective Clothing for Structural Firefighting: Standard on Protective Clothing for Proximity Fire Fighting. Quincy, MA: National Fire Protection Association, Inc.

Nordon, P. & David, H. (1967). Coupled diffusion of moisture and heat in hygroscopic textile materials. International Journal of Heat and Mass Transfer, 10, 853-866.

Parsons, K.C. (1994). Heat transfer through human body and clothing systems. M. Raheel & M. Dekker, (Eds.), Protective Clothing Systems and Materials. New

York, NY: , 137-171.

Rossi, R.M. & Zimmerli, T. (1996). Influence of humidity on the radiant, convective, and contact heat transmission through protective clothing materials. J.S. Johnson & S.Z. Mansdorf, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 1237. PA: American Society for Testing and Materials, 269-280.

Sari, H. & Berger, X. (2000). A new dynamic clothing model, Part 2: Parameters of the underclothing microclimate. International Journal of Thermal Science, 39, 684-692.

Satsumoto, Y., Ishikawa, K, & Takeeuchi, M. (1997). Evaluating quasi-clothing heat transfer: A comparison of the vertical hot plate and the thermal manikin. Textile Research Journal, 67(7), 503-510.

Schneider, A, Hoschke, B. & Goldsmid, H. (1992). Heat transfer through moist fabrics. Textile Research Journal, 62(2), 61-66.

Shivers, J. (1980). Physical measures of clothing comfort: A literature review. Canadian Home Economics Journal, 30, 241-244.

Stoll, A.M. & Chianta, M.A. (1969). Method and rating system for evaluation of thermal protection. Aerospace Medicine, 1232-1238.

Stull, J.O. (2000a). Comparative thermal insulative performance of reinforced knee areas of firefighter protective clothing. C. Nelson & N. Henry, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386. West Conshohocken, PA: American Society for Testing and Materials, 312-328.

Stull, J.O. (2000b). The effect of moisture on firefighter protective clothing thermal insulation: a review of industry research. C. Nelson & N. Henry, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386. West Conshohocken, PA: American Society for Testing and Materials, 557-576.

Stull, J.O. (2000c). Special radiant testing of Hydroweave™ material to determine potential for steam release. Prepared for S. Bumbarger at AquaTex Industries, Huntsville, AL. Retrieved March 14, 2002 from http://www.hydroweave.com/study-stull1.pdf

Sun, G., Yoo, H., Zhang, X., & Pan, N. (2000). Radiative protective and transport properties of fabrics used by wildland firefighters. Textiles Research Journal, 70(7), 567-573.

Tan, Y., Crown, E.M., & Capjack, L. (1998). Design and evaluation of thermal protective flightsuits, Part I: The design process and prototype development. Clothing and Textiles Research Journal, 16(1), 1-9.

Tien, C. & Chen, G. (1992). Challenges in microscale radiative and conductive heat transfer. Y. Bayazitoglu & G. Peterson, (Eds.), Fundamental Issues in Small Scale Heat Transfer. New York, NY: The American Society of Mechanical Engineers, 1-12.

Torvi, D.A. & Dale, J.D. (1998). Effects of variations in thermal properties on the performance of flame resistant fabrics for flash fires. Textile Research Journal 68(11), 787-796.

Torvi, D.A., Dale, J.D., Ackerman, M.Y., & Crown, E.M. (1997). A study of new and existing bench top tests for evaluating fabrics for flash fire protective clothing. J.O. Stull & A.D. Schwope, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1273. West Conshohocken, PA: American Society for Testing and Materials, 108-125.

Torvi, D.A. & Hadjisophocleous, G.V. (1999). Research in protective clothing for firefighters: State of the art and future directions. Fire Technology, 35(2), 111-130.

Umeno, T., Hokoi, S., & Takada, S. (2001). Prediction of skin and clothing temperatures under thermal transient considering moisture accumulation in clothing. ASHRAE Transactions, 107(1), 1-10.

Veghte, J.H. (1986). Functional integration of fire fighters' protective clothing. R.L. Barker & G.C. Coletta, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 900. Philadelphia, PA: American Society for Testing and Materials, 487-496.

Veghte, J. (1987). Effect of moisture on the burn potential in fire fighter's gloves. Fire

Technology, 23(4), 313-322.

Wang, J.H. & Yasuda, H. (1991). Dynamic water vapour and heat transport through layered fabrics, part I: Effects of surface modification. Textile Research Journal, 10-20.

Watkins, S.M. (1984). Clothing: The Portable Environment. Ames: Iowa State University Press.

Weder, M.S., Zimmerli, T., & Rossi, R.M. (1996). A sweating and moving arm for the measurement of thermal insulation and water vapour resistance of clothing. J.S. Johnson & S.Z. Mansdorf, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century, ASTM STP 1237. PA: American Society for Testing and Materials, 257-268.

Woo, S. Shalev, I., & Barker, R. (1994). Heat and moisture transfer through nonwoven fabrics part II: Moisture diffusivity. Textile Research Journal, 64(4), 190-197.

Xin-Gui, L. & Mei-Rong, H. (1999). Thermal degradation of Kevlar fiber by high-resolution thermogravimetry. Journal of Applied Polymer Science, 71, 565-571.

Yamada, J., Kurosaki, Y., & Take-Uchi, M. (1992). Radiation transfer in a fibrous medium with fiber orientations. S. Thynell, M. Modest, L. Burmeister, M. Hunt, T. Tong, R. Skocypes, W. Yuen, & W. Fiveland, (Eds.), Developments in Radiative Heat Transfer. New York, NY: The American Society of Mechanical Engineers, 63-70.

Yasuda, T., Miyama, M., & Muramoto, A. (1994). Dynamic water vapor and heat transport through layered fabrics part III: Surface temperature change. Textile Research Journal, 64(8), 457-461.

Yoo, H., Hu, Y.S., & Kim, E.A. (2000). Effects of heat and moisture transport in fabrics and garments determined with a vertical plate sweating skin model. Textile Research Journal, 70(6), 542-549.

Yoo, H., Sun, G. & Pan, N. (2000). Thermal protective performance and comfort of wildland firefighter clothing: The transport properties of multilayer fabric systems. C. Nelson & N. Henry, (Eds.), Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386. West Conshohocken, PA: American Society for Testing and Materials, 504-518.

Appendix A

Thermal Protective Clothing Focus Group Moderator Guide

Thermal Protective Clothing Focus Group Moderator Guide

Introduction:

Hello everyone. Thank you for taking the time to participate in this group discussion. My name is Lelia Kotowich, and I am a graduate student from the University of Alberta. My main area of interest is in thermal protective clothing, and I basically want to gain a better understanding of how this clothing is used in your occupation as wildland firefighters. I encourage all of you to share your opinions on the topics discussed even if your opinion differs from others in the room.

I want to mention that our discussion will be recorded to ensure that none of your comments are missed. I also want to mention that all of you are assured complete confidentiality. We will be on a first name basis only, and your names will not be included in any later reports. Once again, I encourage all of you to share your opinions, regardless if they are negative or positive. Both negative and positive comments are quite useful. This session will last about an hour and a half, and we will have a short break at about the one-hour mark. Do any of you have any questions before we begin?...

To start things off, lets all introduce ourselves – mention your name and position....

Warm-up:

Now that we are all acquainted, I would like to point out the pencil and piece of paper in front of each of you. When I ask a question, I'll give you some time to quickly jot down some responses, and then each of us will share our comments.

Question 1: *What types of protective clothing do you wear while you are fighting a fire? What are your coveralls/protective garments made from – Nomex®, cotton, Kevlar®/PBI®?*

Question 2: *Who provides your protective coveralls – your employer or yourself?*

Question 3: Personal opinion questions –

> *How would you rate the comfort level of your protective coveralls?*
> *Protection?*
> *Dislikes/likes of the clothing in general? design?*
> *What concerns would you like to bring up with the purchaser of your garments?*

Question 4: *What do you wear under your protective coveralls?*

(If a unique response is given, ask: *Why do you wear that?*)

Question 5: *Do you wear your coveralls buttoned all the way to the collar when you are fighting a fire? Why/Why not?*
Do you tuck your leg cuffs into your boots or socks? wrist cuffs into your gloves?
If there are snap/Velcro closures on your wrist and leg cuffs, do you wear them on the tightest setting?

Question 6: When you are out fighting a fire, how dirty do your coveralls get? Are your coveralls cleaned after every time you go out to fight a fire? How are your coveralls cleaned?

Details Section:

Question 7: When you are out fighting a grass fire, what concerns or issues do you have? When you are out fighting a bush/forest fire, what concerns or issues do you have?

Probing questions:

Injury? Burns?
Heat Stress? Perspiration?
Fatigue?
Spray from water hoses?

Why do you have these concerns or issues?

Probing questions:

Do you feel that your clothing performs poorly? If yes, how?
-in terms of heat stress? too warm to wear? perspiration levels are high?
-in terms of thermal protection?

Key Content Section

In your responses, some of you/none of you mentioned perspiration as being a concern or issue in terms of heat stress.

Question 8: How long do you normally wear your protective clothing before being soaked with perspiration? When you are fighting a fire, do you instantly perspire more when you come in contact with a high heat source, or is your level of perspiration consistent during your work?

(If the participants wear more than one type of protective coverall, i.e., FR cotton and Nomex®, ask them which coverall they perspire less in).

Question 9: While fighting a fire, have any of you experienced burns? If yes, where? What specifically were you doing at the moment you were burned?

Question 10: Are you aware that perspiration, along with water from hoses, rain, or high humidity, increases your risk of experiencing a steam burn? Of those that experienced a burn injury, is it possible that the burn injury was a result of steam? If yes, was the steam a result of perspiration or from water from other sources, such as water hoses, or both perspiration and external water?

Have any of you been exposed to a high heat source, such as direct flames, a burning log, smoldering underbrush etc., and not experienced a burn? If yes, can *you describe what you were wearing and doing at the time? Were you perspiring, or were you wet from any other source?*

Question 11: Do any of you have suggestions in terms of clothing design to reduce the risk of steam burns? If yes, what are they?

Probing questions:

Water repellant knee/elbow patches?
Moisture barrier liners?
Underwear suggestions?

Summary:

As some of you may have concluded from the last few questions, my research topic involves studying how moisture affects the rate of heat transfer through a thermal protective clothing system. We already know that steam burns are one of the leading causes of injury for wildland firefighters, but we have to understand the interaction between heat and moisture in order to reduce the risk of experiencing steam burns.

Do any of you have any further comments or suggestions?....

Thank you everyone for participating in this discussion. If you have any further comments, feel free to contact me at the University. I'll give each of you a card with my name and phone number.

Appendix B

Summary of Focus Group Participant Responses

Participant Responses

Question 1: What types of protective clothing do you wear while you are fighting a fire? What are your coveralls/protective garments made from – Nomex®, cotton, Kevlar®/PBI®?

All wear Nomex® aramid coveralls. One individual has worn 2-piece garments in previous work.

Question 2: Who provides your protective coveralls – your employer or yourself?

Coveralls are provided by their employer.

Question 3: Personal opinion questions –
Dislikes/likes of the clothing in general? design?

Likes of Clothing/Design	Dislikes of Clothing/Design
-breathable (1) -flame resistance increases confidence (2) -bright colour of the clothing (2) -Velcro straps (4) -generic fit (1) -easily identifiable due to colour and style (1) -none (2) -durable stitching (1) -visibility strips (1)	-restricitve (1) -not properly sized/sizing difficulties (2) -sizing problems lead to hindrance in movement (3) -bathroom difficulties (2) -no cargo pockets (2) -too hot with undergarments (4) -movement restriction when wet (2) -not enough shoulder room -colour (yellow) makes them look like a "bunch of bananas"

Comfort Level (rated from 1-5 with 1 being the lowest comfort):

2/5- if extra layers are worn underneath coveralls, the coveralls are too tight
2/5
1/5- mobility restricted when wearing undergarments; too hot
0/5- two-piece is more comfortable
0/5- too tight around shoulders; hard to move
2/5- can not wear thick undergarments
2.5/5- they do meet basic requirements, but the comfort could be improved

Protection Level (rated from 1-5 with 1 being the lowest protection):

4/5- meets safety requirements
4/5- "feels safe"
2.5/5- too wet underneath – potential for steam burns
2.5/5-potential for steam burns; too hot; dehydration a concern; heat stress
2/5- sweating a problem – potential for steam burns

4/5- "feels safe" because they are made from Nomex®
3/5- adequate to meet minimum requirements, but…
Extra comments:
-coverall is a 1-piece garment – if damaged, the whole garment is damaged
-mobility is reduced with extra clothing underneath when in an intense situation

What concerns would you like to bring up with the purchaser of your garments?

-All would like to have a 2-piece rather than a 1-piece garment.

Changes or additions to the clothing:
-cargo pockets (5)
-slash pockets with snaps or other type of closure (2)
-more room in the shoulders (3)
-not as baggy in the crotch (1)
-custom-sized (3)
-tailored (2)
-reinforced elbows and knees – durability and extra protection from heat and sticks
-reinforced front of leg
-Velcro adjusters for sizing since elastics in the back of the coveralls wear out

Question 4: What do you wear under your protective coveralls?

-cotton pants
-T-shirt
-shorts
-sweatshirt
-shorts/no shirt
-sleeveless T-shirt and shorts/pants
-"when it's hot outside, as little as possible"
-thinnest T-shirt as possible/shorts
-no heavy garments – they get too heavy when wet
-poly/cotton shirt

Question 5: Do you wear your coveralls buttoned all the way to the collar when you are fighting a fire? Why/Why not?

Yes	No
-when it's cold outside -if working near a fire in order to keep the ash/heat out	-too hot -too hot – will even roll up sleeves to try to cool off

Do you tuck your leg cuffs into your boots or socks?

None of them do. They Velcro the pants tight on the outside of the boots. Some even use duct tape to tape their cuffs to their boots in order to keep out ash and embers.

wrist cuffs into your gloves?

-Gloves are too short to do this – fitted gloves would work better
-Some actually roll their sleeves up

If there are snap/Velcro closures on your wrist and leg cuffs, do you wear them on the tightest setting?

All of them normally use the Velcro closures, but not on their tightest setting – too restrictive.
-Duct tape cuffs to keep out bugs and leeches; keeps ash from going up the legs

Question 6: When you are out fighting a fire, how dirty do your coveralls get?

Filthy

Are your coveralls cleaned after every time you go out to fight a fire?

No – cleaning them depends on how dirty they are. Some go for months before laundering.
Swamp water cleans them, so they do not clean them often.

How are your coveralls cleaned?

-combination of drycleaning and home laundering

Question 7: When you are out fighting a bush/forest fire, what concerns or issues do you have?

-that you do not get burned
-heat/comfort (exhaustion)
-heat stress
-water from swamps – weighs down garments

When you are out fighting a grass fire, what concerns or issues do you have?

-Less worried than when fighting a forest fire even though a grass fire is faster
-depends on the intensity of the grass fire
-protection of legs since the fire is wind-driven – fire is close to the ground
-fabric does not ignite as easily
-always wet – cotton undergarments absorb and hold moisture

For both forest and grass fires:
-Burns
-Heat Stress and Perspiration
-Fatigue
-Spray from water hoses – mist cools them down

Do you feel that your clothing performs poorly?

-when wet - heat stress
- if cold outside – hypothermia; clothing does not dry

Question 8: How long do you normally wear your protective clothing before being soaked with perspiration?

-even just walking in the morning, perspiration will immediately soak garments
-become soaked just waiting for a fire

When you are fighting a fire, do you instantly perspire more when you come in contact with a high heat source, or is your level of perspiration consistent during your work?

All replied "yes".
-extra activity also leads to increased perspiration and heat stress

Question 9: While fighting a fire, have any of you experienced burns? If yes, where?

All replied "yes":
-embers that get inside the garments
-fingers
-knees, elbows, face
-sunburn-type of burn

What specifically were you doing at the moment you were burned?

-kneeling
-checking ground temperature
-(no serious burns were experienced)

Question 10: Are you aware that perspiration, along with water from hoses, rain, or high humidity, increases your risk of experiencing a steam burn?

All replied "yes".

Of those that experienced a burn injury, is it possible that the burn injury was a result of steam?

No serious burns were received. "Perspiration acts as a temperature gauge" – if you are cool, you move closer to the fire, if you are hot, you move away from the fire.

If yes, was the steam a result of perspiration or from water from other sources, such as water hoses, or both perspiration and external water?

Moisture holds the heat – it does not cool off quickly.

Have any of you been exposed to a high heat source, such as direct flames, a burning log, smoldering underbrush etc., and not experienced a burn?

All responded "yes".
-sparks, ash, smoldering chunks in the air, embers

If yes, can you describe what you were wearing and doing at the time?

-kneeling, ...

Were you perspiring, or were you wet from any other source?

All responded "yes".

Question 11: Do any of you have suggestions in terms of clothing design to reduce the risk of steam burns? If yes, what are they?

-vents in shoulders/underarms
-possible moisture barrier liners in knee region

Final Comments:
-If there is air movement, steam burns are less likely to happen.
-Stay hot longer if wet.

Appendix C

Three-Way ANOVAs, Descriptives, and Homogeneity Tests for Flame Exposure (FE)

Three-Way ANOVAs for FE

Heat Flux

Tests of Between-Subjects Effects

Dependent Variable: Peak Heat Flux (kW/m sq.)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	98944.076[a]	59	1677.018	120.360	.000
Intercept	275577.248	1	275577.248	19778.205	.000
FABRIC	26866.499	3	8955.500	642.737	.000
CONDITIO	55765.213	4	13941.303	1000.569	.000
REP	109.605	2	54.802	3.933	.021
FABRIC * CONDITIO	15563.603	12	1296.967	93.083	.000
FABRIC * REP	55.120	6	9.187	.659	.683
CONDITIO * REP	279.290	8	34.911	2.506	.012
FABRIC * CONDITIO * REP	304.746	24	12.698	.911	.587
Error	3344.011	240	13.933		
Total	377865.335	300			
Corrected Total	102288.087	299			

a. R Squared = .967 (Adjusted R Squared = .959)

Tests of Between-Subjects Effects

Dependent Variable: Time at Peak Heat Flux (sec.)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1464.080[a]	59	24.815	40.981	.000
Intercept	17999.070	1	17999.070	29724.850	.000
FABRIC	448.874	3	149.625	247.100	.000
CONDITIO	317.797	4	79.449	131.208	.000
REP	8.532	2	4.266	7.045	.001
FABRIC * CONDITIO	646.725	12	53.894	89.004	.000
FABRIC * REP	7.767	6	1.294	2.138	.050
CONDITIO * REP	11.471	8	1.434	2.368	.018
FABRIC * CONDITIO * REP	22.913	24	.955	1.577	.047
Error	145.325	240	.606		
Total	19608.476	300			
Corrected Total	1609.405	299			

a. R Squared = .910 (Adjusted R Squared = .888)

Transferred Energy

Tests of Between-Subjects Effects

Dependent Variable: Total Energy (kJ)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.252[a]	59	2.123E-02	143.277	.000
Intercept	27.298	1	27.298	184254.8	.000
FABRIC	3.808E-02	3	1.269E-02	85.671	.000
CONDITIO	1.118	4	.280	1886.761	.000
REP	1.177E-03	2	5.887E-04	3.974	.020
FABRIC * CONDITIO	6.816E-02	12	5.680E-03	38.338	.000
FABRIC * REP	5.608E-03	6	9.347E-04	6.309	.000
CONDITIO * REP	1.049E-02	8	1.311E-03	8.852	.000
FABRIC * CONDITIO * REP	1.075E-02	24	4.481E-04	3.025	.000
Error	3.556E-02	240	1.482E-04		
Total	28.586	300			
Corrected Total	1.288	299			

a. R Squared = .972 (Adjusted R Squared = .966)

Tests of Between-Subjects Effects

Dependent Variable: Time @ 0.1 kJ

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1375.218[a]	59	23.309	255.632	.000
Intercept	19522.301	1	19522.301	214104.5	.000
FABRIC	223.500	3	74.500	817.056	.000
CONDITIO	929.506	4	232.376	2548.514	.000
REP	3.381	2	1.690	18.538	.000
FABRIC * CONDITIO	194.529	12	16.211	177.787	.000
FABRIC * REP	.839	6	.140	1.533	.168
CONDITIO * REP	19.121	8	2.390	26.213	.000
FABRIC * CONDITIO * REP	4.342	24	.181	1.984	.005
Error	21.883	240	9.118E-02		
Total	20919.403	300			
Corrected Total	1397.102	299			

a. R Squared = .984 (Adjusted R Squared = .980)

Descriptives and Homogeneity Tests for FE

Indura®/Cotton

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	47.2840	6.04334	1.56038	43.9373	50.6307	39.89	57.63
	Cond/Cond	15	49.3293	6.33167	1.63483	45.8230	52.8357	40.11	62.70
	Wet/Cond	15	14.5500	1.32095	.34107	13.8185	15.2815	13.07	17.09
	Cond/Wet	15	57.6900	7.52242	1.94228	53.5242	61.8558	49.82	72.49
	Wet/Wet	15	14.9653	.99024	.25568	14.4170	15.5137	13.70	17.12
	Total	75	36.7637	19.11184	2.20685	32.3665	41.1610	13.07	72.49
Time at Peak Heat Flux (sec.)	Dry/Dry	15	4.0540	.36816	.09506	3.8501	4.2579	3.46	4.72
	Cond/Cond	15	5.3720	.28201	.07282	5.2158	5.5282	4.67	5.61
	Wet/Cond	15	9.3107	1.27839	.33008	8.6027	10.0186	7.69	11.59
	Cond/Wet	15	5.2560	.36455	.09413	5.0541	5.4579	4.67	5.99
	Wet/Wet	15	9.4253	1.08421	.27994	8.8249	10.0257	8.13	11.59
	Total	75	6.6836	2.38402	.27528	6.1351	7.2321	3.46	11.59
Total Energy (kJ)	Dry/Dry	15	.3549	.01239	.00320	.3481	.3618	.34	.37
	Cond/Cond	15	.3491	.01038	.00268	.3434	.3549	.32	.36
	Wet/Cond	15	.2372	.02396	.00619	.2239	.2505	.20	.27
	Cond/Wet	15	.2996	.01110	.00286	.2935	.3057	.27	.31
	Wet/Wet	15	.2390	.01334	.00344	.2316	.2464	.22	.27
	Total	75	.2960	.05342	.00617	.2837	.3083	.20	.37
Time @ 0.1 kJ	Dry/Dry	15	5.0713	.27931	.07212	4.9167	5.2260	4.72	5.82
	Cond/Cond	15	5.6360	.15642	.04039	5.5494	5.7226	5.54	6.04
	Wet/Cond	15	9.6820	.56240	.14521	9.3706	9.9934	9.00	10.71
	Cond/Wet	15	5.8753	.17200	.04441	5.7801	5.9706	5.55	6.04
	Wet/Wet	15	10.8300	.48061	.12409	10.5638	11.0962	10.00	12.03
	Total	75	7.4189	2.40201	.27736	6.8663	7.9716	4.72	12.03

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	11.489	4	70	.000
Time at Peak Heat Flux (sec.)	11.965	4	70	.000
Total Energy (kJ)	3.973	4	70	.006
Time @ 0.1 kJ	7.793	4	70	.000

*Peak Heat Flux, Time At Peak Heat Flux, Total Energy, and Time at 0.1 kJ results all have unequal variances.

Indura®/Nomex®

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	59.3525	6.71744	1.73444	55.6325	63.0725	49.27	69.00
	Cond/Cond	15	59.1807	8.00267	2.06628	54.7489	63.6124	46.11	70.22
	Wet/Cond	15	15.1823	1.51970	.39239	14.3408	16.0239	12.28	17.58
	Cond/Wet	15	59.5533	4.78396	1.23521	56.9041	62.2026	51.10	65.89
	Wet/Wet	15	15.8273	.99627	.25724	15.2756	16.3791	14.11	17.60
	Total	75	41.8192	22.21563	2.56524	36.7079	46.9306	12.28	70.22
Time at Peak Heat Flux (sec.)	Dry/Dry	15	3.8700	.48165	.12436	3.6033	4.1367	3.40	4.72
	Cond/Cond	15	5.0413	.45637	.11783	4.7886	5.2941	4.28	6.04
	Wet/Cond	15	8.7767	.49338	.12739	8.5034	9.0499	7.68	9.45
	Cond/Wet	15	5.1753	.30213	.07801	5.0080	5.3426	4.72	5.62
	Wet/Wet	15	8.9973	.64152	.16564	8.6421	9.3526	7.70	10.27
	Total	75	6.3721	2.17067	.25065	5.8727	6.8716	3.40	10.27
Total Energy (kJ)	Dry/Dry	15	.4265	.01689	.00436	.4172	.4359	.39	.46
	Cond/Cond	15	.4046	.01335	.00345	.3972	.4120	.38	.43
	Wet/Cond	15	.2284	.01853	.00479	.2181	.2387	.20	.25
	Cond/Wet	15	.3133	.01443	.00373	.3053	.3213	.29	.33
	Wet/Wet	15	.2323	.01278	.00330	.2253	.2394	.21	.25
	Total	75	.3210	.08509	.00983	.3014	.3406	.20	.46
Time @ 0.1 kJ	Dry/Dry	15	4.5227	.22183	.05728	4.3998	4.6455	4.18	4.73
	Cond/Cond	15	5.2173	.15402	.03977	5.1320	5.3026	5.11	5.60
	Wet/Cond	15	9.5313	.56071	.14478	9.2208	9.8418	8.63	10.44
	Cond/Wet	15	5.3760	.21343	.05511	5.2578	5.4942	5.11	5.61
	Wet/Wet	15	10.4173	.55066	.14218	10.1124	10.7223	9.45	11.53
	Total	75	7.0129	2.49558	.28817	6.4388	7.5871	4.18	11.53

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	15.066	4	70	.000
Time at Peak Heat Flux (sec.)	2.706	4	70	.037
Total Energy (kJ)	.821	4	70	.516
Time @ 0.1 kJ	10.085	4	70	.000

*Peak Heat Flux, Time At Peak Heat Flux, and Time at 0.1 kJ results all have unequal variances.

Nomex®/Cotton

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	35.7393	2.18959	.56535	34.5268	36.9519	32.65	39.83
	Cond/Cond	15	35.5380	1.45727	.37627	34.7310	36.3450	33.23	38.28
	Wet/Cond	15	10.8993	.78788	.20343	10.4630	11.3356	9.82	12.17
	Cond/Wet	15	28.1860	1.87238	.48345	27.1491	29.2229	24.06	30.18
	Wet/Wet	15	13.0880	.81125	.20946	12.6387	13.5373	12.20	14.55
	Total	75	24.6901	10.91460	1.26031	22.1789	27.2014	9.82	39.83
Time at Peak Heat Flux (sec.)	Dry/Dry	15	8.9760	.93156	.24053	8.4601	9.4919	7.69	10.77
	Cond/Cond	15	9.5307	.69369	.17911	9.1465	9.9148	8.57	10.66
	Wet/Cond	15	7.2260	1.34075	.34618	6.4835	7.9685	5.10	9.83
	Cond/Wet	15	9.1880	.89669	.23153	8.6914	9.6846	7.69	10.65
	Wet/Wet	15	10.1027	1.44673	.37354	9.3015	10.9038	6.75	11.97
	Total	75	9.0047	1.44642	.16702	8.6719	9.3375	5.10	11.97
Total Energy (kJ)	Dry/Dry	15	.3713	.01746	.00451	.3617	.3810	.35	.40
	Cond/Cond	15	.3411	.01955	.00505	.3302	.3519	.32	.37
	Wet/Cond	15	.2249	.01157	.00299	.2185	.2313	.21	.25
	Cond/Wet	15	.3129	.01379	.00356	.3053	.3206	.28	.33
	Wet/Wet	15	.2327	.01251	.00323	.2257	.2396	.22	.26
	Total	75	.2966	.06066	.00700	.2826	.3105	.21	.40
Time @ 0.1 kJ	Dry/Dry	15	7.7453	.32985	.08517	7.5627	7.9280	7.30	8.57
	Cond/Cond	15	8.3053	.25111	.06484	8.1663	8.4444	7.74	8.57
	Wet/Cond	15	10.1713	.66033	.17050	9.8057	10.5370	9.17	11.26
	Cond/Wet	15	7.4567	.22595	.05834	7.3315	7.5818	7.09	7.75
	Wet/Wet	15	10.7860	.33062	.08537	10.6029	10.9691	10.26	11.15
	Total	75	8.8929	1.39934	.16158	8.5710	9.2149	7.09	11.26

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	5.446	4	70	.001
Time at Peak Heat Flux (sec.)	1.844	4	70	.130
Total Energy (kJ)	2.339	4	70	.064
Time @ 0.1 kJ	10.028	4	70	.000

*Peak Heat Flux and Time at 0.1 kJ results have unequal variances.

Nomex®/Nomex®

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	18.1827	.79040	.20408	17.7450	18.6204	16.99	19.67
	Cond/Cond	15	17.1144	.51707	.13351	16.8281	17.4007	16.30	18.10
	Wet/Cond	15	11.4587	.97335	.25132	10.9196	11.9977	9.97	13.14
	Cond/Wet	15	29.4760	2.16321	.55854	28.2781	30.6739	23.99	33.36
	Wet/Wet	15	13.5680	1.68518	.43511	12.6348	14.5012	10.93	17.73
	Total	75	17.9599	6.42537	.74194	16.4816	19.4383	9.97	33.36
Time at Peak Heat Flux (sec.)	Dry/Dry	15	10.2200	.65568	.16930	9.8569	10.5831	9.39	11.15
	Cond/Cond	15	10.4353	.55651	.14369	10.1272	10.7435	9.40	11.15
	Wet/Cond	15	6.5100	.87134	.22498	6.0275	6.9925	5.10	7.69
	Cond/Wet	15	7.6013	.85330	.22032	7.1288	8.0739	5.55	9.39
	Wet/Wet	15	9.8467	1.17717	.30394	9.1948	10.4986	6.43	11.15
	Total	75	8.9227	1.78755	.20641	8.5114	9.3339	5.10	11.15
Total Energy (kJ)	Dry/Dry	15	.3615	.01157	.00299	.3551	.3679	.35	.39
	Cond/Cond	15	.3258	.01491	.00385	.3175	.3341	.29	.35
	Wet/Cond	15	.2322	.01785	.00461	.2223	.2421	.20	.26
	Cond/Wet	15	.3181	.01239	.00320	.3112	.3250	.29	.34
	Wet/Wet	15	.2275	.01520	.00393	.2191	.2360	.20	.25
	Total	75	.2930	.05582	.00645	.2802	.3059	.20	.39
Time @ 0.1 kJ	Dry/Dry	15	8.9873	.32940	.08505	8.8049	9.1698	8.57	9.44
	Cond/Cond	15	9.1480	.31308	.08084	8.9746	9.3214	8.56	9.45
	Wet/Cond	15	9.6847	.68442	.17672	9.3056	10.0637	8.57	10.71
	Cond/Wet	15	6.5707	.34891	.09009	6.3774	6.7639	6.32	7.69
	Wet/Wet	15	10.3227	.74836	.19322	9.9082	10.7371	9.44	12.41
	Total	75	8.9427	1.37976	.15932	8.6252	9.2601	6.32	12.41

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	4.047	4	70	.005
Time at Peak Heat Flux (sec.)	1.167	4	70	.333
Total Energy (kJ)	.693	4	70	.599
Time @ 0.1 kJ	3.673	4	70	.009

*Peak Heat Flux and Time at 0.1 kJ results have unequal variances.

Appendix D

Three-Way ANOVAs, Descriptives, and Homogeneity Tests for Radiant Exposure (RE)

Three-Way ANOVAs for RE

Heat Flux

Tests of Between-Subjects Effects

Dependent Variable: Peak Heat Flux (kW/m sq.)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	54.069[a]	59	.916	22.264	.000
Intercept	3233.361	1	3233.361	78553.996	.000
FABRIC	4.754	3	1.585	38.500	.000
CONDITIO	28.736	4	7.184	174.535	.000
REP	6.388	2	3.194	77.601	.000
FABRIC * CONDITIO	3.398	12	.283	6.878	.000
FABRIC * REP	1.705	6	.284	6.904	.000
CONDITIO * REP	5.523	8	.690	16.772	.000
FABRIC * CONDITIO * REP	3.565	24	.149	3.609	.000
Error	9.879	240	4.116E-02		
Total	3297.309	300			
Corrected Total	63.948	299			

a. R Squared = .846 (Adjusted R Squared = .808)

Tests of Between-Subjects Effects

Dependent Variable: Time at Peak Heat Flux (sec.)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	130734.845[a]	59	2215.845	52.295	.000
Intercept	496208.976	1	496208.976	11710.741	.000
FABRIC	3501.700	3	1167.233	27.547	.000
CONDITIO	116887.573	4	29221.893	689.649	.000
REP	1303.362	2	651.681	15.380	.000
FABRIC * CONDITIO	5144.921	12	428.743	10.119	.000
FABRIC * REP	561.036	6	93.506	2.207	.043
CONDITIO * REP	1046.131	8	130.766	3.086	.002
FABRIC * CONDITIO * REP	2290.121	24	95.422	2.252	.001
Error	10169.310	240	42.372		
Total	637113.131	300			
Corrected Total	140904.154	299			

a. R Squared = .928 (Adjusted R Squared = .910)

Transferred Energy

Tests of Between-Subjects Effects

Dependent Variable: Total Energy (kJ)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.189[a]	59	2.016E-02	128.925	.000
Intercept	27.414	1	27.414	175347.1	.000
FABRIC	4.797E-02	3	1.599E-02	102.271	.000
CONDITIO	1.004	4	.251	1604.855	.000
REP	4.437E-02	2	2.218E-02	141.896	.000
FABRIC * CONDITIO	5.613E-02	12	4.677E-03	29.916	.000
FABRIC * REP	4.082E-03	6	6.803E-04	4.352	.000
CONDITIO * REP	1.555E-02	8	1.943E-03	12.431	.000
FABRIC * CONDITIO * REP	1.751E-02	24	7.296E-04	4.667	.000
Error	3.752E-02	240	1.563E-04		
Total	28.641	300			
Corrected Total	1.227	299			

a. R Squared = .969 (Adjusted R Squared = .962)

Tests of Between-Subjects Effects

Dependent Variable: Time @ 0.1 kJ

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6801.124[a]	59	115.273	27.572	.000
Intercept	450299.041	1	450299.041	107705.4	.000
FABRIC	718.567	3	239.522	57.290	.000
CONDITIO	4108.167	4	1027.042	245.655	.000
REP	646.273	2	323.136	77.290	.000
FABRIC * CONDITIO	482.204	12	40.184	9.611	.000
FABRIC * REP	28.246	6	4.708	1.126	.348
CONDITIO * REP	354.726	8	44.341	10.606	.000
FABRIC * CONDITIO * REP	462.941	24	19.289	4.614	.000
Error	1003.401	240	4.181		
Total	458103.566	300			
Corrected Total	7804.525	299			

a. R Squared = .871 (Adjusted R Squared = .840)

Descriptives and Homogeneity Tests for RE

Indura®/Cotton

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	3.3393	.21329	.05507	3.2212	3.4574	2.96	3.87
	Cond/Cond	15	3.1347	.22828	.05894	3.0082	3.2611	2.69	3.48
	Wet/Cond	15	3.4107	.31773	.08204	3.2347	3.5866	2.91	3.92
	Cond/Wet	15	2.4860	.17908	.04624	2.3868	2.5852	2.16	2.75
	Wet/Wet	15	3.2307	.23218	.05995	3.1021	3.3592	2.82	3.61
	Total	75	3.1203	.40585	.04686	3.0269	3.2136	2.16	3.92
Time at Peak Heat Flux (sec.)	Dry/Dry	15	61.0767	9.80158	2.53076	55.6487	66.5046	43.62	79.37
	Cond/Cond	15	83.6433	5.43433	1.40314	80.6339	86.6528	78.32	96.18
	Wet/Cond	15	20.2300	2.77109	.71549	18.6954	21.7646	14.17	24.70
	Cond/Wet	15	31.6547	9.22886	2.38288	26.5439	36.7654	20.54	54.15
	Wet/Wet	15	28.2973	9.20083	2.37564	23.2021	33.3926	18.40	45.75
	Total	75	44.9804	25.08888	2.89701	39.2080	50.7528	14.17	96.18
Total Energy (kJ)	Dry/Dry	15	.3561	.01569	.00405	.3474	.3648	.32	.39
	Cond/Cond	15	.3131	.02406	.00621	.2997	.3264	.27	.35
	Wet/Cond	15	.2592	.01322	.00341	.2519	.2665	.24	.28
	Cond/Wet	15	.2393	.01559	.00402	.2306	.2479	.21	.27
	Wet/Wet	15	.2626	.01986	.00513	.2516	.2736	.22	.29
	Total	75	.2860	.04640	.00536	.2754	.2967	.21	.39
Time @ 0.1 kJ	Dry/Dry	15	41.8980	1.76527	.45579	40.9204	42.8756	39.43	45.75
	Cond/Cond	15	44.3387	4.19927	1.08425	42.0132	46.6641	38.40	52.07
	Wet/Cond	15	33.7660	1.77100	.45727	32.7853	34.7467	31.04	37.35
	Cond/Wet	15	45.7400	3.34975	.86490	43.8850	47.5950	40.48	51.02
	Wet/Wet	15	38.8060	2.74920	.70984	37.2835	40.3285	35.21	43.67
	Total	75	40.9097	5.15985	.59581	39.7226	42.0969	31.04	52.07

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	2.415	4	70	.057
Time at Peak Heat Flux (sec.)	3.984	4	70	.006
Total Energy (kJ)	1.920	4	70	.117
Time @ 0.1 kJ	3.437	4	70	.013

* Time At Peak Heat Flux and Time at 0.1 kJ results have unequal variances.

Indura®/Nomex®

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	3.4820	.16845	.04349	3.3887	3.5753	3.16	3.72
	Cond/Cond	15	3.1560	.15347	.03963	3.0710	3.2410	2.89	3.49
	Wet/Cond	15	3.6200	.42474	.10967	3.3848	3.8552	2.71	4.21
	Cond/Wet	15	2.6827	.14330	.03700	2.6033	2.7620	2.33	2.87
	Wet/Wet	15	3.3727	.31990	.08260	3.1955	3.5498	2.89	3.89
	Total	75	3.2627	.41926	.04841	3.1662	3.3591	2.33	4.21
Time at Peak Heat Flux (sec.)	Dry/Dry	15	55.6093	9.98626	2.57844	50.0791	61.1395	41.52	78.26
	Cond/Cond	15	80.4873	3.11541	.80440	78.7621	82.2126	74.09	86.73
	Wet/Cond	15	21.0733	2.34616	.60578	19.7741	22.3726	16.31	23.67
	Cond/Wet	15	29.2673	12.99314	3.35481	22.0720	36.4627	15.26	61.52
	Wet/Wet	15	25.2080	5.83390	1.50631	21.9773	28.4387	16.32	40.48
	Total	75	42.3291	24.01254	2.77273	36.8043	47.8539	15.26	86.73
Total Energy (kJ)	Dry/Dry	15	.3751	.01328	.00343	.3678	.3825	.35	.39
	Cond/Cond	15	.3282	.02290	.00591	.3155	.3409	.29	.36
	Wet/Cond	15	.2681	.01696	.00438	.2587	.2775	.24	.29
	Cond/Wet	15	.2442	.01398	.00361	.2365	.2519	.21	.26
	Wet/Wet	15	.2727	.01202	.00310	.2661	.2794	.25	.29
	Total	75	.2977	.05039	.00582	.2861	.3093	.21	.39
Time @ 0.1 kJ	Dry/Dry	15	39.9253	2.01187	.51946	38.8112	41.0395	37.35	43.61
	Cond/Cond	15	42.9347	2.82251	.72877	41.3716	44.4977	39.43	46.81
	Wet/Cond	15	31.8000	3.28737	.84880	29.9795	33.6205	27.85	38.39
	Cond/Wet	15	42.8127	2.93189	.75701	41.1890	44.4363	39.43	48.94
	Wet/Wet	15	37.2627	2.46521	.63651	35.8975	38.6279	34.16	41.53
	Total	75	38.9471	4.94660	.57118	37.8090	40.0852	27.85	48.94

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	9.059	4	70	.000
Time at Peak Heat Flux (sec.)	5.916	4	70	.000
Total Energy (kJ)	4.511	4	70	.003
Time @ 0.1 kJ	1.652	4	70	.171

*Peak Heat Flux, Time At Peak Heat Flux, and Total Energy results all have unequal variances.

Nomex®/Cotton

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	3.6987	.24295	.06273	3.5641	3.8332	3.28	4.02
	Cond/Cond	15	3.3780	.26695	.06893	3.2302	3.5258	3.01	3.81
	Wet/Cond	15	3.3700	.43797	.11308	3.1275	3.6125	2.52	3.85
	Cond/Wet	15	2.7493	.34121	.08810	2.5604	2.9383	2.07	3.29
	Wet/Wet	15	3.1793	.46021	.11883	2.9245	3.4342	2.50	3.82
	Total	75	3.2751	.47039	.05432	3.1668	3.3833	2.07	4.02
Time at Peak Heat Flux (sec.)	Dry/Dry	15	55.5540	3.75863	.97047	53.4725	57.6355	49.98	64.65
	Cond/Cond	15	67.7980	10.73866	2.77271	61.8511	73.7449	56.24	90.90
	Wet/Cond	15	22.2727	2.08692	.53884	21.1170	23.4284	17.36	24.72
	Cond/Wet	15	26.3920	7.35220	1.89833	22.3205	30.4635	18.40	39.44
	Wet/Wet	15	26.1120	8.46888	2.18665	21.4221	30.8019	18.40	47.84
	Total	75	39.6257	19.87396	2.29485	35.0531	44.1983	17.36	90.90
Total Energy (kJ)	Dry/Dry	15	.4108	.01350	.00349	.4033	.4183	.37	.43
	Cond/Cond	15	.3538	.02826	.00730	.3381	.3695	.29	.41
	Wet/Cond	15	.2541	.02146	.00554	.2422	.2660	.21	.27
	Cond/Wet	15	.2381	.02080	.00537	.2265	.2496	.19	.26
	Wet/Wet	15	.2655	.03096	.00799	.2484	.2827	.22	.30
	Total	75	.3045	.07097	.00820	.2881	.3208	.19	.43
Time @ 0.1 kJ	Dry/Dry	15	35.3180	1.20238	.31045	34.6521	35.9839	33.18	37.35
	Cond/Cond	15	42.5027	4.01083	1.03559	40.2815	44.7238	36.31	52.01
	Wet/Cond	15	33.6967	3.14784	.81277	31.9535	35.4399	29.98	40.48
	Cond/Wet	15	42.2333	1.84569	.47656	41.2112	43.2554	40.48	45.70
	Wet/Wet	15	39.0733	4.56325	1.17823	36.5463	41.6004	34.16	46.80
	Total	75	38.5648	4.75815	.54942	37.4701	39.6595	29.98	52.01

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	3.238	4	70	.017
Time at Peak Heat Flux (sec.)	6.986	4	70	.000
Total Energy (kJ)	3.980	4	70	.006
Time @ 0.1 kJ	6.293	4	70	.000

*Peak Heat Flux, Time At Peak Heat Flux, Total Energy, and Time at 0.1 kJ results all have unequal variances.

Nomex®/Nomex®

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Peak Heat Flux (kW/m sq.)	Dry/Dry	15	3.9413	.22045	.05692	3.8193	4.0634	3.42	4.33
	Cond/Cond	15	3.6187	.31353	.08095	3.4450	3.7923	3.03	4.06
	Wet/Cond	15	3.6033	.46136	.11912	3.3478	3.8588	2.81	4.41
	Cond/Wet	15	2.9553	.24698	.06377	2.8186	3.0921	2.49	3.48
	Wet/Wet	15	3.2507	.47125	.12168	2.9897	3.5116	2.51	4.01
	Total	75	3.4739	.48802	.05635	3.3616	3.5861	2.49	4.41
Time at Peak Heat Flux (sec.)	Dry/Dry	15	51.1320	7.94229	2.05069	46.7337	55.5303	36.25	62.56
	Cond/Cond	15	55.4673	6.28399	1.62252	51.9874	58.9473	44.66	66.79
	Wet/Cond	15	20.7280	2.94854	.76131	19.0952	22.3608	15.27	26.80
	Cond/Wet	15	27.3793	8.54789	2.20706	22.6457	32.1130	20.54	56.25
	Wet/Wet	15	24.0127	5.74860	1.48428	20.8292	27.1961	17.35	41.53
	Total	75	35.7439	15.99254	1.84666	32.0643	39.4234	15.27	66.79
Total Energy (kJ)	Dry/Dry	15	.4375	.01489	.00384	.4292	.4457	.42	.47
	Cond/Cond	15	.3816	.03246	.00838	.3636	.3996	.31	.42
	Wet/Cond	15	.2678	.02268	.00586	.2552	.2804	.22	.29
	Cond/Wet	15	.2464	.01887	.00487	.2360	.2568	.21	.27
	Wet/Wet	15	.2717	.02362	.00610	.2586	.2847	.23	.30
	Total	75	.3210	.07874	.00909	.3029	.3391	.21	.47
Time @ 0.1 kJ	Dry/Dry	15	32.9273	1.77890	.45931	31.9422	33.9125	29.99	35.21
	Cond/Cond	15	39.9240	3.28535	.84827	38.1046	41.7434	36.31	48.88
	Wet/Cond	15	32.1520	2.70561	.69858	30.6537	33.6503	28.95	39.43
	Cond/Wet	15	41.1833	3.60107	.92979	39.1891	43.1775	36.25	49.99
	Wet/Wet	15	36.5593	3.48990	.90109	34.6267	38.4920	32.08	42.57
	Total	75	36.5492	4.69290	.54189	35.4695	37.6289	28.95	49.99

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Peak Heat Flux (kW/m sq.)	3.468	4	70	.012
Time at Peak Heat Flux (sec.)	1.728	4	70	.154
Total Energy (kJ)	3.145	4	70	.019
Time @ 0.1 kJ	1.824	4	70	.134

*Peak Heat Flux and Total Energy results have unequal variances.