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Heat strain in chemical protective ensembles: Effects of fabric thermal properties

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ABSTRACT

An ongoing challenge in material science has been to reduce heat strain experienced by individuals wearing chemical protective ensembles. The objective of this study is to analyze the relationship between the thermal properties of eight chemical protective fabrics and heat strain in ten chemical protective ensembles constructed with those fabrics. The fabric samples were tested on a sweating guarded hot plate to measure fabric thermal and evaporative resistance. The ensembles were then tested on thermal manikins to measure ensemble thermal and evaporative resistance. An empirical thermoregulatory model, the Heat Strain Decision Aid (HSDA), was used to predict thermal responses of core temperature and endurance times. Model inputs included ensemble thermal and evaporative resistances, four environmental conditions and a metabolic rate of 400 W. The fabric intrinsic thermal and evaporative resistances ranged from 0.01 to 0.05 $m^2\,°C\cdot W^{-1}$ and from 5.9 to 12.82 $m^2\,Pa\cdot W^{-1}$, respectively. Ensemble intrinsic thermal and evaporative resistances ranged from 0.23 to 0.31 $m^2\,°C\cdot W^{-1}$ and 51.7–67.8 $m^2\,Pa\cdot W^{-1}$, respectively. Predicted endurance times varied from 170 to 300 min at 20 °C/50% RH/2 $m\,s^{-1}$ and 26 °C/55% RH/9 $m\,s^{-1}$ conditions, and varied from 91 to 98 min at 30 °C/75% RH/2 $m\,s^{-1}$ and 40 °C/20% RH/2 $m\,s^{-1}$ conditions. Improved fabric thermal properties reduced heat strain and extended endurance times, but the magnitude of the extended times is dependent on the environmental conditions. Consequently, the benefits of improved fabric thermal properties may only be observed under certain environmental conditions.

1. Introduction

An ongoing challenge in material science has been to reduce heat strain experienced by individuals wearing chemical protective ensembles. Chemical protective ensembles are designed to protect individuals from hazardous agents, such as chemical, biological, radiological, nuclear and explosive threats. On the other hand, chemical protective ensembles increase thermal resistance and evaporative resistance, thereby limiting heat loss from the body to the environment, and increasing the risk of heat illness and injury (Nunneley, 1989; O'Brien et al., 2011; Bernard et al., 2010; Bensel and Santee, 2006; Xu et al., 2016b). The chemical protective fabrics, i.e. barrier components of protective materials, have been considered one of the major obstacles to reducing the thermal burden of personal protective equipment. These can include, but are not limited to, membranes, sorptive fabrics, and aerosol filtration materials. Fabric properties (e.g., thermal resistance, evaporative resistance, and thickness) have improved over time (Xu et al., 2019; Havenith et al., 2011). However, the improvements have not always translated into significant improvements at the ensemble level, nor have the improvements resulted in a significant reduction in heat strain during human physiological studies.

The thermal properties of a protective ensemble differ from the thermal properties of fabric, and are influenced by not only the fabric, but also by the airgap, design and any layers added to the ensemble, e.g. mask, gloves (Xu et al. 2016b, 2019; Holmer, 2006; Psikuta et al., 2018; Mert et al., 2015). A recent study showed that the fabric thermal properties contribute about 10–14% to the thermal properties of multilayer protective ensembles (Xu et al., 2019). In addition to ensemble thermal properties, heat strain in a chemical protective ensemble is also influenced by its mass and an increase in metabolic heat production associated with the mass and hobbling effects (Xu et al., 2016b; Taylor et al., 2012; Dorman and Havenith, 2009; McLellan et al.,

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2013). The heat strain experienced when chemical protective ensembles are worn is determined by a number of factors. Fabric thermal properties are just one of the factors contributing to the thermal burden of chemical protective clothing. A few studies have examined the effect of fabric thermal and evaporative resistances on heat strain (Wen et al., 2016; Kim et al., 2014; Epstein et al., 2013; Havenith et al., 2011). Their study results have not been consistent. One study found a strong correlation between heat strain and fabric evaporative resistances (Wen et al., 2016), and another study found little correlation (Epstein et al., 2013). It is thus not clear to what extent fabric thermal properties affect heat strain.

The purpose of this paper is to examine the relationship between the thermal properties of eight fabrics and heat strain in ten chemical protective ensembles constructed with those fabrics. This study measures the thermal properties of eight fabrics on a hotplate, and then the thermal properties of the ten chemical protective ensembles constructed with those fabrics on a thermal manikin. An empirical thermal model was then used to predict the heat strain in these ensembles for four environmental conditions. These results will be analyzed to gain insight into the effects of fabric thermal properties on heat strain.

2. Methods

2.1. Fabric and ensemble samples

Eight fabrics and ten ensembles (configurations) were included in this study. The fabrics, as shown in Table 1 and Table 2, include a reference fabric (RF-A) used in a standard issue work or duty uniform (RG-A), and seven other chemical protective materials. The RF-A properties were included to establish an upper performance limit for the analysis incorporated into this study.

The ten ensembles are listed in Tables 1 and 2. All the ensembles were adult male medium regular size for thermal manikin fit. Each ensemble included a garment, undergarments (100% polyester, 307g, DSCP by Skilcraft), socks (100% cotton Crew Length Athletic Socks, 49 g, Hanes), boots (Hot Weather Combat Boots, 1662 g, Belleville), backpack, hydration pack, and load carriage belt (MOLLE Rifleman Kit with Assault Pack). In addition, each ensemble included the following chemical protective layers: gloves, boots, and mask with a chemical protective hood worn and tightened around the mask. Seven ensembles include body armor as well.

Table 1
Fabric thermal resistance measured on hotplate and ensemble thermal resistance measured on thermal manikin.

No.	Fabric	Thermal Resistance $m^2 \cdot {}^\circ C \cdot W^{-1}$		Ensemble[a]		Thermal Resistance $m^2 \cdot {}^\circ C \cdot W^{-1}$	
		Total	Intrinsic	Garment[b]	Layers[c]	Total	Intrinsic
1	RF-A	0.087	0.017	RG-A		0.25	0.17
2	RF-A	0.087	0.017	RG-A	I	0.31	0.24
3	F-A	0.098	0.029	G-A2		0.32	0.25
4	F-A	0.098	0.029	G-A1		0.31	0.24
5	F–B	0.086	0.016	G-B	I	0.32	0.25
6	F–C	0.099	0.029	G-C	I	0.35	0.28
7	F-D	0.083	0.013	G-D	I	0.30	0.23
8	F-E	0.089	0.020	G-E	I	0.30	0.23
9	F–F	0.100	0.030	G-F	I	0.32	0.25
10	F-G	0.117	0.048	G-G	I	0.38	0.31

Bare plate thermal resistance 0.070 $m^2 \, {}^\circ C \cdot W^{-1}$, nude manikin thermal resistance 0.1 $m^2 \, {}^\circ C \cdot W^{-1}$.

[a] Ensembles consist of a garment and additional protective layers: (i.e., gloves, boots, and mask with a chemical protective hood worn and tightened around the mask).

[b] Garments consist of chemical protective clothing made from a fabric on the same row, and includes undergarments, socks, boots, backpack, hydration pack, and load carriage belt.

[c] Additional layers: I: body armor.

Table 2
Fabric evaporative resistance measured on hotplate and ensemble evaporative resistance measured on thermal manikin.

No.	Fabric	Evaporative Resistance $m^2 \cdot Pa \cdot W^{-1}$		Ensemble[a]		Evaporative Resistance $m^2 \cdot Pa \cdot W^{-1}$	
		Total	Intrinsic	Garment[b]	Layers[c]	Total	Intrinsic
1	RF-A	9.66	3.84	RG-A		37.7	28.1
2	RF-A	9.66	3.84	RG-A	I	46.7	38.0
3	F-A	11.7	5.9	G-A2		60.6	52.0
4	F-A	11.7	5.9	G-A1		60.4	51.7
5	F–B	14.4	8.6	G-B	I	67.4	58.8
6	F–C	13.6	7.8	G-C	I	69.6	61.3
7	F-D	15.3	9.5	G-D	I	64.7	55.9
8	F-E	13.1	7.2	G-E	I	64.7	55.9
9	F–F	14.8	9.0	G-F	I	62.3	53.7
10	F-G	18.6	12.8	G-G	I	75.8	67.8

Bare plate evaporative resistance 5.82 $m^2 \, Pa \cdot W^{-1}$, nude manikin evaporative resistance 12.7 $m^2 \, Pa \cdot W^{-1}$.

[a] Ensembles consist of a garment and additional protective layers (i.e., gloves, boots, and mask with a chemical protective hood worn and tightened around the mask).

[b] Garments consist of chemical protective clothing made from a fabric on the same row, and includes undergarments, socks, boots, backpack, hydration pack, and load carriage belt.

[c] Additional layers: I: body armor.

The garments were constructed from the fabric listed on the same rows of Tables 1 and 2. These garments were designed for various applications. For example, as shown Fig. 1, the garment was designed to be a continuous use garment worn in place of the standard duty uniform, and thus the design was based off of the standard duty uniform with only a T-shirt worn underneath. The garment material consists of a flame resistant ripstop cover fabric with a microporous expanded polytetrafluoroethylene (ePTFE) aerosol protective liner laminated to the cover fabric. Below the cover fabric and attached at the sewn seams is an

Fig. 1. Typical Garment with protective equipment, and associated concept sketch.

activated carbon cloth (187 g·m^{-2}). The total weight of the material composite is 420 g m^{-2}. The average weight of the eight garments was 2.01 kg, the RG-A weight was the lowest of 1.04 kg and the G-G weight was the highest of 3.68 kg. Some garments, such as the G-A2 and G-A1, have zippers that can be opened to vent the uniform in lower protection level and dissipate excessive body heat in order to reduce the thermal burden (Zippers were closed during manikin tests).

2.2. Measurement of fabric thermal and evaporative resistance

Fabric thermal and evaporative resistances were measured on a sweating guarded hotplate (Thermetrics, Seattle WA). Detailed methods for the measurement are provided by ASTM F1868-17 (ASTM International, 2009). The sweating guarded hotplate was installed inside a test chamber and each zone in the hotplate assembly was maintained at a constant temperature of 35 ± 0.1 °C during the measurement period. The test specimen rests flat against the plate and covers the measurement area of the hotplate as well as the surrounding thermal guard zone. For thermal resistance measurements, the environmental conditions were controlled at an ambient temperature of 20 °C ± 0.1 °C and a relative humidity (RH) of 50 ± 5%. For evaporative resistance measurements, the environmental conditions were maintained at 35 ± 0.1 °C and 40 ± 4% RH. The air velocity was maintained at 1.0 ± 0.1 m s^{-1} for both measures.

2.3. Measurement of ensemble thermal and evaporative resistance

Ensemble thermal and evaporative resistances were measured on a sweating thermal manikin (Thermetrics, Seattle WA) at static conditions (i.e., standing manikin, constant manikin surface temperature and constant chamber conditions), using standard procedures. Standard operating procedures for the thermal manikin included regulating the manikin surface at a constant temperature, and controlling environmental conditions, such as the ambient temperature, relative humidity and air velocity in the climatic chamber housing the manikin. Widely accepted test procedures for the operation of a thermal manikin are published by ASTM International (ASTM International, 2016b, a). Some requirements of the procedure include controlling the thermal manikin at a mean surface temperature of 35 ± 0.2 °C and using the parallel method for calculation of the total resistance. The ambient conditions for thermal resistance testing were 20 ± 0.5 °C, 50 ± 5% RH and a 0.4 ± 0.1 m s^{-1} air velocity. The ambient conditions for evaporative resistance testing were 35 ± 0.5 °C, 40 ± 5% RH and a 0.4 ± 0.1 m s^{-1} air velocity. During sweating tests, each manikin zone was controlled to a specific flow rate setpoint to ensure the skin fabric is saturated. The mean sweat rate was 680 ml h^{-1}·m^{-2}, with a range from ~100 to 1500 ml h^{-1}·m^{-2}.

2.4. Heat strain prediction

USARIEM has a well-established approach, combining manikin testing and mathematical modeling, to evaluate the thermal performance of ensembles and support the development of new ensembles (O'Brien et al., 2011; Xu et al., 2016b; Gonzalez et al., 1997; Potter et al., 2015a; Potter et al., 2015b; Xu et al., 2016a). This approach consists of two steps. First, the ensemble thermal and evaporative resistances are measured on a thermal manikin. Second, these thermal and evaporative resistances are used as inputs into a thermoregulatory model to predict human thermal responses under various combinations of physical activities and environmental conditions. This approach translates the ensemble biophysical properties into physiological responses, including heat strain and endurance times, thereby allowing garment and materiel developers to understand how their designs will affect human thermal responses.

The USARIEM's Heat Strain Decision Aid (HSDA) was used to predict heat strain in the chemical protective ensembles. The HSDA is an empirical model derived from an extensive database of human studies and has been validated with comprehensive data of human studies (Givoni and Goldman, 1972; Pandolf et al., 1986; Gonzalez et al., 1997; Potter et al., 2017). This model has been used to support development of guidance and doctrine for the military and public health (Department of the Army and Air Force, 2003; Institute of Medicine, 2005) and has been used extensively by USARIEM to evaluate heat strain in protective clothing, such as chemical protective clothing and body armor, and fluid intake (Potter et al. 2015a, 2015b; Gonzalez et al., 1997; Xu and Santee, 2011).

The HSDA predicts rise of the core temperature as a function of metabolic rate, clothing thermal properties and environmental conditions. Details and equations about HSDA have been reported in papers (Gonzalez et al., 1997; Givoni and Goldman, 1972; Pandolf et al., 1986) and thus only a few main equations are summarized here. The transient core temperature is calculated by:

$$T_{c,t} = T_{c,0} + \left(T_{c,f} - T_{c,0}\right)\cdot\left\{1 - e^{-K_{work}\cdot\left(t - t_{delay}\right)}\right\}$$

where $T_{c,t}$ is transient core temperature in °C; $T_{c,0}$ is initial core temperature in °C; $T_{c,f}$ is the equilibrium core temperature in °C; t is time in min; t_{delay} is time lag for work to induce the change in core temperature in min; K_{work} is a time constant for work output in min^{-1} and is determined by:

$$K_{work} = \frac{1 + 3\cdot e^{-0.3\cdot\left(T_{c,f} - T_{c,0}\right)}}{225}$$

The final equilibrium core temperature is calculated by:

$$T_{c,f} = T_{c,0} + 0.004\cdot(M - W_{ex}) + 0.0011\cdot Dry + 0.8\cdot e^{0.0047\cdot\left(E_{req} - E_{max}\right)}$$

Where M is metabolic rate in W; W_{ex} is external mechanical work in W; Dry is radiative and convection heat exchange in W (negative for heat loss); E_{req} is evaporative heat loss required in W; E_{max} is maximum possible evaporative heat exchange in W. Dry, E_{req} and E_{max} are determined by

$$D_{ry} = \frac{T_s - T_a}{R_t}\cdot A$$

$$E_{req} = (M - W_{ex}) + Dry$$

$$E_{max} = \frac{P_{s,sk} - P_{av}}{R_{et}}\cdot A$$

Where T_s is mean skin temperature in °C; T_a is ambient temperature in °C; R_t is ensemble total thermal resistance in m^2·°C·W^{-1}; A is body surface area in m^2; $P_{s,sk}$ is body skin saturation vapor pressure in Pa; P_{av} is ambient vapor pressure in Pa; R_{et} is ensemble total evaporative resistance m^2·Pa·W^{-1}.

HSDA inputs include: height, weight, metabolic rate (based on the activity), clothing parameters (i.e., thermal and evaporative resistances), and environmental conditions (e.g., temperature, humidity, air velocity). Model's outputs are: core temperature, sweat loss, and endurance times. The endurance time for this study is the time needed to reach a core temperature of 39 °C, and represents the level of heat strain. For HSDA simulation, the height, weight and metabolic rate were 1.77 m, 81.3 kg and 400 W, respectively. The metabolic rate of 400 W was selected to represent moderate work similar to some activities associated with chemical protective clothing. Then the HSDA model was run to predict endurance times under the following environmental conditions: 20 °C/50% RH/2 m s^{-1} (Temperate), 26 °C/55% RH/9 m s^{-1} (Hawaii), 30 °C/75% RH/2 m s^{-1} (Jungle) and 40 °C/20% RH/2 m s^{-1} (Desert). The mean radiant temperatures were 60 °C, 66 °C, 70 °C and 80 °C for Temperate, Hawaii, Jungle and Desert conditions respectively.

3. Results

Table 1 shows fabric thermal resistances measured on the hotplate and ensemble thermal resistances measured on the thermal manikin. The fabric intrinsic thermal resistances ranged from 0.013 to 0.048 $m^2\,°C{\cdot}W^{-1}$ while ensemble intrinsic thermal resistances ranged from 0.17 to 0.31 $m^2\,°C{\cdot}W^{-1}$. Table 2 shows fabric intrinsic evaporative resistances measured on the hotplate and ensemble intrinsic evaporative resistances measured on the thermal manikin. The fabric intrinsic evaporative resistances ranged from 3.84 $m^2\,Pa{\cdot}W^{-1}$ to 12.8 $m^2\,Pa{\cdot}W^{-1}$ while ensemble intrinsic evaporative resistances ranged from 28.1 to 67.8 $m^2\,Pa{\cdot}W^{-1}$.

Fabric intrinsic thermal resistances and predicted endurances are shown in Fig. 2. Fabric intrinsic evaporative resistances and predicted endurance times are shown in Fig. 3. Endurance times were affected by fabric thermal and evaporative resistances, but the magnitudes of its effects were dependent on environmental conditions. Endurance times varied from 170 to 300 min under the more moderate Temperate and Hawaii conditions while endurance times varied from 90 to 170 min in the more extreme Desert and Jungle conditions. At the latter two conditions, endurance times among the eight prototype chemical protective ensembles, No.3-No.10, were almost identical and varied only from 91 to 98 min although their fabric intrinsic thermal and evaporative resistances reduce from 0.048 to 0.013 $m^2\,°C{\cdot}W^{-1}$ and from 12.8 to 5.9 $m^2\,Pa{\cdot}W^{-1}$, respectively.

Predicted sweat losses were shown in Table 3. Average sweat losses were 1.07 and 0.99 $L\,h^{-1}$ under more moderate Temperate and Hawaii conditions, respectively. Average sweat losses were 1.32 and 1.33 $L\,h^{-1}$ in the more extreme Desert and Jungle conditions, separately. In general, the sweat losses reduce as the fabric thermal and evaporative resistances reduce.

4. Discussion

This report analyzed the relationships among thermal properties of eight chemical protective fabrics, thermal properties of ten multi-layer prototype chemical protective ensembles, and the predicted heat strain that would be experienced while wearing the prototype protective

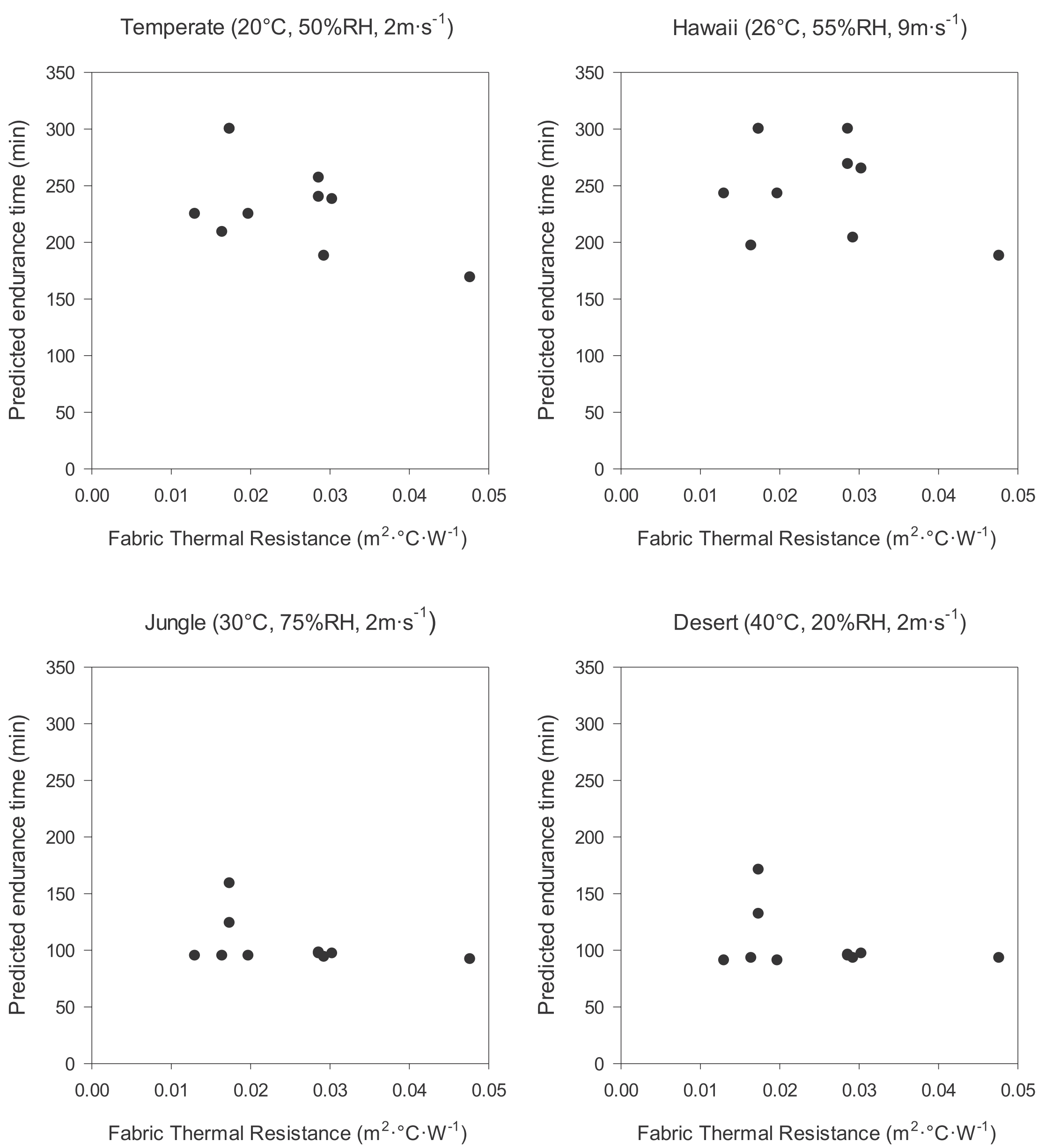

Fig. 2. Fabric intrinsic thermal resistances and predicted endurance times while wearing protective ensembles constructed with these fabrics and working at 400 W.

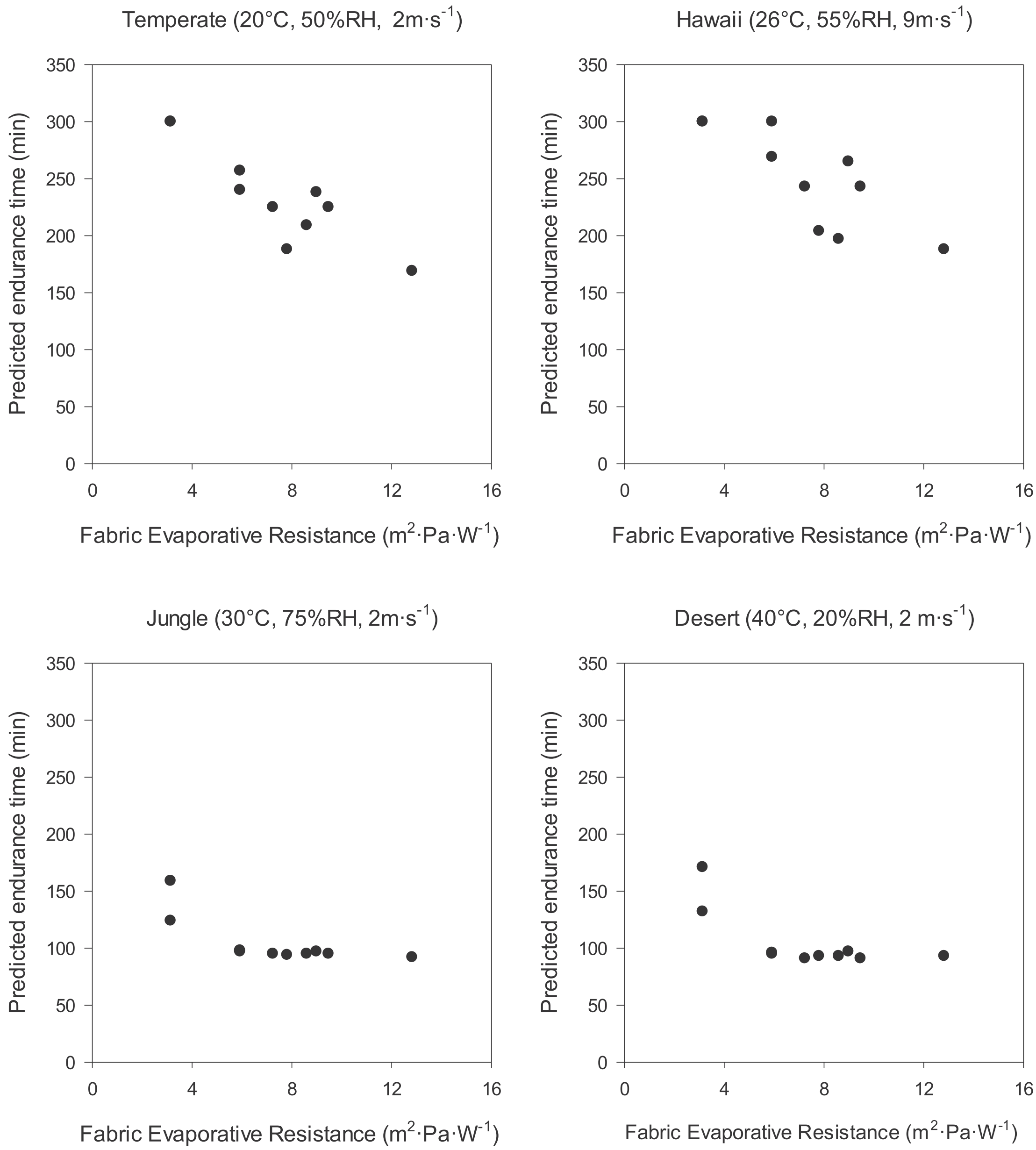

Fig. 3. Fabric intrinsic evaporative resistances and predicted endurance times while wearing protective ensembles constructed with these fabrics and working at 400 W.

Table 3
Predicted sweat loss while wearing protective ensembles constructed with these fabrics and working at 400 W

No.	Fabric	Garment	Sweat Loss ($L{\cdot}h^{-1}$)			
			Temperate	Hawaii	Jungle	Desert
1	RF-A	RG-A	0.75	0.55	0.99	0.99
2	RF-A	RG-A	0.95	0.81	1.16	1.15
3	F-A	G-A2	1.09	1.05	1.35	1.35
4	F-A	G-A1	1.08	1.07	1.34	1.35
5	F–B	G-B	1.14	1.07	1.43	1.41
6	F–C	G-C	1.18	1.08	1.43	1.41
7	F-D	G-D	1.1	1.05	1.37	1.37
8	F-E	G-E	1.1	1.05	1.37	1.37
9	F–F	G-F	1.09	1.05	1.35	1.35
10	F-G	G-G	1.24	1.13	1.49	1.45

ensembles during moderate exercise in four operational environments. The analyses reveal that the improvements in fabric thermal properties result in only modest improvements in the thermal properties of a chemical protective ensemble. It further reveals that improved fabric thermal properties reduce heat strain and extend endurance times, but the magnitude of the improved endurance times are dependent on the environmental conditions.

Figs. 2 and 3 illustrate that the effects of fabric thermal properties on predicted endurance times are dependent on the environmental conditions. The intrinsic evaporative resistances of the chemical protective fabrics, excluding the reference fabric RF-A, reduced from 12.8 to 5.9 $m^2\,Pa{\cdot}W^{-1}$, the corresponding predicted endurance times increased from 169 to 257 min at 20 °C/50% RH/2 $m\,s^{-1}$ conditions (Temperate), and from 188 to 300 min at 26 °C/56% RH/9 $m\,s^{-1}$ (Hawaii), but only change from 92 to 99 min at 30 °C/75% RH/2 $m\,s^{-1}$ conditions (Jungle) and from 91 to 97 min at 40 °C/20% RH/2 $m\,s^{-1}$ conditions (Desert). In general, the pattern of the predicted endurance times are consistent with observed results that endurance times wearing protective ensembles are dependent on environmental conditions (Santee et al. 1992, 1998; McLellan et al. 1993, 2013; Maley et al., 2017; Kim et al., 2014). For example, in one study 12 volunteers wore two chemical protective ensembles, exercised at metabolic rate of 378 W, and their endurance times at three environments of 18 °C/70% RH, 32 °C/50% RH and 32 °C/80% RH were 100 vs 100 min (trial limit), 95 vs 70 min, and 67 vs 52 min respectively (Santee et al., 1992). Similarly, when overt and covert protective ensembles were evaluated at a wet bulb globe temperature of 21, 30 and 37 °C (neutral, warm/wet and hot/dry), the work tolerance times were 120 vs 120 min (trial limit), 166 vs 89 min and 37 vs 48 min respectively (Maley et al., 2017). Additionally, as shown in Table 3, there is reduced sweat loss as fabric thermal performance increases, i.e., its thermal and evaporative resistances decrease. Thus, improved fabric thermal properties do translate into reduced heat strain in chemical protective clothing, but the magnitude of the reduction in heat strain, and resulting improved performance, is dependent on the environmental conditions.

Tables 1 and 2 show that fabric thermal and evaporative resistances make only a small contribution to the ensemble thermal and evaporative resistances. The remaining contributions to the ensemble thermal and evaporative resistances can be attributed to the additional protective layers in the ensemble and airgaps (Xu et al. 2017b, 2019). The head, hands and feet represent about 18% of the body surface area (Xu et al., 2017a), and are covered by chemical protective layers, e.g., masks, impermeable rubber gloves and boots, as shown in Fig. 1. The masks and rubber gloves alone can increase ensemble thermal resistances by about 15% and evaporative resistances by 19% (Xu et al., 2019). Body armor covers the torso area, which represents about 30% of the body surface area (Xu et al., 2017a), and can increase the ensemble thermal resistances by approximately 38% and the ensemble evaporative resistances by approximately 30% (Xu et al., 2017b). When convection is minimal in airgaps, thermal resistances increase by 0.038 $m^2\,°C{\cdot}W^{-1}$ per mm of airgap thickness (Gonzalez, 1988; Lotens, 1993) and evaporative resistances by 2.3 $m^2\,Pa{\cdot}W^{-1}$ per mm of airgap thickness (Psikuta et al., 2018; Wissler and Havenith, 2009). Airgaps vary by location, and range from about 3–4 mm to 50–60 mm for a shirt or normal uniform (Psikuta et al. 2012, 2018; Li et al., 2000; Mert et al., 2015). These airgaps may add a significant amount of thermal and evaporative resistance to an ensemble, and reducing airgap thicknesses will likely reduce ensemble thermal and evaporative resistances significantly.

The findings of this study have three practical implications. First, improved fabric thermal properties reduce heat strain and increase endurance times under some environmental conditions. For example, as shown in Table 2, intrinsic evaporative resistances of fabric F-G and F-E reduces from 12.8 to 7.2 $m^2\,Pa{\cdot}W^{-1}$. As a result, the corresponding predicted endurance times increase by about 55 min for the Temperate and Hawaii conditions, but only differ slightly for the Jungle and Desert conditions. If the endurance time could be extended by 55 min, that would clearly be operationally significant. To take full advantage of the extended endurance time afforded by an improved fabric, it is critical to know the environmental conditions under which endurance times would be extended. A mission planning tool, such as HSDA, can help mission planners assess various scenarios and make informed decisions. In other words, with help of HSDA or similar tool, mission planners can take full advantage of the improved fabric. A second consideration is that when human studies have been used to evaluate performance of chemical protective ensembles, the ambient conditions likely marked the uniform differently. The differences in measured physiological responses were often too small and/or variable to justify rank ordering the candidate chemical protective ensembles (Santee et al., 1998; Levine et al., 2001). When too hot or humid, the small but real difference can not be detected. When eight chemical protective ensembles were evaluated at 35 °C/50% RH environmental conditions and 400 W metabolic rates, no consistent differences were found among five prototypes of chemical protective clothing (Levine et al., 2001). Therefore, conditions for human studies, i.e., environmental conditions and activity levels, should be carefully selected to ensure there will be a wide enough range in the physiology responses to capture the small differences in fabric effects as well as differences among configurations. The manikin testing and modeling approach can help researchers select appropriate experimental conditions. Third, a final consideration is that heat strain in chemical protective clothing is the product of many factors. Therefore, it is incumbent on the research and development team to explore other options at the material level to maximize the potential for reducing the thermal burden, such as novel materials that actively transport water vapor away from the body or actively reducing heat gain from the environment.

The scope of this paper is limited to the relationship between fabric thermal and evaporative resistances and heat strain, excluding other fabric properties. Improvements in fabric porosity could also increase moisture transfer through the fabric and increase evaporative heat loss, thus reducing heat strain in chemical protective clothing (Havenith et al., 2011; Bernard et al., 2010; Epstein et al., 2013). Although chemical protective materials in protective clothing have been considered a major barrier to reducing heat strain, there is lack of research directed at those relationships. Often the thermal properties of fabrics are ignored, or barely reported. To fully understand and manage heat strain in chemical protective clothing, more research is needed to establish the connection between fabrics, ensembles, physiological responses and environmental conditions to properly capture subtle effects of fabric improvement.

5. Conclusions

This paper analyzed the relationship between the thermal properties of eight chemical protective fabrics and heat strain in ten chemical protective ensembles constructed with those fabrics. Improvements in fabric thermal properties reduced heat strain and extended endurance times, but the magnitude of the improvements were dependent on environmental conditions. Therefore, the benefits of improved fabric thermal properties may be observed and exploited only under certain environmental conditions.

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