Effect of Wool Components in Pile Fabrics on Water Vapor Sorption, Heat Release and Humidity Buffering

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ABSTRACT
Experimental measurements of water vapor sorption and desorption in wool/polyester blend fabrics are used to assess associated changes in temperature and heat flux during varying relative humidity levels. The results aid further development and adoption for military applications of cold-weather wool blend fabrics that are more flame resistant and warmer than 100% polyester garments. Two types of bi-sided fabrics were tested: 1) thin knit fabrics designed to be worn next to the skin, usually as undergarments, and 2) thick fleece mid and outer layers with 100% wool on the outer face and 100 % polyester on the inner surface. The following issues were addressed: 1) the effect of wool content on the knit fabrics, 2) the effect of fabric orientation on both the knit and the fleece fabrics, and 3) the effect of durable water-repellent treatment on the fleece fabrics.

INTRODUCTION
The experimental study described in this report examined the effect of wool fibers on thermal effects related to moisture sorption and desorption for several functional fabrics previously manufactured exclusively from polyester fibers. The rationale for this approach is that commercially successful under-garment polyester knits and outer-garment polyester pile fabrics are undergoing further development to add wool fibers into one or more of the pile faces to take advantage of the natural thermal and water vapor regulation properties of wool. Wool clothing actively generates heat when moved from a warm and dry indoor environment to cold and wet outdoor conditions. This is due to the readjustment of water vapor content within wool fibers to maintain equilibrium with the local microclimate. Experimental measurements of the water vapor sorption phenomena associated with these modifications to fabric fiber content will aid in the further development of these fabrics for military clothing applications. This performance advantage of wool fibers over polyester fibers has been widely recognized in the commercial marketplace. Commercially successful blends of knit and woven wool/polyester (e.g. SPORTWOOL) were developed over 15 years ago by partnerships between the Commonwealth Scientific and Industrial Research Organization (CSIRO) and Australian Wool Innovation, Ltd. (AWI). CSIRO performed fundamental research that provided a rationale for the use of fine-diameter merino wool-blend fabrics for enhanced comfort applications [1-3].

The U.S. military uses polyester fleece for several cold weather clothing items. Polyester fleece is lightweight, quick-drying, compressible, durable, easy to care for, and has been well accepted by soldiers. Over the past ten years, fine-denier wool clothing has become popular in outdoor performance clothing and there is a trend towards supplementing and replacing polyester/nylon in undergarment and outerwear applications. The U.S. military is actively investigating some of these new wool fabrics and wool blends for clothing. For example, there are wool/Nomex blends that are of interest, as well as new variations on wool fibers such as enzyme-treated wool fabrics [4-6]. Much of this interest has been spurred by the inherently flame-resistant nature of wool fibers and fabrics.

Wool will ignite and burn with a self-extinguishing flame. This is in contrast to polyester and nylon fabrics, which tend to burn, melt, and drip onto skin, making them unsuitable for protective clothing applications that require resistance to heat and flame. Wool is naturally flame resistant and difficult to ignite; the flame spreads slowly and extinguishes easily [7]. The burn residue is a low-temperature, fragile, non-sticking ash or char (unlike acrylic, nylon, and polyester). The residual char does not melt or drip, and can actually help insulate the skin or other clothing from heat once the wool has burned away to form the char. Wool fibers have a high ignition temperature of around 750°C and high limiting-oxygen index (25%), and a low heat of combustion and heat release rate.

Wool fibers added to underwear and next-to-skin wicking layers have had some commercial success. Apparel companies are now exploring the addition of wool fibers to insulating pile fabrics to increase their performance. Possible performance advantages include improved flame retardancy, moisture buffering, comfort, and improved static resistance (due to high water content). This study addresses measurements related to the moisture buffering and heat release to water vapor sorption of wool fiber incorporated into knitted base layer and pile fabrics.

Wool fibers are proteinaceous fibers composed of keratin. Hair fibers from mammalian species are superficially similar; "wool" is distinguished mainly in terms of the numbers of overlapping scales, and in the twists/kinks (crimps) present in the fiber [8], as shown in *Figure 1*.

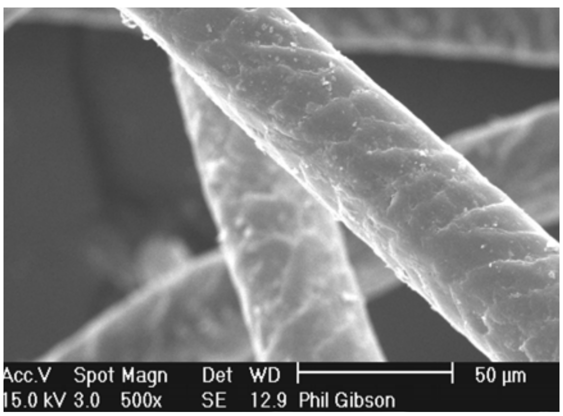

FIGURE 1. Scanning electron micrograph of lamb's wool fibers showing overlapping scales that form during growth.

The interior of wool fibers is hygroscopic, while the exterior is hydrophobic. This means that the overall wool fiber can absorb or desorb water vapor from the environment, but will tend to repel liquid water from the surface of the fiber or fabric. Wool can absorb up to one-third of its own weight in water, in contrast to polyester fibers, which absorb less than 2% by weight of water.

In 1787, Count Rumford (Benjamin Thompson) was among the first to document measurements of the ability of wool fibers to absorb and release water vapor from the atmosphere [9, 10]. Wool undergoes a rise in temperature when moved from a relatively dry environment to conditions that are more humid. When water vapor is absorbed into wool's internal structure, it transforms from gas to liquid, and the energy liberated during the condensation phase change produces the temperature increase. This liberated energy is called the "heat of sorption." The heat release and temperature change are dependent on the "regain" or ability of the fiber to absorb water vapor. Fibers with the highest regain have the best ability to buffer humidity and temperature changes by absorbing and releasing water vapor from the environment and human sweat.

The temperature change due to water vapor sorption can be quite large, and is easily measured. *Figure 2* and *Figure 3* show a typical experimental system to measure the rise in fabric temperatures when the environmental relative humidity changes in a stepwise fashion [11, 12].

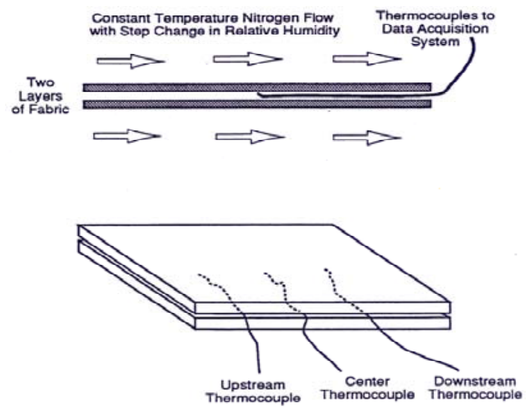

FIGURE 2. Experimental arrangement for measuring fabric temperature during changes in environmental relative humidity.

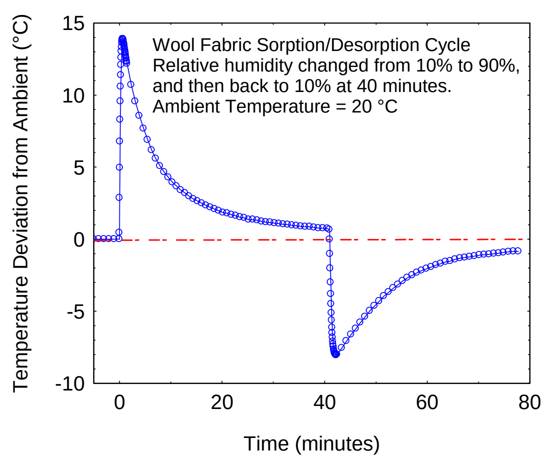

FIGURE 3. Temperature change in wool fabric due to water vapor sorption.

Temperature changes in wool fabric due to water vapor sorption can be as much as 15°C (~27°F). Water vapor sorption related temperature changes in hygroscopic fabrics (especially wool) are physiologically significant, and account for differences in perceived comfort amongst different types of fabrics [13].

MATERIALS

A commercial manufacturer provided six fabrics containing various amounts of wool fibers. The manufacturer requested details of fabric construction remain confidential, since these fabrics are currently under active development. The only information related here is the fabric thickness, areal density and location of the wool fibers. The fibers consisted of polyester, wool, and polylactic acid (PLA). PLA is a biodegradable, thermoplastic polyester fiber derived from cornstarch, and behaves like normal polyester with respect to its water vapor sorption characteristics. The diameter of the wool fibers are less than 21 microns, which puts them in the range of fine to medium grade merino wool, and less apt to cause skin discomfort due to a "prickling" sensation, especially in warm and humid conditions [14, 15].

Knit Fabrics

Three of the materials were thin knit fabrics designed to be worn next to the skin, usually as undergarments, and were very similar in weight and thickness:

- Knit A - 100% polyester knit fabric;
  thickness: 1.1 mm, areal density: 208 g/m²
- Knit B - 45% wool / 55% polyester on face; 100% polyester on back;
  thickness: 1.3 mm, areal density: 276 g/m²
- Knit C - 100% wool on face;
  100% PLA on back;
  thickness: 1.5 mm, areal density: 261 g/m²

Fleece Fabrics

The other three fabrics were thick bi-faced mid and outer layers with 100% wool on one face and 100% polyester on the other face:

- Fleece A – 100% wool on face (velour pile); 100% polyester on back (shearling pile);
  thickness: 5.1 mm, areal density: 364 g/m²
- Fleece B – 100% wool on face (straight pile); 100% polyester on back (straight pile);
  thickness: 6.8 mm, areal density: 408 g/m²
- Fleece C – same as Fleece B, but includes a durable water repellent (DWR) treatment;
  thickness: 6.8 mm, areal density: 410 g/m²

EXPERIMENTAL METHOD

Experiments examined three main issues: effect of wool content, effect of fabric orientation, and effect of DWR treatment:

1) Effect of Wool Content on the Knit Fabrics – It is assumed that a higher proportion of wool fibers in similar fabrics will result in a higher heat of sorption and a higher heat flux into the skin during water vapor sorption, and higher heat flux out of the skin during vapor desorption. An instrumented water vapor sorption test using a heat flux sensor mounted on a simulated human skin surface tested this hypothesis.

2) Effect of Fabric Orientation on Knit and Fleece Fabrics - The instrumented water vapor sorption test was repeated for the Knit C (Wool/PLA) and Fleece A (Wool/Polyester) fabrics with the wool face toward the heat flux sensor (representing the human body), and for the conditions of the wool face away from the heat flux sensor. Both of these fabrics have 100% wool on one side, and 100% PLA or polyester on the other side. This test determined whether the orientation of the bi-faced fabric would affect the response measured in the water vapor sorption test. In other words, if the hygroscopic wool side is oriented to the skin, is there more of an effect than if the wool is facing away from the skin?

3) Effect of DWR Treatment on Bi-Faced Fleece Fabrics – DWR treatments applied to fabrics increase the liquid water repellency of the fabric surfaces. DWR finishes applied too heavily can seal off the fiber surface from interaction with the environment. The instrumented sorption test was repeated on the treated and untreated fabrics to determine if the DWR treatments on wool/polyester pile fabrics affect the water vapor sorption process.

Figure 4 shows the experimental setup. Step changes in relative humidity maximized the thermal effects due to water vapor sorption and desorption. A gas humidifying system changed gas flow relative humidity in a step-wise fashion over the surface of the fabric sample. Humidity-controlled gas flowed through the top portion of the flow cell and over a fabric sample placed on top of a heat flux sensor.

The heat flux sensor mounted underneath the sample on a flat rubber sheet recorded the actual heat flow from the fabric into the sheet. The rubber sheet simulated human skin thermal properties. The heat flux sensor was oriented so that a heat flow from the environment to the body would show as negative, and a heat flow from the body to the environment would show as positive. A non-contact infrared thermocouple mounted above the sample observed the change in fabric surface temperature. More information on the general apparatus is available in Reference 16.

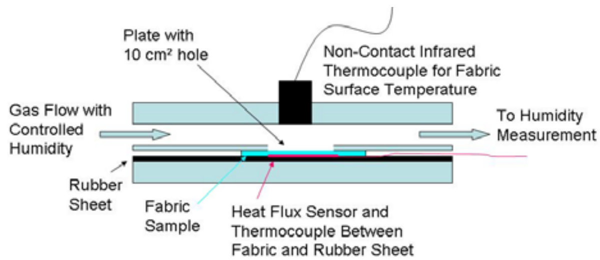

FIGURE 4. Test cell setup to observe temperature and heat flow for fabrics subjected to a step change in relative humidity.

A second thermocouple mounted on the rubber sheet near the heat flux sensor recorded the temperature change underneath the fabric. The exposed fabric sample area was 10 cm². Temperature was controlled at 30°C (~86°F). All samples were initially tested with the wool side towards the "body" side (directly contacting the heat flux sensor).

A series of three gas flow rates (2, 1.0 and 0.5 liters/minute) were cycled between 1% and 99% relative humidity *Table I*. Each condition of humidity and gas flow rate lasted for one hour. Varying gas flow rates helped determine the importance of boundary layer resistance on the rate of heat transfer from the surface of the test sample.

TABLE I. Humidity and Flow Conditions

Setpoint	Relative Humidity (%)	Flow Rate (liter/minute)
1	1	2.0
2	99	2.0
3	1	1.0
4	99	1.0
5	1	0.5
6	99	0.5

The heat flux sensor was approximately the same size as the exposed area of the textile sample. The sensor is based on standard thermopile heat flux sensor technology [17]. Since the application was for clothing materials, the heat flux is expressed in MET units, rather than the more usual W/m². A MET (metabolic equivalent) is a defined unit. It is equal to the amount of body heat produced by a sedentary human [18], averaged over the standard body surface area of 1.8 m². Conversion of units are: 1 MET = 58.2 W/m² = 18.4 Btu/hour-ft². This body heat is assumed equivalent to the heat flux that must be transferred to the environment to maintain human thermal equilibrium. The heat flux sensor output is 6.37 μV per BTU/ft²-hour, 2.02 μV per Watt/m², or 117 μV per MET. A few typical MET values for human activities are walking (1.9 MET, 110 Watt/m²), golf (5 MET, 290 Watt/m²), and jogging (8.5 MET, 500 Watt/m²).

In this application, there is no simulation of human sweating skin, so a heat flux sensor that is impermeable to water vapor transfer is acceptable. It would be desirable to also measure simultaneous energy transferred away from the skin surface by evaporating sweat, and more advanced heat flux sensor technology would be preferred in this case [19].

RESULTS

Effect of Wool Content on the Knit Fabrics

Figure 5 gives an example of the measured heat flux, surface temperature, and humidity change (measured at the cell outlet) from three knit samples varying in wool fiber content. The fabric with the highest percentage of wool fiber content also has the highest heat flow to the body. The nonhygroscopic polyester fabric control also shows a small measured heat flux. This is probably due to the change in energy content and temperature of the gas stream as the humidity changed from 1% to 99%. Water vapor sorption of the heat flux sensor materials themselves also affected measured heat flux.

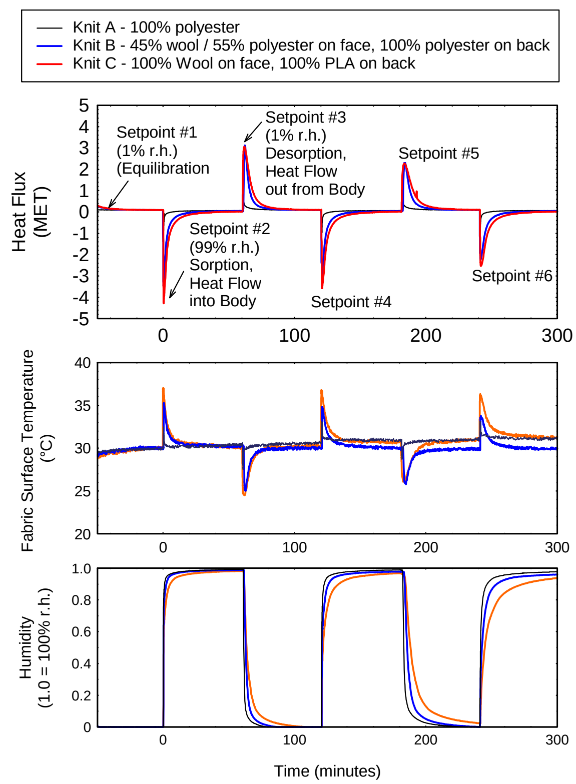

FIGURE 5. Heat flux, temperature, and humidity measurements from flow cell under step changes in relative humidity.

An approximate calculation of the relative difference in heat flows between the different cases can be made by integrating the area under the sorption curves (setpoints #2, #4, #6) (negative heat flow only) and subtracting off the area under the curve with no sample in place. Under these conditions, the Wool/PLA blend sample with highest wool content (Knit C) will provide about twice the energy transfer to or from the body as the Wool/Polyester blend sample with lower wool content (Knit B).

The Knit C fabric also showed the largest temperature changes due to water vapor sorption and desorption, as well as the longest buffering of humidity change due to sorption of hygroscopic fibers. Humidity buffering correlates with fabric wool content, and the buffering period lasts more than an hour for some conditions.

Transient moisture buffering properties are a second-order effect, and are much less important to overall clothing comfort than are steady-state heat and moisture transfer properties. Wang, et al., explored the importance of coupled heat and mass transfer, including the moisture buffering effect, on perceptions of thermal comfort, as one component of a variety of factors that influence thermal and moisture sensations during skin-fabric contact [20].

Results for the thermocouple directly underneath the fabric *Figure 6* showed similar results. The magnitude of the temperature changes underneath the fabrics was smaller than for the surface temperature, but the correlation between temperature change and fabric wool content is clear. *Figure 6* only shows setpoint #2, due to baseline drift of later setpoints.

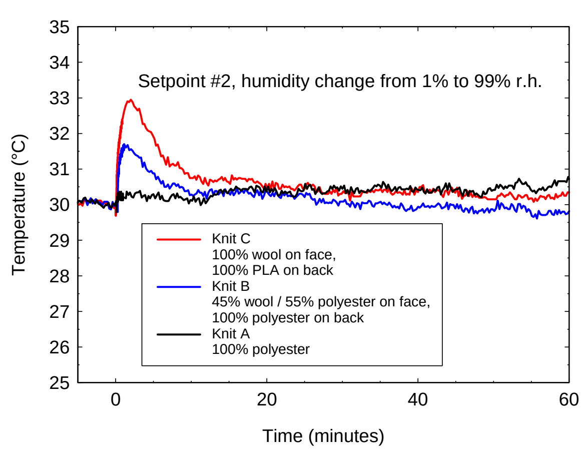

FIGURE 6. Relative temperature change from ambient temperature underneath the fabrics during step changes in humidity.

Fabric Orientation Effects

Two of the samples, Knit C and Fleece A, consist of hygroscopic wool on one face, and nonhygroscopic polyester on the other side. The wool side of the fabric can be oriented toward the human body, or reversed to face the outer environment. The question of the effect of fabric orientation (hygroscopic layer next to the skin surface, or reversed as the outer layer) has been addressed in a previous modeling study [21]. In the previous work, a human thermophysiological model was integrated with a coupled heat and mass transfer fabric model. The modeling study showed that the effect of fabric orientation was minimal, in terms of the differences in energy transferred to the human body during water fabric vapor sorption caused either by an increase in human sweating rate, or by movement from a low-humidity environment to a more humid environment. However, the modeling cases that examined the effects of hygroscopic fabric layer orientation were not backed up with extensive experimental measurements.

For the thin bi-faced wool/PLA fabric (Knit C), as shown in *Figure 7*, the orientation of the wool side did not make a detectable difference for the heat flux into or out of the body during water vapor sorption or desorption from the wool fibers. The fabric was quite thin, and the insulation properties of the non-absorbing polyester layer are minimal. Although the results of this test showed no effect of fabric orientation, a bi-faced insulating fleece fabric would possibly show more of a difference between test results of varying fabric orientation.

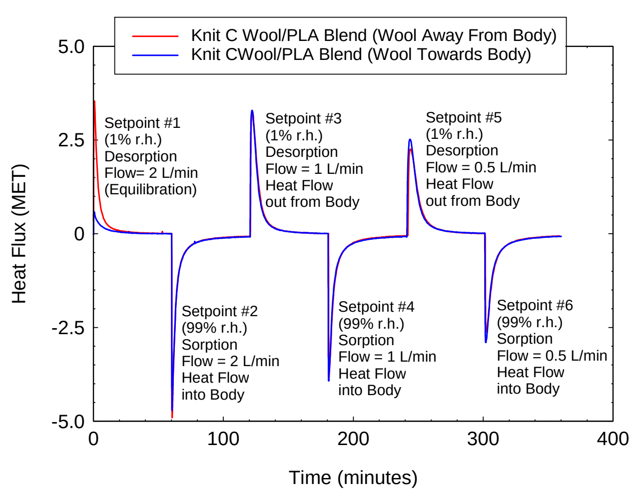

FIGURE 7. Effect of the orientation of the wool side of the 100% Wool / 100% PLA thin knit fabric (Knit C) on the heat flux due to water vapor sorption.

Fleece A consisted of a 100% velour wool fleece on the face and a 100% shearling polyester fleece on the opposite side of the material. Because this fleece was much thicker than the thin bi-faced fabric (Knit C), it should have more potential to show a difference in fabric orientation. However, as shown in *Figure 8*, the instrumented water vapor sorption test did not show this to be the case. Regardless of fabric orientation, the peak and duration of the measured heat flux into the simulated skin surface was similar regardless of the fabric orientation.

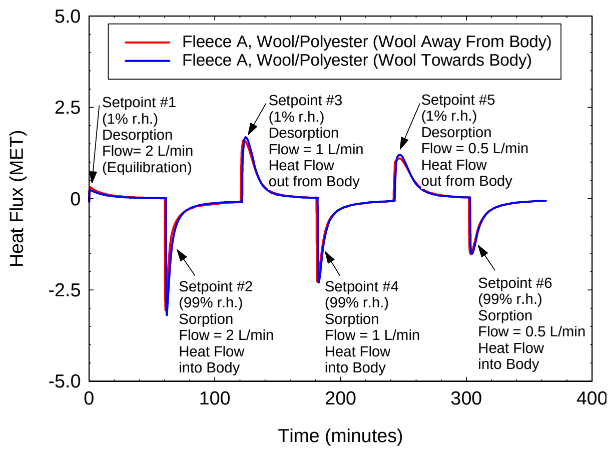

FIGURE 8. Effect of the orientation of the wool side of the wool/polyester thick fleece fabric (Fleece A) on heat flux due to water vapor sorption.

Effect of Durable Water Repellent Treatment on the Bi-Faced Fleece Fabric

A DWR treatment added to the wool/polyester fleece enhances its use in rainy conditions. Does this water repellent treatment also affect water vapor sorption properties?

A bi-faced fleece material, with one side 100% wool, and the other side 100% polyester, was available in two versions of treated (Fleece B) or untreated (Fleece C) on both sides with a DWR coating.

Figure 9 shows that the presence of the DWR treatment on the fleece fabric did not inhibit the sorption or desorption of water vapor from the fiber's interior structure. The treatment did not seal off the hygroscopic interior of the wool fibers from the environment, allowing the wool fibers to continue to act as a buffer to rapid environmental humidity changes. The heat flux sensor data showed no significant difference in the water vapor sorption behavior of the two fabrics. *Figure 9* does not show heat flux surface temperature and outlet humidity, but those results were also very similar between the two fabrics

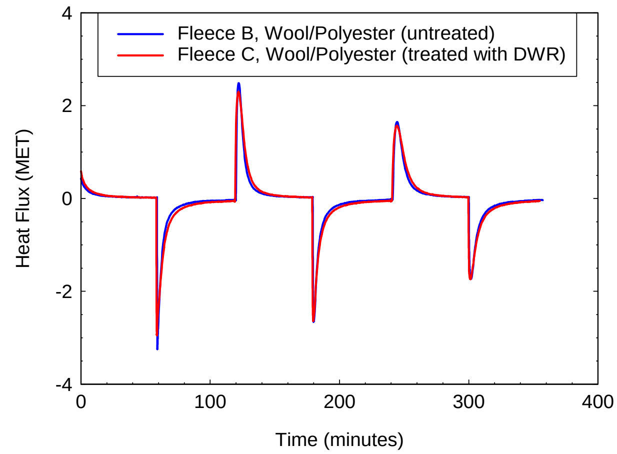

FIGURE 9. The heat flux sensor data for the comparison of a fleece fabric with a DWR treatment (Fleece C) with the same fabric without a DWR treatment (Fleece B).

The measurements and tentative conclusions resulting from these few experimental measurements only apply to the situation of water vapor sorption by hygroscopic wool fibers in these fabric structures. Much larger differences in performance would be evident in some situations due to differences in liquid transport and equilibrium moisture absorption capacity in these fabrics. Thermal effects related to liquid moisture transport and wicking can overwhelm the much smaller differences in heat release due to water vapor sorption. Modeling and experimental studies have shown that when liquid sweat is present, wicking effects quickly overwhelm any of the other transport properties (such as diffusion), due to the evaporation of liquid water within the clothing, and the increase in thermal conductivity of the porous textile matrix due to the liquid water that builds up within the clothing layers [21, 22].

CONCLUSION

Adding wool fibers can enhance standard polyester fleece. Adding wool fibers to polyester fleece fabrics can increase thermal regulation and humidity buffering capacity. Fine denier wool fibers will also have increased tactile comfort over the larger denier polyester fiber fabrics.

Wool fibers in fleece garments have the potential to increase the flame resistance and enhance the flame retardancy of cold-weather military uniforms.

Durable Water Repellent (DWR) treatments can be applied to wool/polyester fleece fabrics so that they

do not interfere with the water vapor sorption and thermal regulation properties of wool fibers.
For both the thin knit fabrics and the thick fleece fabrics, the orientation of the wool side of the bi-faced fabric towards or away from the skin does not affect the magnitude or duration of the measured heat flux due to water vapor sorption or desorption.

Other practical questions remain regarding the incorporation of wool fibers into polyester fiber pile fabrics:

- Do wool fibers affect the pilling and durability of polyester fleece fabrics (modern high-quality polyester fleece is extremely durable and pill-resistant)?
- Is the moisture-buffering capability offered by wool fibers in under-garment or fleece layers enough of a performance advantage to justify the added expense?
- Are enzyme-scoured wool fibers sufficiently flame-retardant to be used in thermally-protective military outerwear, or are more traditional Wool/Nomex blends necessary for this application?

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