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Moisture Effects in Heat Transfer Through Clothing Systems for Wildland Firefighters

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Wildland firefighters work in unfavourable environments involving both heat and moisture. Moisture in clothing systems worn by wildland firefighters may increase or decrease heat transfer, depending on its source and location in the clothing system, location on the body, timing of application and degree of sorption. In this experiment, 4 outerwear/underwear combinations were exposed to 1 of 5 different conditions varying on amount and location of moisture. The fabric systems were then exposed to either a high-heat-flux flame exposure (83 kW/m^2) or a low-heat-flux radiant exposure (10 kW/m^2).

Under high-heat-flux flame exposures, external moisture tended to decrease heat transfer through the fabric systems, while internal moisture tended to increase heat transfer. Under low-heat-flux radiant exposures, internal moisture decreased heat transfer through the fabric systems. The nature and extent of such differences was fabric dependent. Implications for test protocol development are discussed.

heat transfer moisture clothing systems

1. INTRODUCTION

The purpose of this research was to examine the effects of moisture on heat transfer through materials comprising clothing systems worn by wildland firefighters, with particular attention given to source and location of moisture in the system. Concern for individuals working in high-risk environments, especially those with the potential of high heat exposures, has risen in recent years. The ultimate goal is to reduce severe burn injury experienced by individuals in this and similar occupations by gaining a better understanding of the mechanisms underlying heat transfer when moisture is a factor.

Extensive research has been conducted to better understand heat transfer mechanisms and to improve protective clothing design and performance, leading to a decrease in thermal injuries experienced by individuals in high-risk environments. However, Stull [1] and Mäkinen et al. [2] reported that even when wearing improved garments, a substantial number of burn injuries occur.

The performance of thermal protective clothing systems is affected by many variables including environmental conditions (temperature, humidity, wind speed, etc.), the nature of the textile used (weave structure, fiber mass and thickness, fiber type, etc.), the mechanisms of heat transfer (convection,

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conduction, thermal radiation), and the presence of moisture. Moisture in a clothing system can originate from internal or external sources. For wildland firefighters, internal moisture normally comprises perspiration produced by the wearer, while external moisture consists of rain or dew, water spray from hoses, and/or swamp or lake water through which the firefighter must walk. The effect of moisture on heat transfer through a clothing system may depend on the degree of moisture sorption, location of moisture in the system, where it is located on the body, its source (internal or external), the timing of moisture 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 21–35 °C have been evaluated during comfort assessment by several authors [3, 4, 5, 6, 7, and others]. Evaluation of comfort and heat stress has accounted for moisture absorption into, and transport through, clothing systems in interaction with environmental conditions. Some mechanisms outlined in comfort theory can apply to moisture-heat interaction at high heat fluxes, but due to significantly higher exposure temperatures, different mechanisms also occur. Understanding mechanisms by which moisture in textiles affects heat transfer through clothing systems at higher temperatures could lead to improvements in design of thermal protective clothing.

At higher heat fluxes and using common measures of heat transfer such as the heat transfer index, thermal protective performance (TPP) and radiative protective performance (RPP), several authors [1, 8, 9, 10, 11, 12, 13] have found that moisture in a clothing system may either increase or decrease thermal insulation. The effects of both internal and external moisture on heat transfer from convective and radiant sources through two-layered protective clothing systems have not been studied, however; nor has the effect of moisture applied during or after heat exposure. In this paper, the effects of both internal and external moisture on the heat transfer through specimens simulating clothing systems typically worn by wildland firefighters will be discussed.

2. METHODS

This study comprised an experiment in which fabric systems were exposed to both a flame heat source and a purely radiant heat source under five different moisture treatments. Heat flux and transferred energy were plotted against time during and after exposure.

2.1. Materials

Four fabric systems typical of those worn by wildland firefighters and comprising combinations of two different thermal protective outerwear materials and two different underwear materials were evaluated. The two outerwear fabrics were a plain weave fire resistant (FR) cotton (337.5 g/m^2) and a plain weave aramid (211.5 g/m^2). The two underwear fabrics were a 100% cotton jersey knit (176.5 g/m^2) and an aramid rib knit (164.0 g/m^2).

2.2. Moisture Application

The five moisture treatments were as follows:

1. Both layers oven-dried at 105°C for 1 hr and placed in a desiccator for a maximum of 4 hrs prior to testing. Specimens were tested within 40 s of removal from the desiccator;
2. Both layers conditioned in a standard atmosphere (65% RH, 21°C) for at least 8 hrs prior to testing to allow specimens to reach moisture equilibrium according to

CAN/CGSB-4.2 No.2-M88 [14]. Specimens were placed in a sealed plastic bag to prevent moisture loss when removed from the standard atmosphere and were tested within 40 s of removal from the plastic bag;
3. Outer layer saturated and inner layer conditioned in the standard atmosphere;
4. Underwear layer saturated and outer layer conditioned in the standard atmosphere; and
5. Both outer and underwear layer saturated.

For conditions 3 to 5, specimens were conditioned in the standard atmosphere for 24 hrs prior to moisture application and testing. Appropriate layers were saturated with moisture following ASTM D-461: Standard Test Method for Felts, Section 17 [15]. Specimens were immersed in water for a minimum of 5 min, removed from the water, placed between sheets of commercial blotting paper, and rolled over with a 2,000-g metal roller to remove excess moisture. Saturated moisture content of each of the materials was as follows: FR cotton outerwear—35%; aramid outerwear—40%; 100% cotton underwear—50%; and aramid underwear—45%.

2.3. Flame Exposure (FE)

After appropriate moisture application, specimens were tested following CAN/CGSB-4.2 No. 78.1, with a 6.4-mm spacer, and a calibrated heat flux of 83 kW/m^2 [16]. 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. In the standard test, the rate at which the specimen allows heat to pass through to the sensor is determined until the second-degree burn criterion, a function of time-to-burn using the Stoll curve, is reached [1, 16]. Specimens are 100 mm by 100 mm square and are 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.

The standard 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 as is done in standard testing. Rather, the flame remained under the specimen for 10 ± 0.5 s in order to drive off excess moisture. Heat flux and transferred energy were measured for 60 s. Moisture loss was not determined quantitatively. However, moisture presence on the copper calorimeter sensor after the test exposure was noted and defined as specimen moisture loss and moisture condensation.

2.4. Radiant Exposure (RE)

After appropriate moisture application, specimens were tested using equipment for the NFPA 1977 Test, but using a 6.4-mm spacer and a calibrated heat flux of 10 kW/m^2 [17]. In this 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. 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.

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 s. Heat flux and transferred energy were measured during this time. Moisture loss was not determined quantitatively. However, moisture presence on the copper calorimeter sensor after the test exposure was noted and defined as specimen moisture loss and moisture condensation.

2.5. Measurement and Calculation of Dependent Variables

During and after exposure to both radiant and flame heat sources, data for four different dependent variables were collected and calculated: (a) peak heat flux through the fabric systems, (b) time to reach peak heat flux, (c) energy transferred through the fabric systems, and (d) time to reach 0.1 kJ of transferred energy. To accurately determine the total heat flux and total energy received by the copper calorimeter for both FE and RE tests, heat losses during exposure were calculated[1]. Such 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.

3. STATISTICAL ANALYSIS

After correcting for energy loss, data for heat flux and transferred energy were plotted versus time and the dependent variables were determined from the plots. For each dependent variable, two-way analyses of variance (ANOVAs) were performed to determine interaction effects between fabric system and moisture condition. One-way ANOVAs were performed separately with post hoc tests for each fabric system to determine which moisture conditions significantly differed from each other for each dependent variable

4. RESULTS AND DISCUSSION

Two-way ANOVAs determined significant differences for all dependent variables among the fabric systems and among moisture treatments as well as interaction effects, indicating that the effects of moisture on heat transfer depend on the fabric system being tested. One-way ANOVAs conducted separately for each fabric system indicated significant differences in some of the dependent variables among the moisture treatments for each system. However, such analyses do not take into account the very different shapes of the heat flux or transferred energy curves, as shown in Figures 1 to 8. Depending on the condition or system, these curves illustrate both dramatic and gradual changes in heat flux and transferred energy through the fabric systems over time.

4.1. Differences Among Moisture Treatments at 83 kW/m^2 FE

Results of one-way ANOVAs for each dependent variable are given in Table 1 for each fabric system. For peak heat flux, total transferred energy, and time at 0.1 kJ of transferred energy, moisture treatments wet/conditioned and wet/wet always show greater thermal protection than the other moisture treatments. This trend is also visible in time to reach peak heat flux for FR cotton

1 For details on heat loss calculations see Lawson [18].

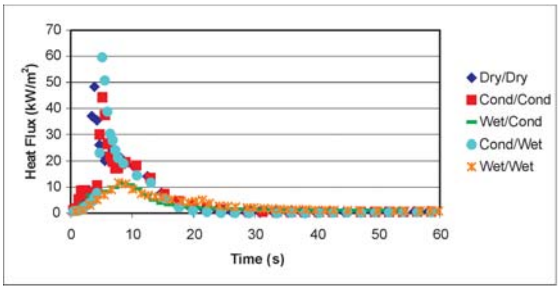
TABLE 1. ANOVA: the Effects of Moisture on Heat Transfer and Transferred Energy Through Four Different Fabric Systems: 83 kW/m² Flame Exposure (FE)

Fabric System	Moisture Condition	Mean Peak Heat Flux (kW/m²) (*SD*)	Mean Time at Peak Heat Flux (s) (*SD*)	Mean Total Energy (kJ) (*SD*)	Mean Time at 0.1 kJ (s) (*SD*)
FR cotton with 100% cotton	Dry/Dry	47.28^{b} (6.04)	4.05^{c} (0.37)	0.355^{a} (0.01)	5.07^{e} (0.28)
	Cond/Cond	49.33^{b} (6.33)	5.37^{b} (0.28)	0.349^{a} (0.01)	5.64^{d} (0.16)
	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)
FR cotton with aramid	Dry/Dry	59.35^{a} (6.72)	3.87^{c} (0.48)	0.426^{a} (0.02)*	4.52^{d} (0.22)
	Cond/Cond	59.18^{a} (8.00)	5.04^{b} (0.46)	0.405^{b} (0.01)*	5.22^{c} (0.15)
	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)
Aramid with 100% cotton	Dry/Dry	35.74^{a} (2.19)	8.98^{b} (0.93)*	0.371^{a} (0.02)*	7.75^{d} (0.33)
	Cond/Cond	35.54^{a} (1.46)	9.53^{ab} (0.69)*	0.341^{b} (0.01)*	8.31^{c} (0.25)
	Wet/Cond	10.90^{d} (0.79)	7.23^{c} (1.34)*	0.225^{d} (0.01)*	10.17^{b} (0.66)
	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)
Aramid with aramid	Dry/Dry	18.18^{b} (0.79)	10.22^{a} (0.66)*	0.362^{a} (0.01)*	8.99^{c} (0.33)
	Cond/Cond	17.11^{c} (0.52)	10.44^{a} (0.56)*	0.326^{b} (0.01)*	9.15^{bc} (0.31)
	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)

Notes. a, b, c, d, e—for each fabric system, means with the same superscript letter do not differ significantly from each other (columns); *—significant differences determined using Duncan's post hoc tests; otherwise, Tamhane's T2 post hoc tests were used due to unequal variances; Cond—conditioned; FR—fire resistant.

outer fabric systems, but not for the aramid outer fabric systems.

Plots for heat flux and transferred energy versus time for all moisture treatments are displayed separately for each fabric system in Figures 1 to 4. In each figure, the curves for different moisture treatments vary considerably, demonstrating that source and location of



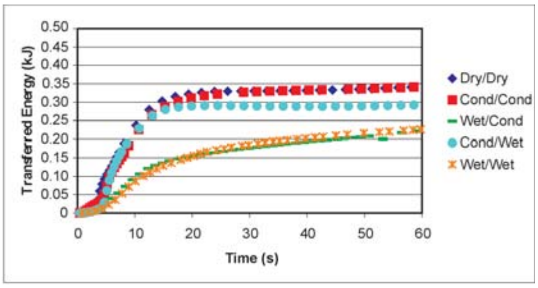


Figure 1. The effects of moisture on heat flux and transferred energy through fire resistant cotton/cotton fabric system: flame exposure. *Notes*. Cond—conditioned.

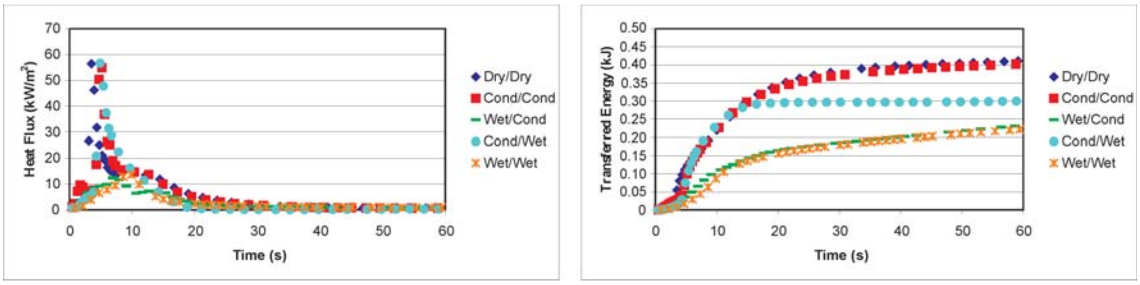


Figure 2. The effects of moisture on heat flux and transferred energy through fire resistant cotton/aramid fabric system: flame exposure. *Notes*. Cond—conditioned.

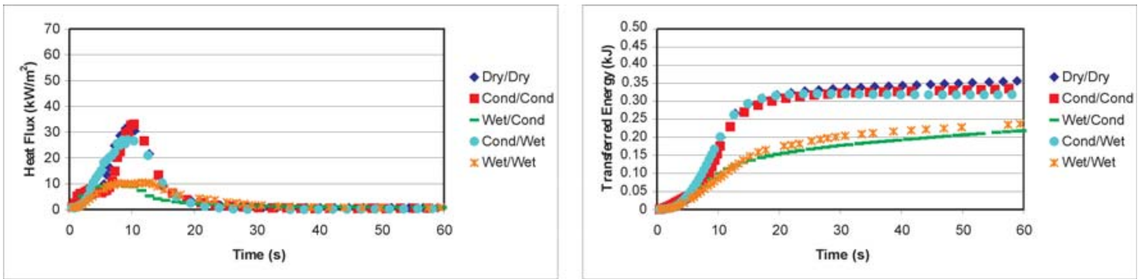


Figure 3. The effects of moisture on heat flux and transferred energy through aramid/cotton fabric system: flame exposure. *Notes*. Cond—conditioned.

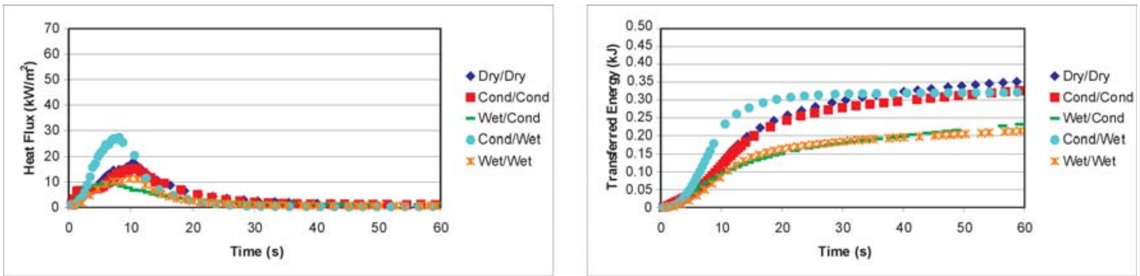


Figure 4. The effects of moisture on heat flux and transferred energy through aramid/aramid fabric system: flame exposure. *Notes*. Cond—conditioned.

moisture in a clothing system does affect the rate of heat transfer through fabric systems at high heat fluxes. 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 moisture is still present after heat exposure. When exposed to a high heat flux, external moisture in a fabric system stores energy and evaporates out of the system. If the fabric system is both externally and internally wet, the external moisture will still store energy and evaporate out of the system. As a result, the presence of external moisture appears to increase thermal protection. However, if the fabric system is internally wet only, vapour is unable to escape the fabric system quickly and, as noted in this experiment, condenses on the sensor, resulting in a decrease in thermal protection without the counteracting effects of external moisture.

4.2. Differences Among Moisture Treatments at 10 kW/m² RE

Results of one-way ANOVAs for each dependent variable are given in Table 2 for each fabric system. For peak heat flux, total transferred energy, and time at 0.1 kJ of

TABLE 2. ANOVA: the Effects of Moisture on Heat Transfer and Transferred Energy Through Four Different Fabric Systems: 10 kW/m^2 Radiant Exposure (RE)

Fabric System	Moisture Condition	Mean Peak Heat Flux (kW/m^2) (*SD*)	Mean Time at Peak Heat Flux (s) (*SD*)	Mean Total Energy (kJ) (*SD*)	Mean Time at 0.1 kJ (s) (*SD*)
FR cotton with 100% cotton	Dry/Dry	3.34^a (0.21)*	61.08^b (9.80)	0.356^a (0.02)*	41.90^b (1.77)
	Cond/Cond	3.13^b (0.23)*	83.64^a (5.43)	0.313^b (0.02)*	44.34^{ab} (4.20)
	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)
FR cotton with aramid	Dry/Dry	3.48^a (0.17)	55.61^b (9.99)	0.375^a (0.01)	39.93^b (2.01)*
	Cond/Cond	3.16^b (0.15)	80.49^a (3.12)	0.328^b (0.02)	42.93^a (2.82)*
	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)*
Aramid with 100% cotton	Dry/Dry	3.70^a (0.24)	55.55^b (3.76)	0.411^a (0.01)	35.32^{bc} (1.20)
	Cond/Cond	3.38^b (0.27)	67.80^a (10.74)	0.354^b (0.03)	42.50^a (4.01)
	Wet/Cond	3.37^{ab} (0.49)	22.27^c (2.09)	0.254^c (0.02)	33.70^c (3.15)
	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)
Aramid with aramid	Dry/Dry	3.94^a (0.22)	51.13^a (7.94)*	0.438^a (0.01)	32.93^c (1.78)*
	Cond/Cond	3.62^b (0.32)	55.47^d (6.28)*	0.382^b (0.03)	39.92^a (3.29)*
	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)	24.01b^c (5.75)*	0.272^{cd} (0.02)	36.56^b (3.49)*

Notes. a, b, c, d, e—for each fabric system, means with the same superscript letter do not differ significantly from each other (columns); *—significant differences determined using Duncan's post hoc tests; otherwise, Tamhane's T2 post hoc tests were used due to unequal variances; Cond—conditioned; FR—fire resistant.

transferred energy, moisture treatment conditioned/wet always has values that show greater thermal protection than the other moisture treatments. For time at peak heat flux, moisture treatments dry/dry and conditioned/ conditioned took the longest time to reach peak heat flux. This suggests that small amounts of moisture in a clothing system decrease the rate at which heat is transferred through the clothing system.

Plots for heat flux and transferred energy versus time for all moisture treatments are displayed separately for each fabric system in Figures 5 to 8. With lower heat-flux exposures, it appears that internal moisture tends to increase thermal protection somewhat. Unlike the higher heat-flux condition described earlier, internal moisture in a fabric system absorbs thermal energy, due to the high heat capacity of water, slowing the transfer of heat through the fabric. As a result, moisture is able to evaporate and slowly move through the fabric layers out to the external environment.

It is interesting to note that in Figures 5 to 8, the plot for conditioned/conditioned moisture treatment exhibits an inflection, where heat flux increases rapidly to a low peak heat flux, at which time the curve gradually decreases,

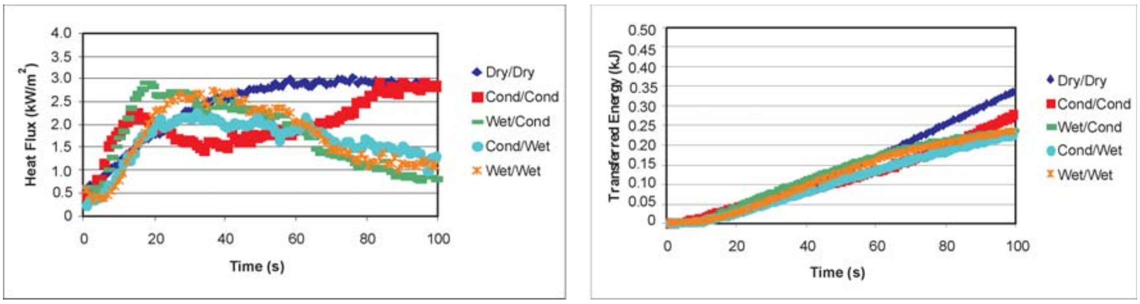


Figure 5. The effects of moisture on heat flux and transferred energy through fire resistant cotton/cotton fabric system: radiant exposure. *Notes*. Cond—conditioned.

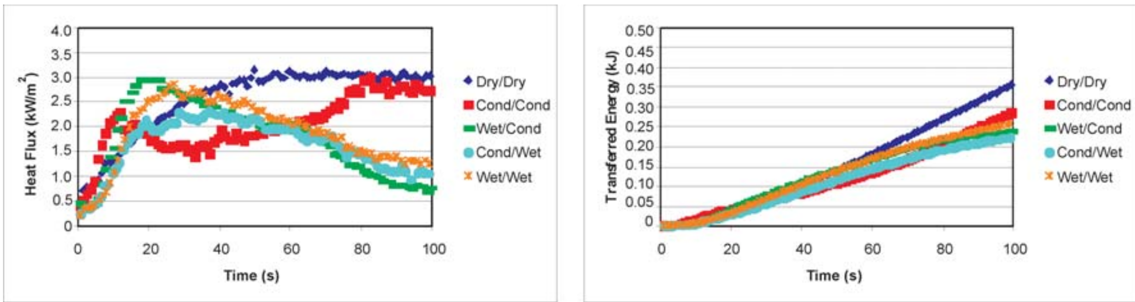


Figure 6. The effects of moisture on heat flux and transferred energy through fire resistant cotton/aramid fabric system: radiant exposure. *Notes*. Cond—conditioned.

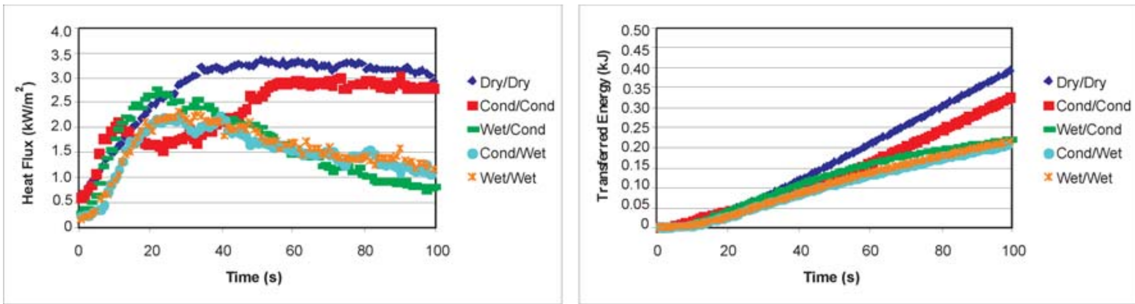


Figure 7. The effects of moisture on heat flux and transferred energy through aramid/cotton fabric system: radiant exposure. *Notes*. Cond—conditioned.

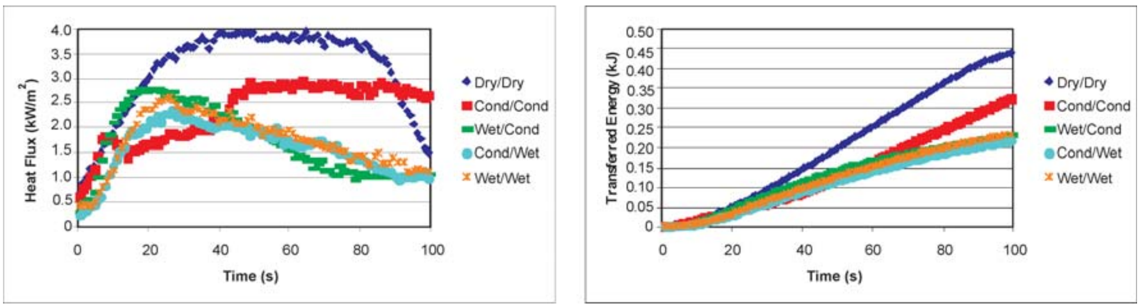


Figure 8. The effects of moisture on heat flux and transferred energy through aramid/aramid fabric system: radiant exposure. *Notes*. Cond—conditioned.

increases again, and then eventually plateaus. This indicates that during initial heat exposure, the small amount of moisture present in the material is driven off and escapes from the fabric systems. Once the moisture is driven off, the fabrics are dry, so the heat flux curves parallel those for the dry/dry moisture condition. Initially, the small amount of moisture present in the conditioned/ conditioned specimens improves the thermal performance, but heat flux and transferred energy increase after this moisture dissipates.

4.3. Differences Among Fabric Systems

When exposed to a high-heat-flux flame exposure, the four fabric systems behaved differently for moisture treatments dry/dry, conditioned/conditioned, and conditioned/wet. For these moisture treatments, FR cotton outer fabric systems showed lower thermal protection than aramid outer fabric systems. No differences exist among the fabric systems for moisture treatments wet/conditioned and wet/wet.

When exposed to a low-heat-flux radiant exposure, the four fabric systems showed similar patterns for all moisture treatments. For moisture treatments dry/dry and conditioned/conditioned, FR cotton outer fabric systems tended to have a lower peak heat flux and total transferred energy than aramid outer fabric systems, indicating that the FR cotton outer fabrics are slightly more protective under these two moisture treatments.

5. CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS

When moisture is a factor, heat transfer through thermal protective textiles differs among conditions of moisture application and among the layered fabric systems. There are significant interaction effects between moisture treatments and fabric layer compositions when determining their effects on heat transfer. For the fabrics and moisture treatments studied here, there are greater differences among moisture treatments for each fabric system than there are differences among fabric systems for each moisture treatment.

In previous studies, Mäkinen et al. [2] examined effects of internal moisture on heat transfer through outer fabric (FR cotton or Karvin®) and underwear (cotton, wool, or aramid knit) 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 [8, 9] and structural firefighter clothing systems [11, 10] using radiant energy also concluded that internal moisture decreased thermal protection. In this study, similar results were found at higher heat flux flame exposures; however, the opposite was found at lower heat flux radiant exposures. At high heat fluxes, external moisture generally decreased heat transfer through fabric systems while internal moisture generally increased heat transfer to the sensor. At low heat fluxes, internal external moisture decreased heat transfer through the fabric systems, while the effect of external moisture is inconclusive.

Layering outer and underwear materials in a clothing system also affects the rate of convective and radiative heat transfer when moisture is a variable. Differences between fabric systems may be due in part to the different masses and saturated moisture contents of the FR cotton and aramid outer fabrics in this experiment.

5.1. Implications for Standard Test Method Development

When conducting many standard TPP and RPP tests, the endpoint is reached when the curve representing the temperature of the calorimeter crosses the Stoll curve, providing valuable information about how human skin responds to a rise in temperature. Under controlled labouratory testing conditions, the Stoll curve predicts the onset of second degree burns. However, the shapes of the heat flux and transferred energy curves are disregarded. The dependent variables in this research better accounted for the shape of these curves. By examining test data in this manner, more information is collected about the actual behaviour of moistened fabric systems, and about mechanisms of the heat transfer through clothing. This information, in turn, may lead to a more comprehensive understanding of thermal protective clothing systems.

For standard TPP and RPP tests, specimens are conditioned in a standard atmosphere of 21 °C and 65% RH prior to testing. No other moisture treatment is evaluated. The specification of one standard procedure to which all test facilities comply facilitates comparison of results. As demonstrated here, however, moisture level and location of moisture in the layers can alter the rate of heat transfer though fabric systems. In the future, end use and work environment should be considered when conducting heat transfer tests on materials, adding other moisture treatments to the standard protocols when appropriate.

5.2. Implications For Development and Use of Protective Clothing

This research has confirmed 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 treatment at a specific heat exposure may eventually arise. For example, wildland firefighters experience clothing conditions ranging from completely dry to completely wet. Due to the complexity of these considerations, there may be merit in developing more complex clothing systems that will accommodate all moisture treatments and environments.

5.3. Recommendations for Further Research

In this research, a 6.4-mm spacer was used to simulate air space between the fabric and the skin. Repeating this experiment without the spacer would provide additional data that can further our understanding. Examination of additional moisture treatments and fabric systems is also required to fully understand how moisture affects heat transfer through clothing systems. In this experiment, moisture was applied before exposure to flame or radiant heat. Specimens moistened internally during heat exposure, such as occurs when one perspires, and specimens moistened externally both during and after heat exposure should be studied under both low- and high-heat flux exposures.

Since only four fabric combinations were evaluated in this experiment (two outer and two underwear material), clothing material recommendations for use in different environmental conditions cannot be made. There are many fabrics and fiber types available for thermal protective apparel. Further candidate outer and underwear fabric combinations should be evaluated and tested to determine how moisture affects the rate of heat transfer through these fabric combinations.

REFERENCES

1. Stull JO. The effect of moisture on firefighter protective clothing thermal insulation: a review of industry research. In: Nelson C, Henry N, editors. Performance of Protective Clothing: Issues and Priorities for the 21st Century,

Seventh Volume (ASTM STP 1386). West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM); 2000. p. 557–76.

2. Mäkinen H, Smolander J, Vuorinen H. Simulation of the effect of moisture content in underwear and on the skin surface on steam burns of fire fighters. In: Mansdorf SZ, Sager R, Nielsen AP, editors. Performance of Protective Clothing: Issues and Priorities for the 21st Century, Second Symposium (ASTM STP 989). Philadelphia, PA, USA: American Society for Testing and Materials (ASTM); 1988. p. 415–21.
3. Farnworth B. A numerical model of the combined diffusion of heat and water vapour through clothing. Text Res J 1986; 56:653–65.
4. Gibson PW. Factors influencing steady-state heat and water transfer measurements for clothing materials. Text Res J 1993;63:749–64.
5. Parsons KC. Heat transfer through human body and clothing systems. In: Raheel M, editor. Protective clothing systems and materials. New York, NY, USA: Decker; 1994. p. 137–71.
6. Weder MS, Zimmerli T, Rossi RM. A sweating and moving arm for the measurement of thermal insulation and water vapour resistance of clothing. In: Johnson JS, Mansdorf SZ, editors. Performance of Protective Clothing: Issues and Priorities for the 21st Century, Fifth Volume (ASTM STP 1237). West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM); 1996. p. 257–68.
7. Yoo H, Hu YS, Kim EA. Effects of heat and moisture transport in fabrics and garments determined with a vertical plate sweating skin model. Text Res J 2000;70:542–9.
8. Chen NY. Transient heat and moisture transfer through thermally irradiated cloth [dissertation]. Cambridge, MA, USA: MIT; 1959. Retrieved October 14, 2001 from http://theses.mit.edu:80/Dienst/UI/2.0/Describe/0018.mit.theses/1959-2
9. Lee YM, Barker RL. Effect of moisture on the thermal protective performance of heat-resistant fabrics. Journal of Fire Sciences 1986;4:315–31.
10. Rossi RM, Zimmerli T. Influence of humidity on the radiant, convective, and contact heat transmission through protective clothing materials. In: Johnson JS, Mansdorf SZ, editors. Performance of Protective Clothing: Issues and Priorities for the 21st Century, Fifth Volume (ASTM STP 1237). West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM) 1996. p. 269–80.
11. Stull JO. Comparative thermal insulative performance of reinforced knee areas of firefighter protective clothing. In: Nelson C, Henry N, editors. Performance of Protective Clothing: Issues and Priorities for the 21st Century, Seventh Volume (ASTM STP 1386). West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM); 2000. p. 312–28.
12. Torvi DA, Dale JD. Effects of variations in thermal properties on the performance of flame resistant fabrics for flash fires. Text Res J 1998;68:787–96.
13. Veghte J. Effect of moisture on the burn potential in fire fighter's gloves. Fire Technol 1987;23:313–22.
14. Canadian General Standards Board (CGSB). Conditioning textile materials for testing (National Standard of Canada

CAN/CGSB-4.2, No. 2-M88). Ottawa, Ont., Canada: CGSB; 1993.

15. American Society for Testing and Materials (ASTM). Standard test method for felts (Standard No. ASTM D-461). Annual book for ASTM standards. Vol. 07.01. Philadelphia, PA, USA: ASTM; 1999.

16. Canadian General Standards Board (CGSB). Thermal protective performance of materials for clothing (National Standard of Canada CAN/CGSB-4.2 No. 78.1-2001). Ottawa, Ont., Canada: CGSB; 2001.

17. National Fire Protection Association (NFPA). NFPA 1977 standard on protective clothing and equipment for wildland fire fighting. Quincy, MA, USA: NFPA; 1998.

18. Lawson L. Effects of moisture on heat transfer through thermal protective fabric systems [Master of Science thesis]. Edmonton, Alta., Canada: University of Alberta; 2002.