WATER-REPELLENT TREATMENT ON MILITARY UNIFORM FABRICS: PHYSIOLOGICAL AND COMFORT IMPLICATIONS

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ABSTRACT

Cost-effective nanotechnology-based water-repellent treatments for clothing fabrics are now commercially available. The effectiveness of these durable water repellent (DWR) fabric treatments were evaluated for application to military uniforms. The addition of a non-wicking finish to clothing fabric negatively impacts comfort in hot and humid environments. Clothing comfort may be improved by refining the DWR fabric treatment process to retain wicking properties on the fabric inner surface.

1. INTRODUCTION

Several water-repellent treatments based on nanotechnology approaches were evaluated on fabrics used for the Advanced Combat Uniform (ACU) and the Battle Dress Uniform (BDU). Various performance properties such as hydrostatic head (resistance to liquid water penetration), liquid spray repellency, fabric breathability/air permeability, and fabric pore size were measured before and after laundering.

The purpose of this testing was to ensure that the treatment didn’t impact the breathability or air permeability of the fabric. Many durable water-repellent (DWR) treatments, if applied too heavily, can close off the fabric pores and reduce water vapor diffusion or convective air flow through the fabric.

Two of the water-repellent treatments had good durability to laundering. One treatment had very poor durability, and lost all its water-repellent properties after 20 laundering cycles. The current standard oil- and water-repellent fluorochemical fabric finish (Quarpel) applied to the control fabric performed better than any of the experimental treatments. None of the water-repellent treatments significantly affected the breathability, air flow resistance, or pore size of the BDU fabric.

The standard BDU fabric can be modified with very effective water-repellent treatments. Soldiers’ duty and combat uniforms can be made water-resistant and retain the same air permeability and “breathability” properties as the untreated wicking fabric. Several questions arose as a result of this work. What are the physiological implications of changing the BDU fabric from a wicking fabric to a non-wicking fabric? Will the fabric still be comfortable when a soldier is sweating heavily? Will liquid sweat now remain on the skin underneath the fabric, and is this bad or good?

Following a separate field trial using combat uniforms with and without a DWR treatment, it was found that these treatments decreased the comfort of the uniform in hot and humid environments. The differences between the comfort of the standard control uniforms and those treated with the DWR treatments are probably not due to intrinsic differences in the air permeability or the water vapor diffusion resistance (breathability) of the fabric. It is more likely that the non-wicking behavior of the fabric was responsible for perceived comfort differences, per comments from the field trial, and by subsequent coupled physiological/fabric modeling.

2. FABRIC PROPERTIES

Three different fabric treatments were selected for application to the Battle Dress Uniform (BDU) fabric. To protect proprietary information, the treatments and companies supplying the treatments are not identified, but are given as the “Red,” “Blue,” and “Green” treatments.

The treatments were applied to the BDU fabric, which is a 50% nylon / 50% cotton blend fabric used in the army combat uniform. The BDU fabric is not normally treated with a water-repellent finish. However, an older version of the U.S. Army’s chemical protective suit (Battle Dress Overgarment or BDO) did use the BDU fabric treated with an oil and water-repellent finish (Quarpel treatment). This BDO fabric was used to compare the effectiveness of the three nanotechnology water-repellent treatments.

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1.1 Test Fabrics

1. BDU Fabric (untreated)
2. Battle Dress Overgarment (BDO) shell fabric (Quarpel water/oil repellent treatment)
3. Green treatment on BDU
4. Blue treatment on BDU
5. Red treatment on BDU

For some of the laboratory tests, a variety of commercial fabrics incorporating various DWR treatments were included to help in the comparison of the performance of the Red, Blue, and Green treatments. The standard comparison fabrics included an expanded polytetrafluoroethylene microporous membrane, the Joint Services Lightweight Integrated Suit Technology (JSLIST) shell fabric with and without the standard Quarpel treatment, and with a nanotech DWR, and several varieties of commercially-available "soft-shell" fabrics (Schoeller Textiles and Nextec) that incorporate differential wicking and durable water-repellent finishes. Typical water repellency of some of these fabrics is shown in Fig. 1.

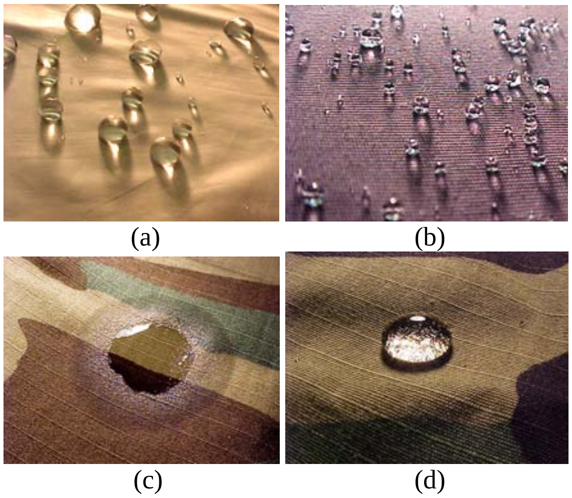

(a) (b) (c) (d)

Fig. 1. Water droplets on (a) porous PTFE membrane standard; (b) silicone encapsulated nylon fabric; (c) untreated military uniform fabric; (d) commercial nanotech DWR on military uniform fabric.

Fabric testing included measurements of the relevant transport properties of water vapor diffusion and air permeability, as well as material characteristics such as water entry pressure (resistance to liquid penetration), liquid spray repellency, and fabric pore size. Since the application of the DWR treatments was for soldier duty uniforms, the durability to laundering was an important issue. Details on the test methods used may be found in the references (Gibson, 1999, 2000; Gibson et al, 1999, 2000).

Two of the water-repellent treatments had good durability to laundering. One treatment had very poor durability, and lost all its water-repellent properties after 20 laundering cycles. The Quarpel-treated control fabric performed better than any of the experimental treatments. None of the water-repellent treatments significantly affected the breathability, air flow resistance, or pore size of the control fabric. (Gibson, 2005).

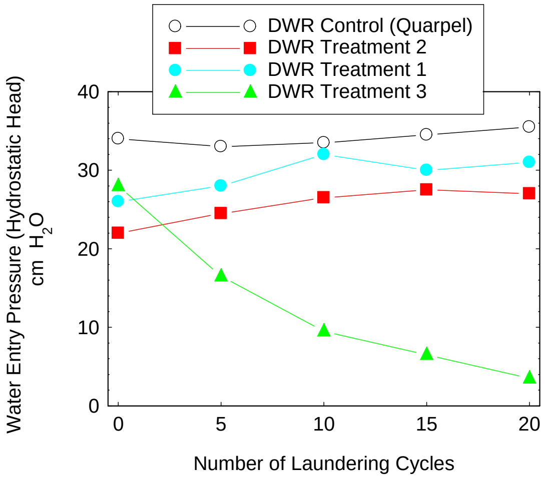


Fig. 2. Laundering affects hydrostatic head of four water-repellent fabric treatments. Fabric shrinkage after laundering can increase hydrostatic head due to smaller fabric pores.

3. PHYSIOLOGICAL MODELING

Following the laboratory characterization of the effectiveness of these DWR treatments, a field trial was conducted to determine the usefulness of making soldiers combat and duty uniforms water-repellent. The previously posed questions of 1) "What are the physiological implications of changing the BDU fabric from a wicking fabric to a non-wicking fabric?"; 2) "Will the fabric still be comfortable when a soldier is sweating heavily?"; and 3) "Will liquid sweat now remain on the skin underneath the fabric, and is this bad or good?", were answered when soldiers found that they disliked the treated uniforms in a hot and humid environment due to the lack of wicking of sweat from their bodies out through the clothing.

Combined physiological/fabric modeling was used to examine the relative importance of wicking versus the other fabric properties for this situation. The case of a wicking versus a nonwicking fabric, using the BDU fabric as the test case, has been examined previously (Gibson et al., 1997), and the results were applicable to this situation.

A physiological model of an exercising human was combined with a fabric model that accounts for heat transfer, sorption, diffusion, and liquid water transport through the fabric structure. The physiological model was based on research done for NASA (Stolwijk and Hardy, 1977), and was combined with a comprehensive model for coupled heat and mass transfer in porous materials (Gibson, 1996).

For the wicking fabric (untreated BDU fabric), the modeling approach assumed a very high liquid permeability and very high capillary pressures, which cause any liquid sweat at the skin surface to be quickly distributed within the free porosity of the fabric. This allows comparison of two different clothing materials that are identical in all their properties except that one material will wick sweat away from the skin surface, while the other does not allow wicking through its structure. For the nonwicking case, the liquid sweat remains on the skin, but it is allowed to evaporate based on the local skin temperature, vapor pressure, and local relative humidity gradient.

For the wicking fabric, 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. An example is shown in Figure 3 for the case of a wicking versus a nonwicking fabric, when a human goes from a light work rate (20 Watt/m^2) to a heavy work rate (200 Watt/m^2) for 1 hour, and then back to a light work rate.

Environmental conditions in both cases are air temperature of 30°C and relative humidity of 65%. Details of the modeling approach are given in the reference (Gibson et al., 1997).

The fabric properties are based on the 50/50 nylon/cotton temperate BDU fabric (twill weave, 0.255 kg/m^2 areal density, 550 kg/m^3 bulk density, 4.6 x 10^{-4} m thickness).

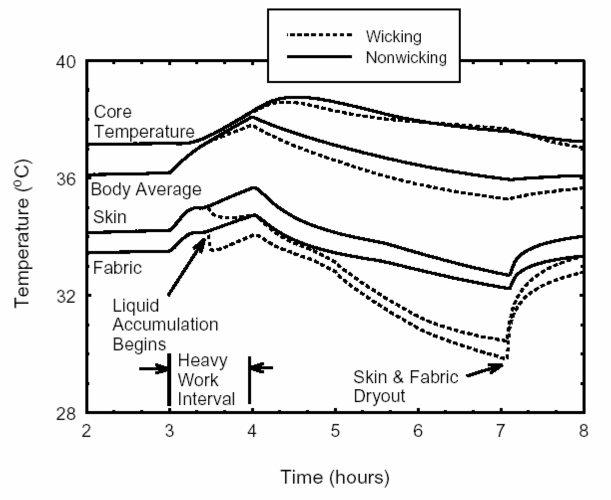


Fig 3. Comparison of a wicking versus a nonwicking fabric (other properties identical) during changes in human work rate.

The model run in Fig. 3 shows that there are some differences in the two fabrics, particularly in the skin temperature and in the fabric temperature. The wicking fabric becomes soggy after a while (from the point indicated as “Liquid Accumulation Begins”), and takes some time to dry out. The nonwicking fabric doesn’t soak up water, so the temperatures of the fabric and of the skin remain higher. Perhaps the nonwicking fabric in this case will feel less comfortable, due to the large differences in calculated skin temperatures between the wicking and nonwicking cases. However, the important physiological parameter for heat stress (core temperature) remains nearly identical, indicating little difference in heat strain potential between the two fabrics.

4. DIFFERENTIAL TREATMENTS:

Water-Repellent Finish on Outer Fabric Surface, Variable Finish on Inner Fabric Surface

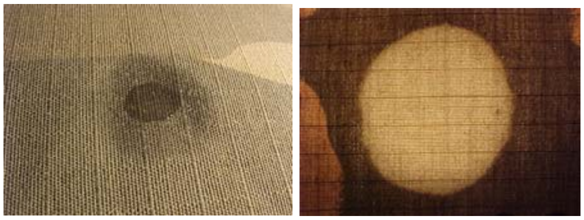
An additional five finish variations were supplied for the advanced combat uniform (ACU) fabric. One of the DWR treatments allows great flexibility in “tailoring” the treatment to various levels on the outer and inner surfaces of fabrics. The treatments provided a gradation of wicking properties on the inner fabric face, and various levels of water repellency on the outer fabric face. The addition of wicking properties to a water-repellent fabric should provide more comfort in hot and humid environments. These variable treatments helped mitigate the shortcomings of the fabric that was fully treated for water-repellency on both the inner and outer faces

The finish variations examined are listed below:

1) Untreated
2) Outer Face: Medium Repellency
   Inner Face: Good Wicking
3) Outer Face: Good Repellency
   Inner Face: Moderate Wicking
4) Good Repellency on
   Both Inner and Outer Face
5) Comparison Reference:
   Stretch-Woven Nylon Fabric
   (Schoeller Dynamic)
   Good Repellency on Outer Face
   Good Wicking on Inner Face

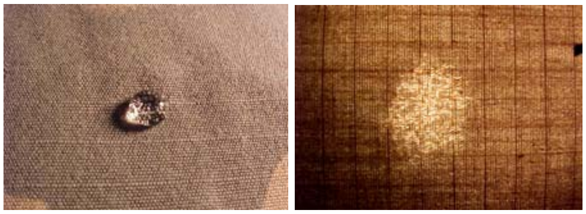
Water drops were applied to either the outer or inner face of fabric (not at the same time). For the inner face, the drop was allowed to spread, and then the wet zone was shown by shining a light through the fabric, as shown in Fig. 4.

Outer Fabric Face **Backlit Inner Fabric Face**
(drop applied to outer face) **(drop applied to inner face)**



1) Untreated Fabric
Wicks on Both Sides

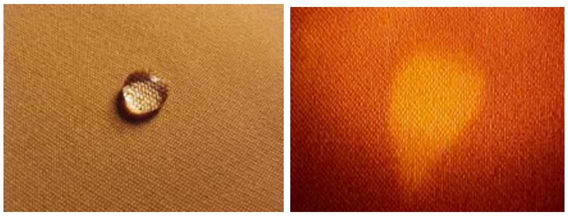
2) Moderate Water Repellent on Outer Face,
Good Wicking Finish on Inner Face



3) Good Water Repellent on Outer Face,
Moderate Wicking Finish on Inner Face

Outer Fabric Face **Backlit Inner Fabric Face**
(drop applied to outer face) **(drop applied to inner face)**

4) Good Water Repellent on Outer and Inner Faces
(backlighting not necessary)



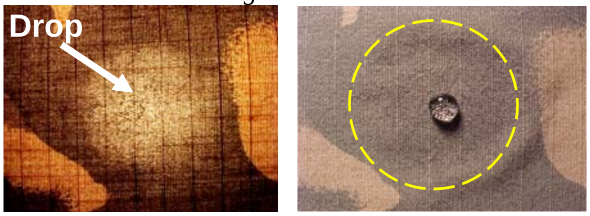
5) Stretch Woven Nylon Commercial Outerwear:
Good Water Repellent on Outer Face,
Good Wicking Finish on Inner Face

Fig. 4. Water drop on inner/outer faces of fabrics with differential treatments.

In Fig. 4, water drops were applied to only the inner or outer fabric face and photographed.

The fabrics that have the differential treatments retain their water repellency on the outer face, even if the inner face has a wicking finish and is wet. As shown in Fig. 5, a drop is applied to the inner fabric face and allowed to spread, and then a drop is applied to the outer face. The first picture shows the fabric backlit to show the extent of wicking/spreading on the inner face, and the second picture shows the same fabric with the lighting changed to better show the water droplet on the outer fabric face.

Treatment (2)
Moderate Water Repellent on Outer Face,
Good Wicking Finish on Inner Face



Backlit Outer Face (difficult to see drop)

Normal Lighting, Outer Face (yellow indicates wet area on inside)

Fig. 5. Wet fabric on inside doesn't affect repellency on outside.

4.1 Drying Experiments on Differential DWR Treatments

Water was applied to the inner surface of the DWR differential-treated fabrics as shown in Fig. 6. The fabric was conditioned in a flow cell, and 0.1 g of water was applied to the surface. Dry air at 30°C flowed past the outer surface of the fabric. A water concentration detector monitored the water vapor concentration of the exiting gas stream. The vapor flux over time was calculated from the gas flow, temperature, and water vapor concentration of the gas stream leaving the test cell.

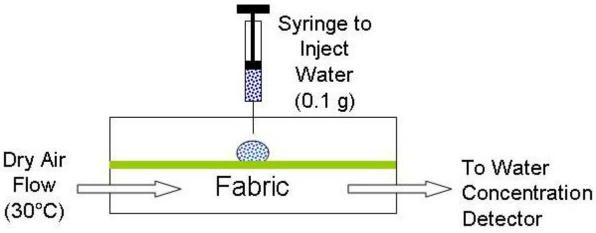


Fig. 6. Test configuration for drying experiments.

The drying time and vapor flux are related to spreading of liquid on the surface and through the fabric thickness. As shown in Fig. 7, the drying time was hindered by the water repellent finish.

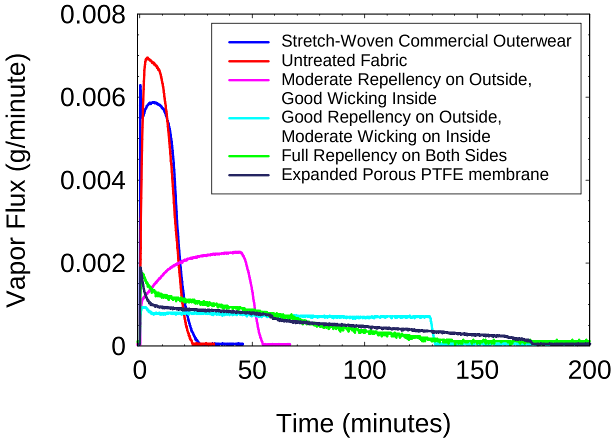


Fig. 7. Drying curves for differential DWR fabric treatments.

The commercial water-repellent "soft-shell" stretch-woven performed as well as the untreated wicking fabric. The "soft-shell" fabric is specifically engineered to provide good water repellency, while proving comfort through a wicking finish on the inner surface. The differential treatment on the ACU fabric is not as effective as for the "soft-shell," probably because the ACU fabric is a much heavier material and is a single woven fabric (the "soft-shell" fabric has different fiber configurations on the two sides of the fabric). The treatment (2) that created an outer face with medium repellency and an inner face with good wicking properties would be a comfortable compromise between a fully-repellent fabric and the fully-wicking fabric.

CONCLUSIONS

Two of the water-repellent treatments had good durability to laundering. One treatment had very poor durability, and lost all its water-repellent properties after 20 laundering cycles. The Quarpel-treated control fabric performed better than any of the experimental treatments. None of the water-repellent treatments significantly affected the breathability, air flow resistance, or pore size of the BDU fabric (Gibson, 2005).

It was found that the standard Battle Dress Uniform (BDU) fabric can be modified with very effective water-repellent treatments. Soldiers' duty and combat uniforms can be made water-resistant and retain the same air permeability and "breathability" properties as the untreated wicking fabric. Following a separate field trial using combat uniforms with and without a DWR treatment, it was found that these treatments decreased the comfort of the uniform in hot environments. The differences between the comfort of the control uniform and those treated with the DWR treatments are probably not due to intrinsic differences in the air permeability or the water vapor diffusion resistance (breathability) of the fabric. It is more likely that the non-wicking behavior of the fabric was responsible for perceived comfort differences, per comments from the field trial, and by analysis of wicking/comfort properties contained in this report.

Some of the DWR treatments are available as coatings on just one side of the fabric. The outer layer of the fabric can be made water-repellent, while the inner surface retains its wicking characteristics. Based on comments from the field trial, and modeling results, such asymmetric treatments would improve the comfort of DWR treatments on military duty uniforms as compared to full water-repellency on both sides of the fabric.

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