Temperature Adaptive Insulation

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Heat Balances, A Rough Guide

Heat loss to night sky

Solar radiation 0 to 680 watts

Heat loss by radiation, conduction, and natural convection

Heat loss by wind
(still air adds ~1 clo)

Internal heat generation

105 watts at rest
300 watts moderate work
500 watts maximum sustained
~1000 watts peak work rate

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

Heat Balances, A Rough Guide

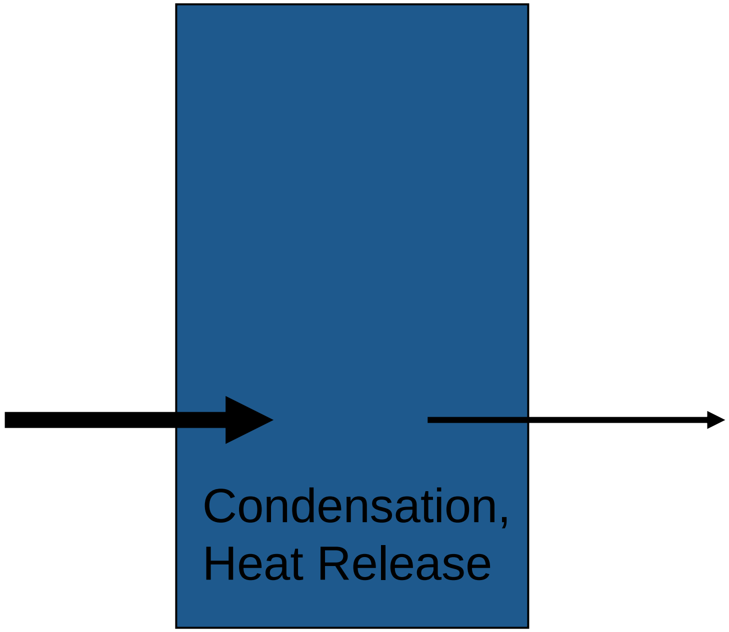
Each 100 watts of excess heat generation produces 148 g sweat/hour

Insulation Layer

Inside,
91 F (33 C)
High humidity

Outside air
Low temperature
Low saturation pressure

Evaporated
sweat



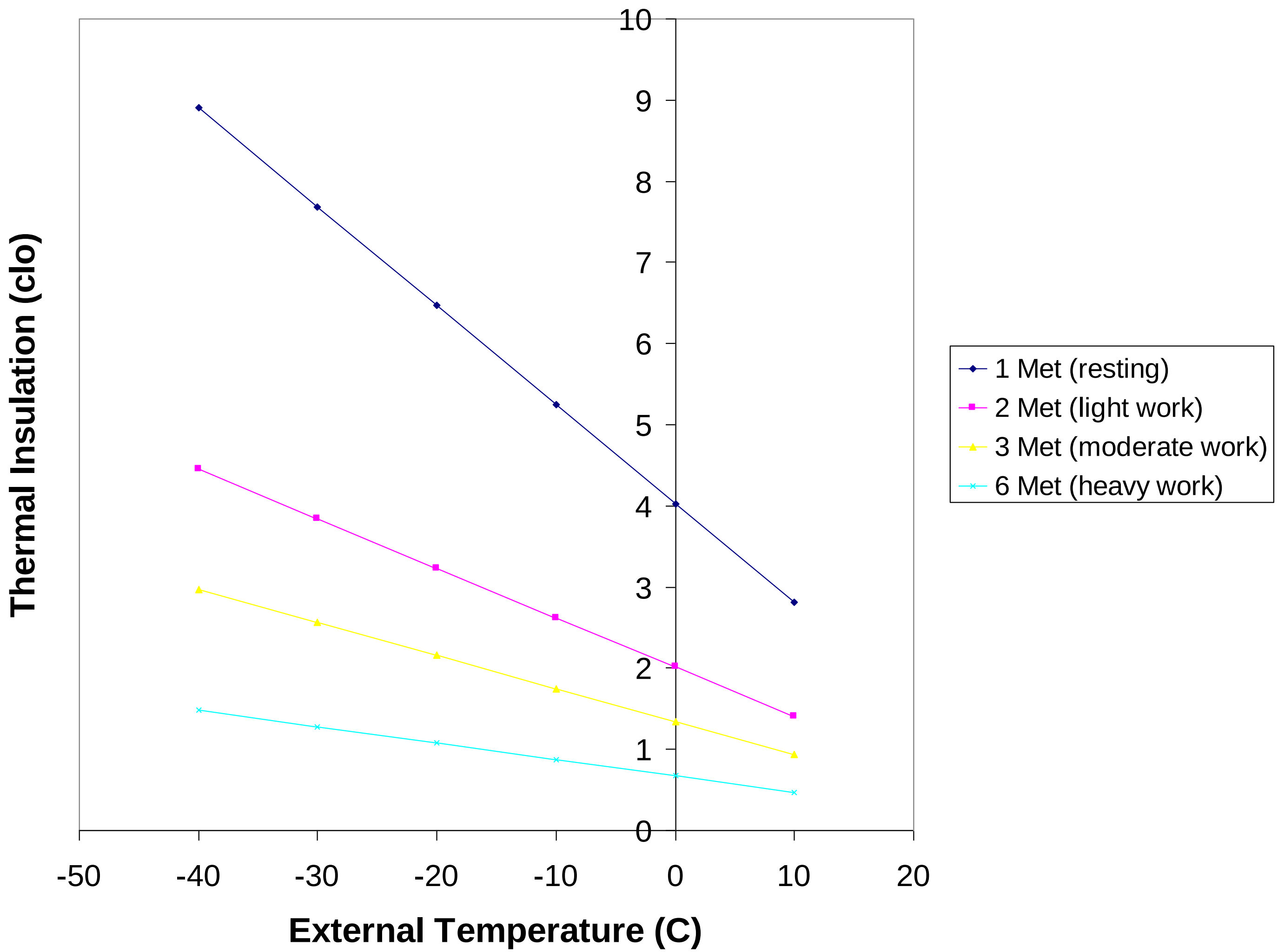
Slowly condensed
Sweat re-evaporates
Removing heat
Possible excess cooling

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



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.

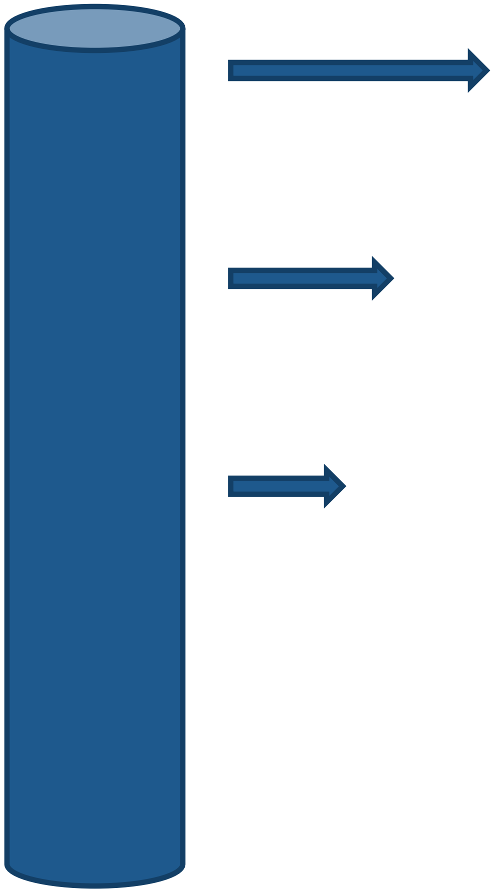
3 different polymers - Fibers curl, batting gets thicker.*

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.

Fiber Bending Theory

- The bending of a bi-metal strip was first calculated by Timoshenko[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[2].



[1]Timoshenko, S. Analysis of Bi-metal Thermostats. *J. Opt. Soc. Am.* 1925, **11** (3), pp.233-255

[2]DeCristofano et al. Proceedings MRS Fall 2010 Boston MA.

A Lot of Math Later…

Response is linear with CTE difference and temperature change.

"Curvature"

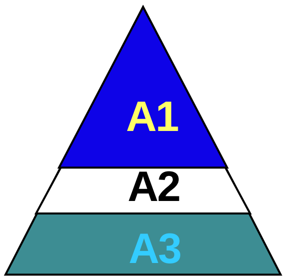
$$\frac{1}{\rho} = \frac{24(\alpha_2 - \alpha_1)(T - T_0)}{h(A + Bn + C/n)}$$

Small fibers have a stronger response.

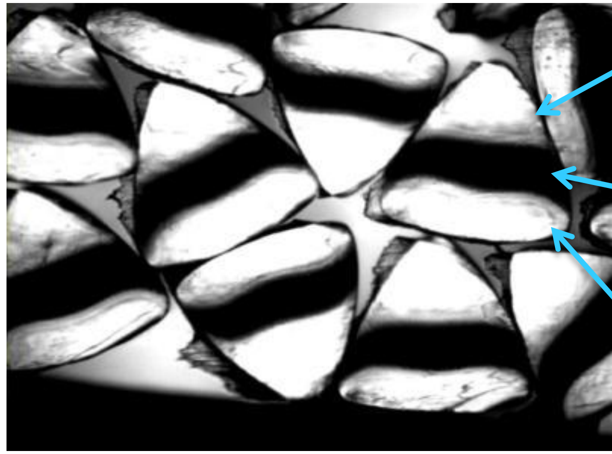
This term can be optimized for any given "n".

Where:
ρ Is the radius of curvature
α 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

Fiber Cross-Section



Concept



Actual fibers

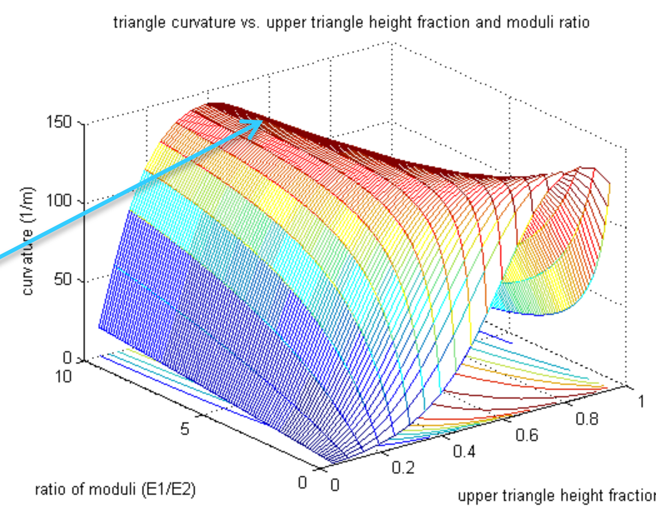
Polymer 1, amorphous
(low modulus, high CTE)

Compatiblizer layer
(plus pigment)

Polymer 3, crystalline
(high modulus, low CTE)

Predicted curvature for bi-component
Triangular cross section fiber

Maximum curvature



High Performance Fiber Facility

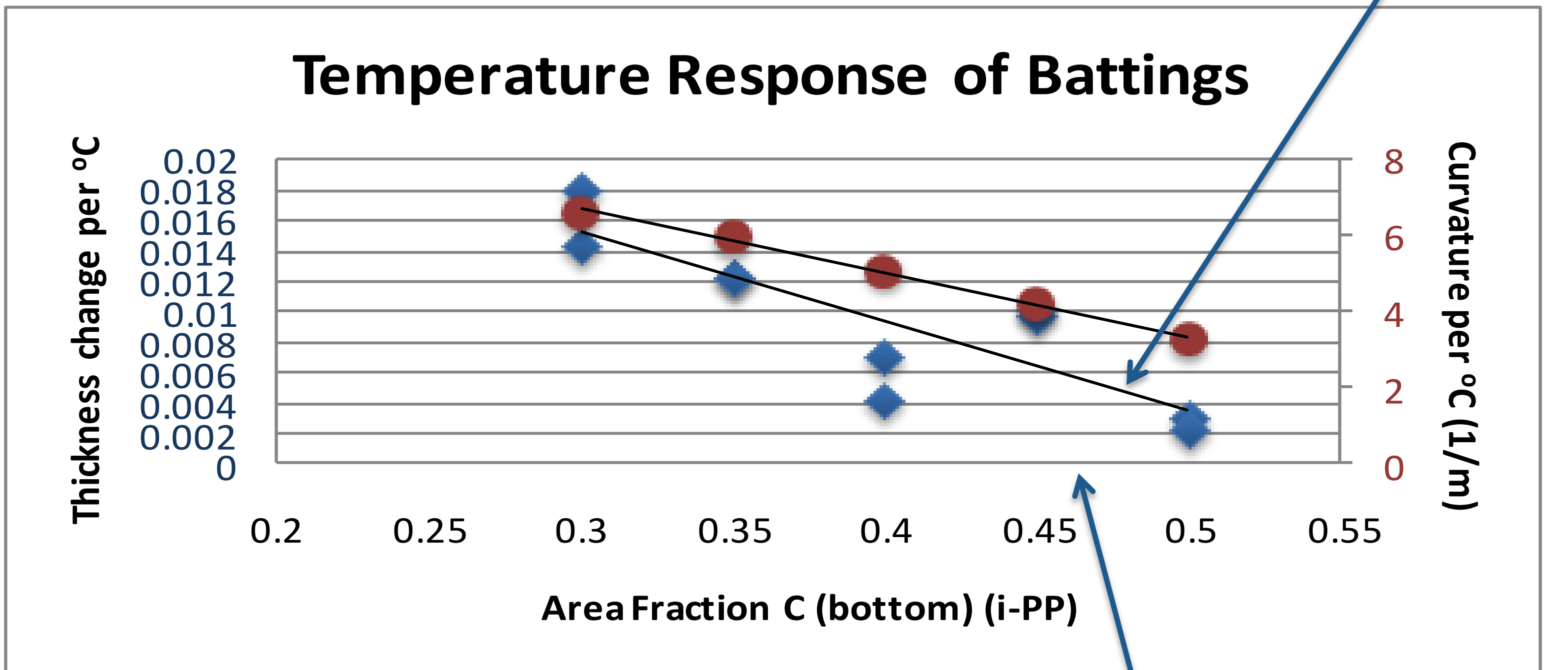
Homo/Bi-/Tri-Component Fiber Extruder

Research-scale Fiber Extruder:

- ***Capacity –1 to 6 pounds/hour***
- ***¾ Inch Diameter Single Screw***
- ***Temperature Limit: 350°C***
- ***Three Melt Pumps are Thermally Isolated***
- ***Nitrogen Ports for Oxygen Sensitive Polymers***
- ***Draw Speed: 500-2500 meters/min.***

Temperature Response

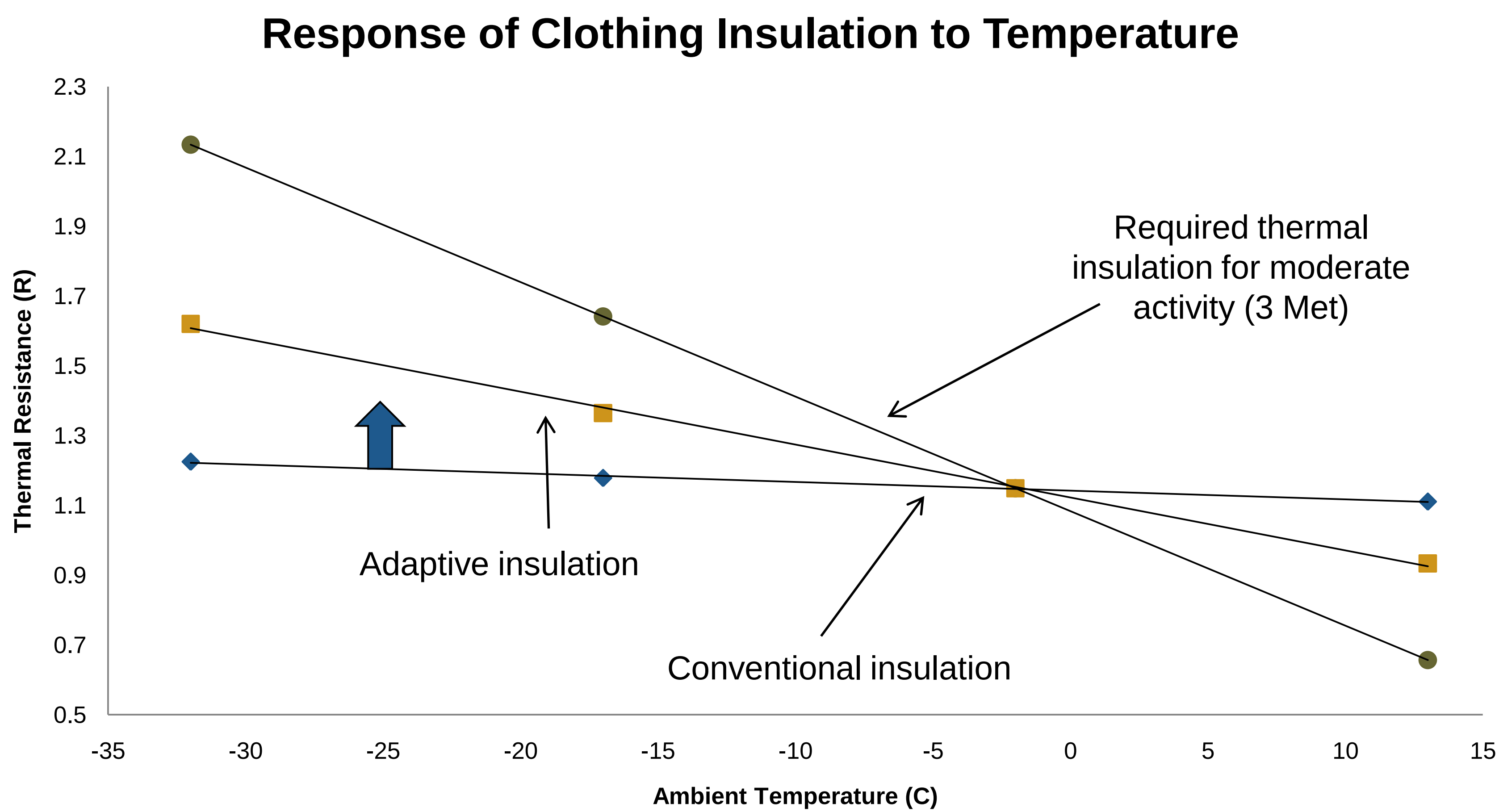
Calculated curvature



Small changes in composition result in large changes in performance.

Measured batting thickness change

Estimated Performance



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

Questions?

- Points of Contact

- Temperature Adaptive Insulation
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Backup Slides

High Performance Fiber Facility

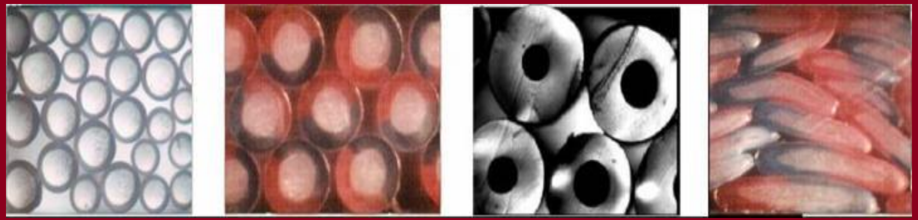
The High Performance Fiber Facility (HPFF) will combine NSRDEC, academia and industry expertise in novel fiber/textile technology to invent and rapidly transition new optical, electronic, high strength, flame retardant and reactive materials to Warfighters and First Responders

- **Optical Fibers**
  Optical Sensing and Communication
- **Electronic Fibers**
  Molten Metal Core/Polymer Sheath Fibers for E-Textile Applications
- **High Strength Fibers**
  Islands-in-the-Sea Nanofibers for Soft Armor or High Strength/Impact Composites
- **Flame Retardant Fibers**
  New Polymers or Nanoparticle Additives for Improved FR
- **Reactive Fibers**
  Tri-Component Fibers for Smart Insulation

BICOMPONENT ISLANDS-IN-THE-SEA (INS) FIBERS

Applications: Production of melt processed nanofibers or optical segregation (Nanofibers for ballistic soft armor/composites, and internal reflection fibers)

BI/TRI-COMPONENT SHEATH/CORE FIBER

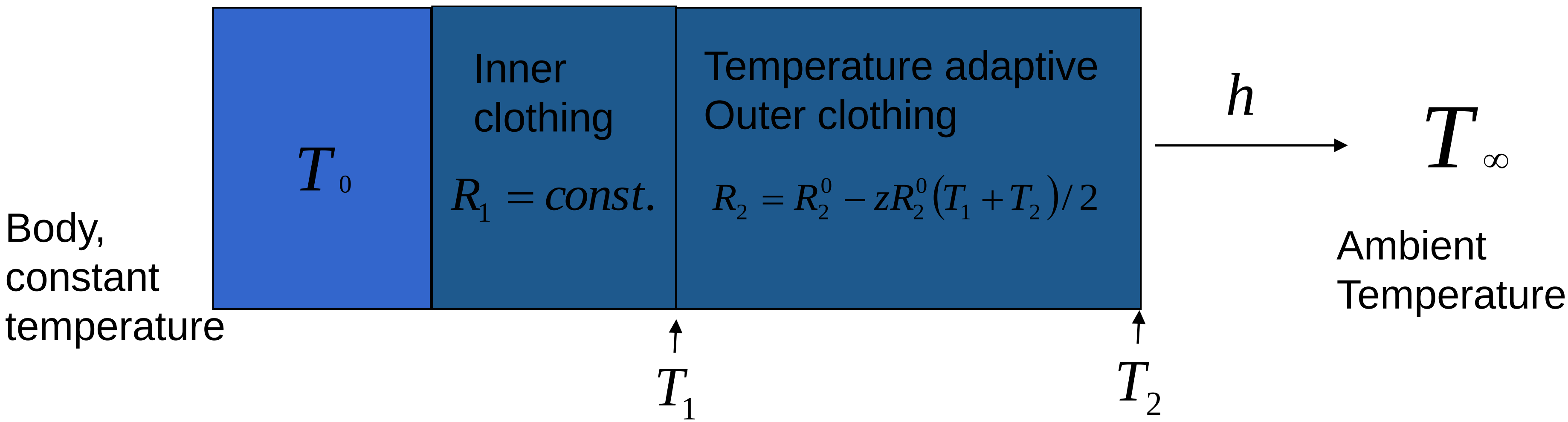


Applications: Concentration of reactive components at the surface of fiber or putting a conductive material in the core, surrounded by an insulating material (CB decontamination, antimicrobials, sensors, electronic textiles)

1D Model for Heat Transfer

- Clothing is composed of a non-adaptive inner layer and a temperature adaptive outer layer
- The outer layer resistance changes linearly with average temperature of the adaptive layer
- The goal is a rough understanding of the effect of the temperature adaptive clothing

1D Model for Heat Transfer



$$q = \frac{(T_0 - T_\infty)}{\left\{\frac{1}{h} + R_1 + R_2^0 - \frac{z}{2} R_2^0 \left[(T_0 + T_\infty) + q\left(\frac{1}{h} - R_1\right) \right] \right\}}$$

Z is a measure of the performance of the batting, percent change in thermal resistance per degree Celsius

R_2^0 Is the thermal resistance of the temperature adaptive batting at 0º C.

1D Model for Heat Transfer

The heat transfer equation is quadratic in q

$$aq^2 + bq + c = 0 \qquad \text{so} \qquad q = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

where

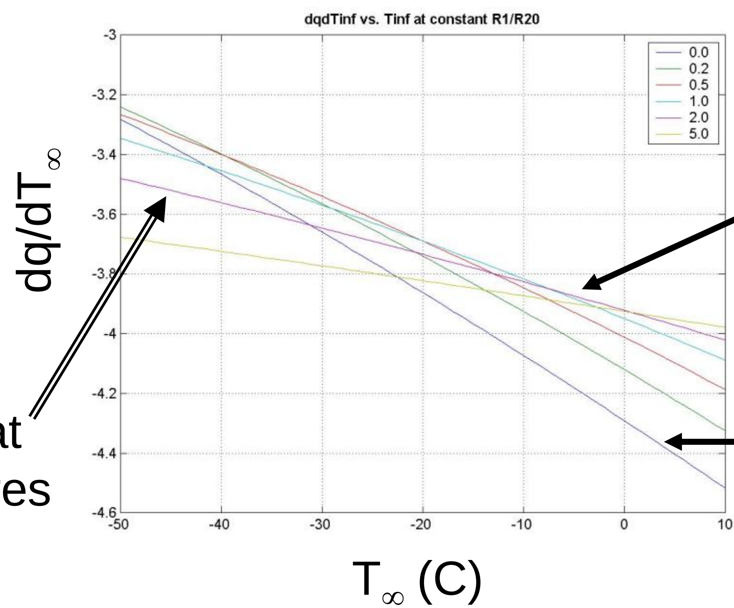
$$b = \left\{ \frac{1}{h} + R_1 + R_2^0 - \frac{z}{2} R_2^0 \left[\left(T_0 + T_\infty \right) \right] \right\}$$

$$a = -\frac{z}{2} R_2^0 \left(\frac{1}{h} - R_1 \right) \quad c = -\left(T_0 - T_\infty \right)$$

UNCLASSIFIED

Change in Heat Loss with Ambient Temperature

- We want heat loss as a function of ambient temperature to be constant.
  - Take the first derivative of the heat loss equation wrt ambient temperature (MATLAB)



Best response when over another insulating layer, $R_1>0$

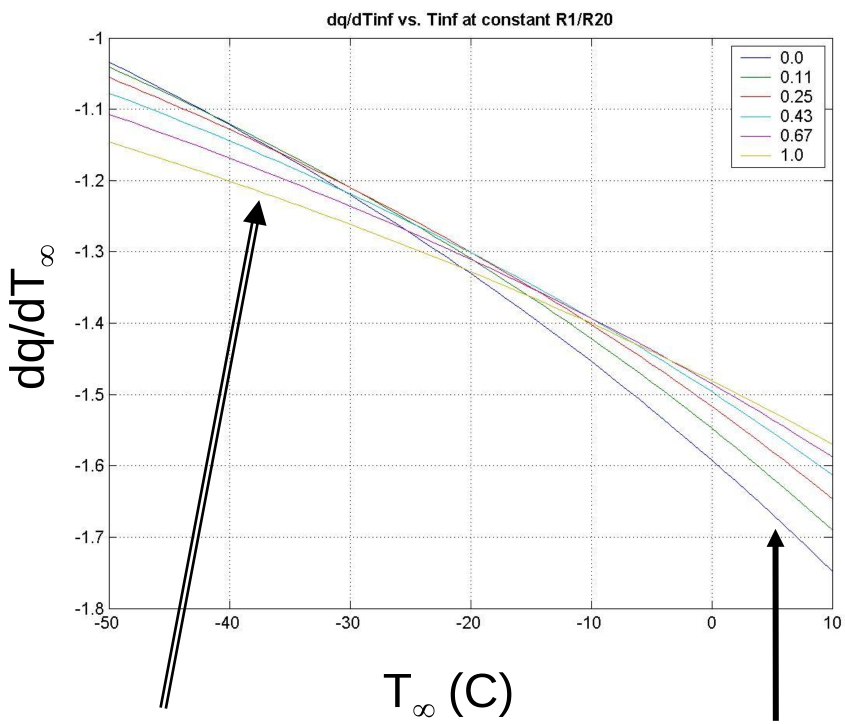
More effective at cold temperatures

No insulation underneath, $R_1 = 0$

Total insulation 0.3 C m²/w

Change in Heat Loss with Ambient Temperature (cont.)

Current Performance



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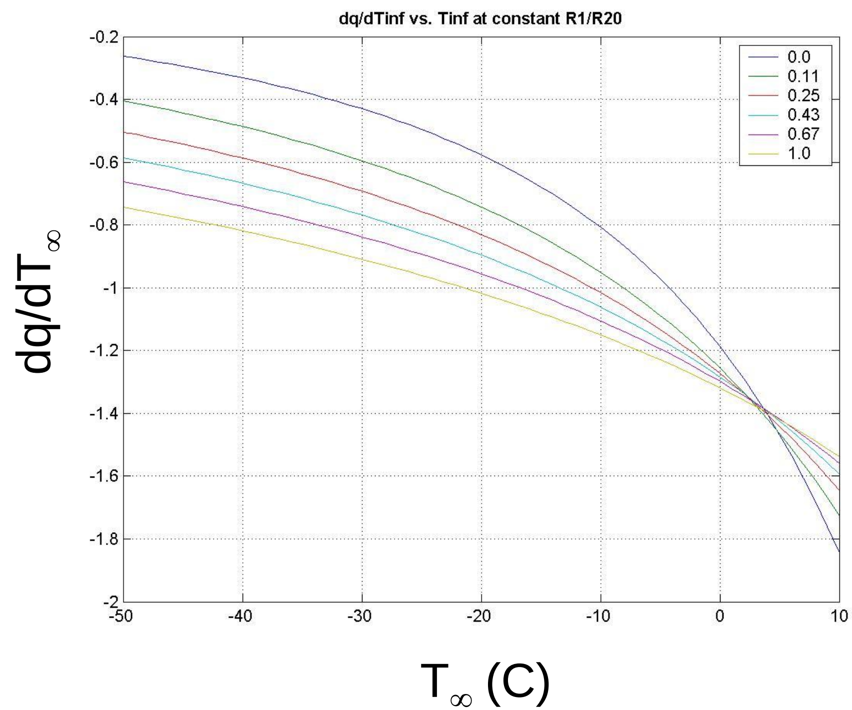
Optimistic Projection



Thick insulation: total R = 1 C m^2/w