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Thermal comfort materials and applications at NSRDEC

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Outline

- Overview of Natick Soldier R,D & E Center
- Application of responsive material to cold weather clothing
- Links for further information on NSRDEC and AFFOA
Non-Medical

Army Material Command

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NSRDEC MISSION
Providing the Army with Innovative Science & Technology Solutions to Optimize the Performance of Our Soldiers.

NSRDEC VISION
The Soldier's RDEC. Ensuring Dominance through Superior Scientific & Engineering Expertise.
Food, Clothing, Shelter, Supplies, Soldier Systems
Combat Feeding: What drives research?

• Processing/ packaging methods that enable production of fresh-like quality food.
• Biologically tailored, performance optimizing Soldier nutrition
• Targeted nutrition to extended physical & cognitive performance
• Reduced Soldier load using compact, performance enhancing rations
• Rapid detection and identification of food pathogens and toxins
• 3-D printing of food products on or near the battlefield
• Leverage biometric information to personalize nutrient needs of Soldiers
Individual Multithreat Protection: What drives research?

- Improved hand, arm, face protection from ballistic, blast, and flame/thermal threats.
- “Smart” fibers to maintain body temperature under a wide range of climatic conditions.
- Lightweight ballistic materials for flexible and hard armor, as well as transparent armor for eye protection.
- Flame resistant fibers and textile treatments with improved performance, domestic availability, and durability.
- Protection against chembio threat agents, disease-carrying insects.
- Capabilities to conceal across the spectrum from visible through thermal.
Expeditionary Basing and Collective Protection: What drives research?

- Multi-functional tactical habitats in diverse geographical climates and locations.
- Rapidly deployable base camp habitat and organizational equipment systems that enhance expeditionary maneuverability.
- Independence from fuel/water resupply, offering operational flexibility.
- Reduce footprint and maintenance requirements.
- Reduce resource consumption and waste generation. Reduce need for fuel resupply, water resupply, waste backhaul.
Air Drop and Aerial Delivery: What drives research?

- Reduce the signature of airdrop operations: Lower IR/RADAR signatures, dissolvable/camouflage canopies.
- New safety technologies for personnel insertion systems to include an automatic opening device for low altitude static line systems and advanced oxygen systems for military free fall systems.
- Enable on-demand tactical resupply to small unit/squads on the move. Payloads of 100-500lbs on request within 10m, with less than 10lb retrograde.
- Develop a high accuracy, low cost aerial delivery system. 1 ton system accuracy <25m, 35Kft altitude, 25+ mile offset.
- Autonomous service life monitoring
Human Performance Optimization: What drives research?

- Optimize the Soldier mind, body, and equipment
- Significantly decrease Soldier load
- Integrate power, data information systems on the Soldier to maximize situational awareness without cognitive overload.
- Novel approaches to enhance human performance (bioengineering)
- Enhanced biofidelic human modeling/encumbered anthropometry
- Sensory analysis and consumer research to optimize rations, clothing, and other areas
- Monitor and optimize cognitive performance of soldiers/squads in high-stakes environments
Technology Focus

- Fibers and Fabrics
- Films
- Coatings
- Printing on fabrics

- High Strength-to-Weight Fibers
- Flame Resistant Fibers
- Antimicrobial Fibers
- Conductive Fibers
- Antistatic Fibers
- Photovoltaic Fibers
- Smart Fibers - Sense and Respond
- Biomimetic Fibers
- Biodegradable Fibers
- Mono/Bi/Tri Component Fibers
- Dye-able High Performance Fibers
- UV Stable High Performance Fibers
- EMI Shielding Fibers
- Super omniphobic fibers
- Multifunctional Fibers
Our Soldiers are more capable than in any time in history, but their capability has come at the expense of over burdening them with systems which often weigh too much, inhibit mobility and contribute to physical and cognitive stress.

Our challenge is to formulate science and technology programs that can contribute to optimizing the performance of individual Soldiers and small squads, by reducing total weight and volume, while enabling increased physical and mental agility, particularly over extended periods.
Keywords for Soldier S&T

- Reduce weight
- Lower cost
- Rely on US materials/manufacturing
- Rapidly field
Soldier Domain Knowledge Network

RDECOM Forward
TRADOC
ARL
MCoE

Army Organizations

National Manufacturing Initiatives
Revolutionary Fibers & Textiles
Additive Manufacturing
Integrated Photonics
Advanced Composites
Flexible Hybrid Electronics

Army, DoD, Customers

NSRDEC
In-house Research

Industry

MIT
UMass Lowell
Tufts
WPI

NSRDEC Academic Collaborations

ARO Extramural Research
MURIs

Single Investigators

ISN
UARCs
ICB
ICT

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Thermal balance maintained by sweating, some change in body temperature AND actions of wearer.

Heat loss to night sky

Solar radiation 0 to 680 watts

Heat loss by radiation, conduction, and natural convection

Internal heat generation
- 105 watts at rest
- 300 watts moderate work
- 500 watts maximum sustained
- ~1000 watts peak work rate

Heat loss by wind
(still air adds ~1 clo)
Heat Balances, Rates of Change

• Change of location, hours – days
  ➢ Mount Washington, 6/20/04
    ▪ Pinkham Notch, 65º F, 15 mph wind, Sunny
    ▪ Summit 23º F, 60 mph wind, Rime Ice

• Solar load – minutes (0 to 680 watts)
  ▪ Adds as much power as hard work
  ▪ Based on AM1.5 solar spectrum

• Wind - minutes (up to 1 Clo)
  ▪ As much as ¼ to ½ of insulation requirement
  ▪ Burton & Edholm “Man in a Cold Environment”

http://www.cs.dartmouth.edu/whites/pinkham.html
Mt Washington observations: A. Jessiman
Required Insulation for Thermal Equilibrium

Edholm & Burton
“Man in a Cold Environment”
Advantages of Adaptive Insulation

• Increased temperature range
  ▪ Possible reduction of number of items

• Requires less user intervention
  ▪ Self regulating
  ▪ Continuously variable insulation

• Improved moisture management
  ▪ Reduce sweating and water requirements
  ▪ Reduce moisture build-up in garments
Adaptive Insulation Concept

- Fibers act like a bi-metal spring coiling when cooled.
- Coiled fibers create loft, which provides insulation.

3 different polymers - Fibers curl, batting gets thicker.*

3 components using the same polymer - No curling or change in thickness.

* In the interests of full disclosure - this initial curling probably includes some stress relaxation.
Batting Thermal Resistance

\[
\frac{1}{R} = \frac{q_{tot}}{A(T_i - T_o)} = \left( \frac{k_a}{x} + I \right)
\]

Thermal resistance \hspace{1cm} Batting thickness \hspace{1cm} Radiant heat transfer (not a function of thickness)

I and \( k_a \) both decrease with temperature.

Fiber Bending Theory

• The bending of a bi-metal strip was first calculated by Timoshenko\textsuperscript{1} in 1925.

• A combination of a crystalline and amorphous polymer will give a large difference in coefficient of thermal expansion.
  • Unfortunately, this combination is not efficient at producing bending because of a large difference in stiffness between the two materials.

• By extending Timoshenko’s analysis to geometries other than flat strips, bending for fibers with very different stiffnesses can be maximized\textsuperscript{2}.


\textsuperscript{2}DeCristofano et al. Proceedings MRS Fall 2010 Boston MA.
• Assuming no slippage at the interface, the elongation in each must be equal:

\[
\alpha_1 (t - t_0) + \frac{P_1}{E_1 A_1} + \frac{a_{11}}{2\rho} = \alpha_2 (t - t_0) - \frac{P_2}{E_2 A_2} - \frac{a_{22}}{2\rho}
\]

thermal strain  axial strain  bending strain

A Lot of Math Later…

Response is linear with CTE difference and temperature change.

\[
\frac{1}{\rho} = \frac{24(\alpha_2 - \alpha_1)(T - T_0)}{h(A + Bn + \frac{C}{n})}
\]

Where:
- \( \rho \) is the radius of curvature
- \( \alpha \) is the coefficient of thermal expansion for material 1 or 2
- \( T \) is the temperature
- \( T_0 \) is a reference temperature where the fiber is straight
- \( n \) is the ratio of the Young’s moduli of the two components
- \( h \) is the height or diameter of the fiber
- \( A, B, \) and \( C \) are a function of the fiber geometry

Small fibers have a stronger response.

This term can be optimized for any given “n”.

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Fiber Cross-Section

Concept

Actual fibers

Polymer 1, amorphous (low modulus, high CTE)

Compatibilizer layer (plus pigment)

Polymer 3, crystalline (high modulus, low CTE)

Predicted curvature for bi-component
Triangular cross section fiber

Maximum curvature
• Looking more closely at the results for the triangle configuration:

Triangular curvature vs. upper triangle height fraction and moduli ratio

Fiber 1 is in this region
Measured Thickness Change

- Test 1 27C
- Test 2 27C
- Test 1 0C
- Test 2 0C
- Test 1 -20C
- Test 2 -20C

-20 C (-4 F)
0 C (32 F)
27 C (80 F)
Small changes in composition result in large changes in performance.
Response of Clothing Insulation to Temperature

- Thermal insulation that adapts to the environment extends the useful temperature range of a clothing item.

- Required thermal insulation for moderate activity (3 Met)

Conventional insulation

Adaptive insulation
\[ q_{\text{conv}} = h(T_s - T_\infty) = \frac{(T_s - T_\infty)}{R_{\text{conv}}} \quad \text{and} \quad q_{\text{cond}} = \frac{(T_0 - T_s)}{R_{\text{cond}}} \]

- We can’t directly measure \( R_{\text{conv}} \) when a sample is in place, but ASTM F1868 provides a method for determining it.
- The resistance used is the resistance calculated from GHP data when no sample is present on the bare plate, \( R_{bp} \).
- The resistance of the sample is the total resistance calculated from GHP with the sample in place, \( R_{tot} \), minus the bare plate resistance.
- Then, \( h(T_s - T_\infty) = \frac{(T_s - T_\infty)}{R_{bp}} \) combined with \( q_{\text{cond}} = \frac{(T_0 - T_s)}{R_{\text{cond}}} \) yields,

\[
\frac{(T_s - T_\infty)}{R_{bp}} = \frac{(T_0 - T_s)}{R_s} \quad \text{(where, } R_{\text{cond}} \text{ has been replaced with } R_s, \text{ the sample resistance.)}
\]
• From the GHP data,

<table>
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<th>$T_\infty$</th>
<th>$T_0$</th>
<th>$R_{tot}$</th>
<th>$R_{bp}$</th>
<th>$R_s$</th>
<th>$T_s$</th>
<th>$T_{sample}$</th>
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<td>20</td>
<td>35</td>
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<td>0.355</td>
<td>1.522</td>
<td>2.6</td>
<td>18.8</td>
</tr>
</tbody>
</table>

(temperatures units are °C and resistance units are clo)

• For a change in sample temperature of 10.3 °C, an increase in clo of 0.211 was measured (over a 25 °C ambient temperature range).

→ 1.56 % / °C
Notes: Specific insulation [Intrinsic Clo/(oz/yd²)] at various air temperatures with plate at 35 C. “Bare plate clo” = 0.355
The thermal conductivity of air is a function of temperature and the net radiant heat transfer through the batting varies approximately as the cube of the mean temperature (absolute) which leads to a slight increase in clo with decreasing temperature for the control.
Thermal Insulation as a Function of Air Temperature in Guarded Hot Plate Test

Total Clo at various air temperatures with plate at 35 C

Note: The thermal conductivity of air is a function of temperature and the net radiant heat transfer through the batting varies approximately as the cube of the mean temperature (absolute) which leads to a slight increase in clo with decreasing temperature for the control.

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Total Clo/(oz/yd²) at various air temperatures with plate at 35 C

Note: The thermal conductivity of air is a function of temperature and the net radiant heat transfer through the batting varies approximately as the cube of the mean temperature (absolute) which leads to a slight increase in clo with decreasing temperature for the control.
• “AFFOA is an advanced manufacturing institute created to bring demonstrated technologies to pilot scale production. Technologies in the DELTA program fit also into AFFOA's mission. I would be delighted to attend this event to define synergies between the outcome of this program and AFFOA's mission to scale and commercialize.”

• Aimee Rose - Chief Technology Officer for Advanced Functional Fabrics of America (AFFOA)
• Partnering with NSRDEC

• Manufacturing USA & AFFOA
  – https://www.manufacturingusa.com/institutes
  – http://join.affoa.org/membership/
US Army Natick Soldier Research, Development & Engineering Center

The Science Behind the Soldier

Yesterday, Today and Tomorrow