Overview of Human Thermal Modeling, Thermoregulation, and Thermal Comfort at NASA

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Overview/Objective

- History of Human Thermal Models
- Human Thermal Models Used at NASA/JSC
- Thermoregulation
- Testing/Correlation
- Core Body Temperature Measurement
- Thermal Comfort Criteria

Focus on applicability of Human Thermal Models to assess Thermoregulation Concepts for Thermal Comfort

History

1927	Bazett and McGlone	Measured temperature gradients in the arm
1934	Alan Burton	1st mathematical model of temperature distribution
1936	Burton and Bazett	1st transient conduction model for the body
1948	Pennes	Blood flow on tissue temperature

1961	Wissler	1st multi-element human thermal model
1964	Wissler	Human thermoregulation model using finite difference method and solved on a digital computer
1966	Stolwijk and Hardy	Skin blood flow, sweating, and shivering

1970	Stolwijk	25 node model used for Apollo PLSS
-	Kuznetz	41 node "metabolic man", LCG, EMU

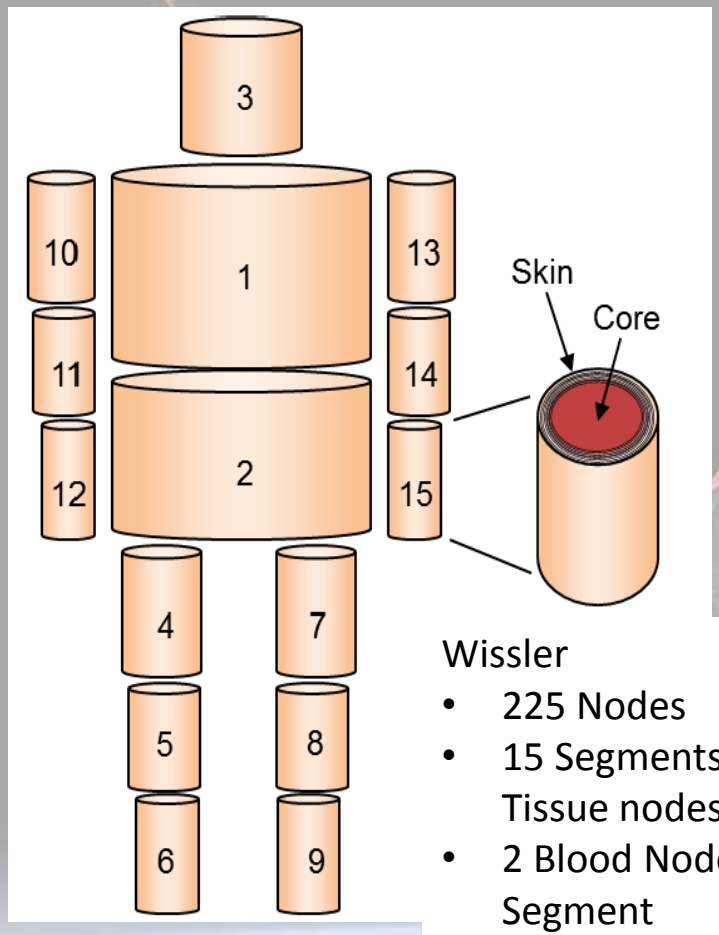
METMAN

2001	Wissler	15 segment, 225 node model modified by Nyberg, added LCVG for Constellation program
2009	Wissler	3780 node model (3D)

Wissler (2D)

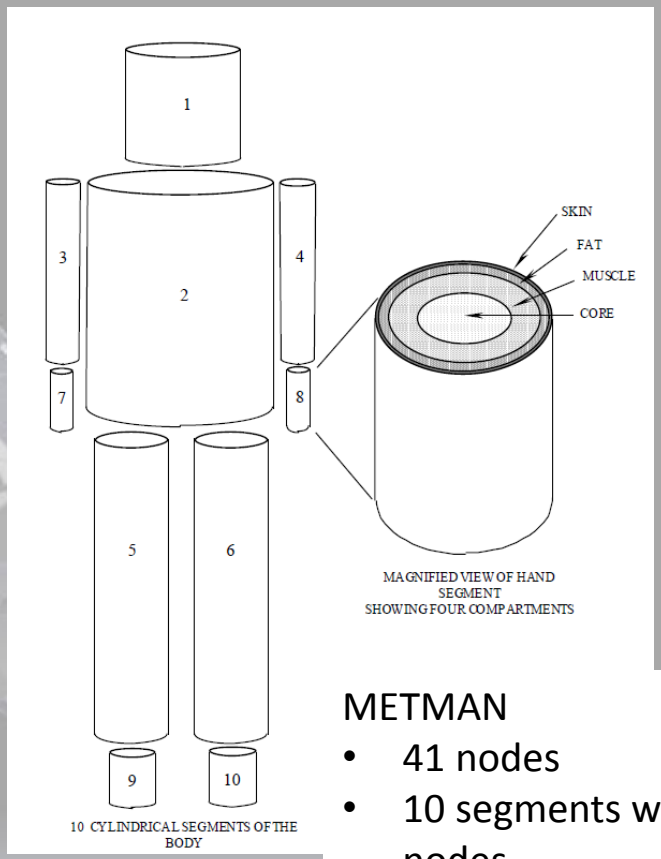
Wissler (3D), developmental

Wissler & METMAN



Wissler

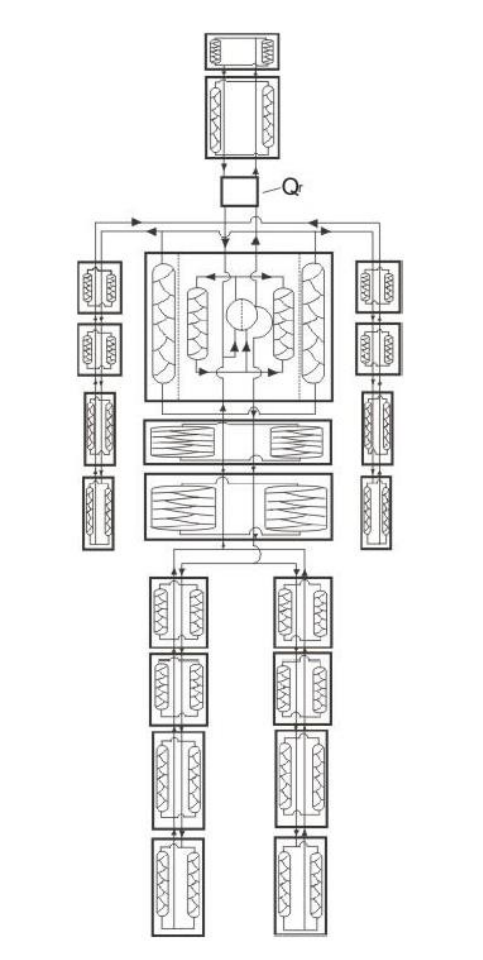
- 225 Nodes
- 15 Segments with 15 Tissue nodes
- 2 Blood Nodes per Segment

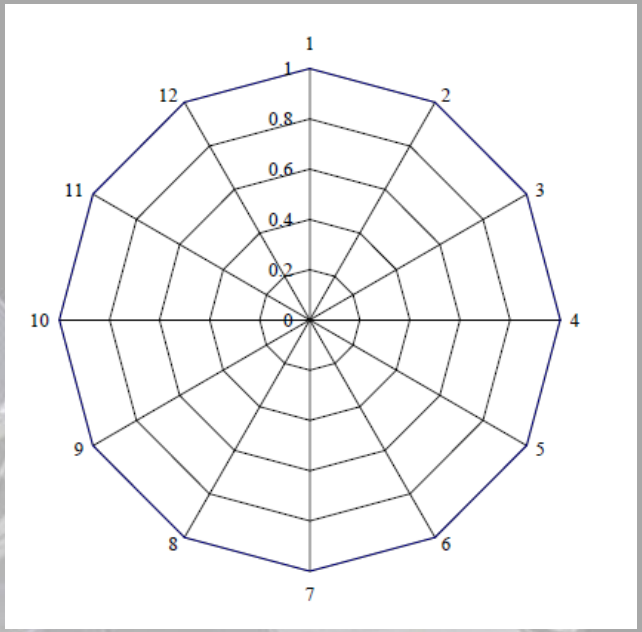


METMAN

- 41 nodes
- 10 segments with 4 nodes
- 1 Central Blood Node

3780-node Wissler

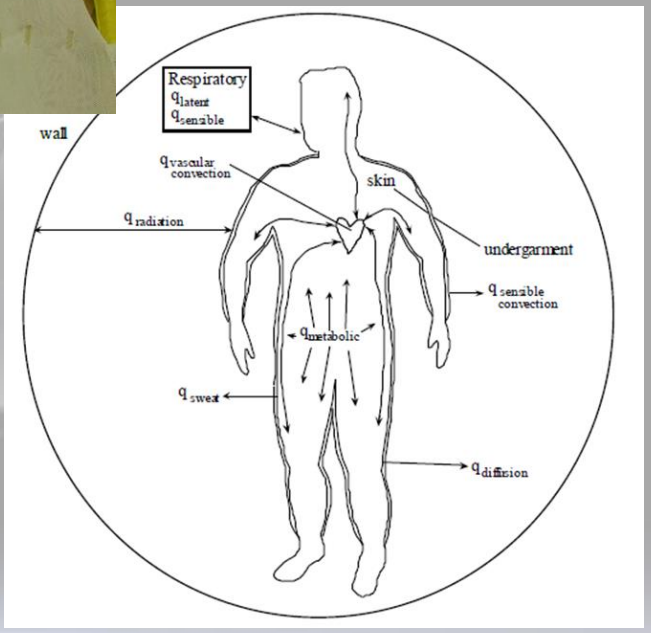




- **Can resolve lateral & circumferential differences**
- **May be need for some localized cooling techniques**

Human Thermal Model

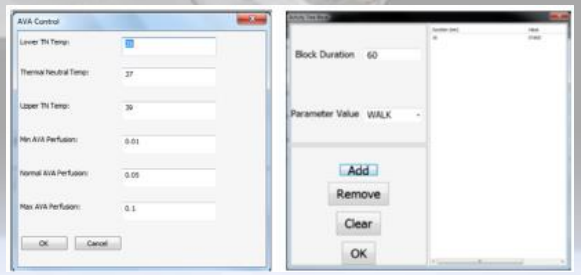
- **Simulation**
  - Linear conduction
  - Blood circulation
  - Vasoconstriction
  - Sweating
  - Shivering
  - Respiration
- **Heat Transfer Modes**
  - Respiratory dry heat
  - Respiratory water vapor exchange
  - Conduction through clothing
  - Convection & radiation from skin to ambient environment
  - Vapor loss from the skin
  - Heat exchange with fluid cooled garment



Input/Output

- **Input**
  - Mode (shirt sleeve, LCVG, IVA/EVA)
  - Metabolic rate
  - Height/weight
  - Environment
    - Temperature
    - Humidity
    - Flow Velocity
  - Respiratory quotient
  - Work efficiency

- **Output**
  - Core body temperature
  - Heat storage
  - Skin temperature
  - Sensible/latent heat
  - Shiver rate
  - Evaporation



Testing/Model Correlation

- **Skin temperatures**
- **Core body temperature**
- **Oxygen Consumption (metabolic rate)**
- **Sweat**

Core Body Temperature

- **SpotOn/Bair Hugger (3M)**

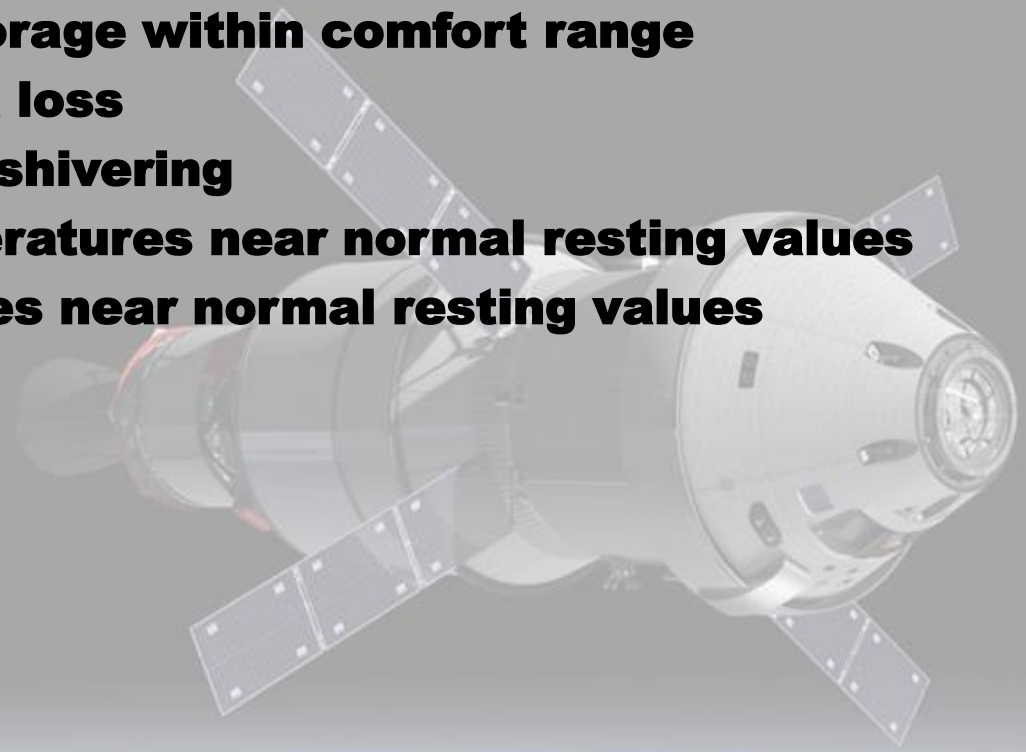
- **CorTemp (HQ Inc)**
  - CorTemp Sensor (pill)
  - Wireless Monitoring Data Recorder

- **Rectal Probe**

Thermal Comfort Criteria

- **Objective vs. Subjective criteria**

- **Body thermal storage within comfort range**
- **Evaporative heat loss**
- **No thermogenic shivering**
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**



Thermal Comfort Criteria

- **Body thermal storage within comfort range**

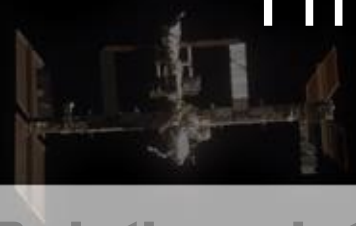
Energy Stored/Mass (BTU/lbm)	Limit
2.0	Hot Impairment
1.3	Hot Comfort
-0.8	Cold Comfort
-1.8	Cold Impairment

- **Evaporative heat loss**
- **No thermogenic shivering**
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**

Thermal Comfort Criteria

- **Body thermal storage within comfort range**
- **Evaporative heat loss**
  - Insensible evaporation only
    - Respiration
    - Diffusion
  - No active sweating
- **No thermogenic shivering**
  - Shivering helps the body create heat. The skeletal muscles create the shivering. There's a little muscle on each hair that helps to create a better blanket for us. The shivering heats up the body. The non-shivering thermogenesis fits into a classification, which is called diet-induced thermogenesis
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**

Thermal Comfort Criteria

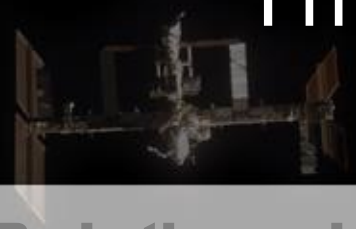


- Body thermal storage within comfort range
- Evaporative heat loss
- No thermogenic shivering
- **Body core temperatures near normal resting values**
  - Approximately 37 °C (99 °F)

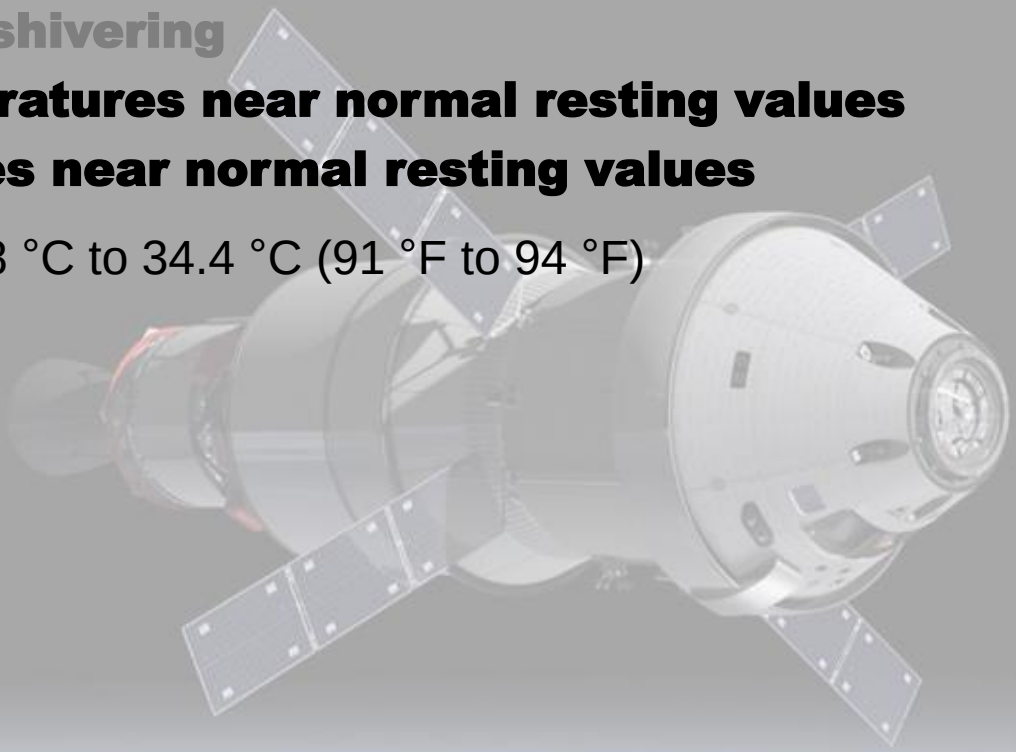
Temperature (°F)	Effects
>102.2	Pyrexia-severe sweating, fainting, dehydration, weakness
>100.4	Moderate to severe sweating, flushed and very red
>99.5	Mild to moderate sweating
96.8-99.5	Normal Body Temperature
<96.8	Mild to moderate shivering
<94.9	Hypothermia-intense sweating, numbness and blue/grey skin
<93.2	Severe Shivering, loss of finger movement, blueness and confusion

- **Skin temperatures near normal resting values**

Thermal Comfort Criteria



- Body thermal storage within comfort range
- Evaporative heat loss
- No thermogenic shivering
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**
  - Approximately 32.8 °C to 34.4 °C (91 °F to 94 °F)



Conclusions/Q&A

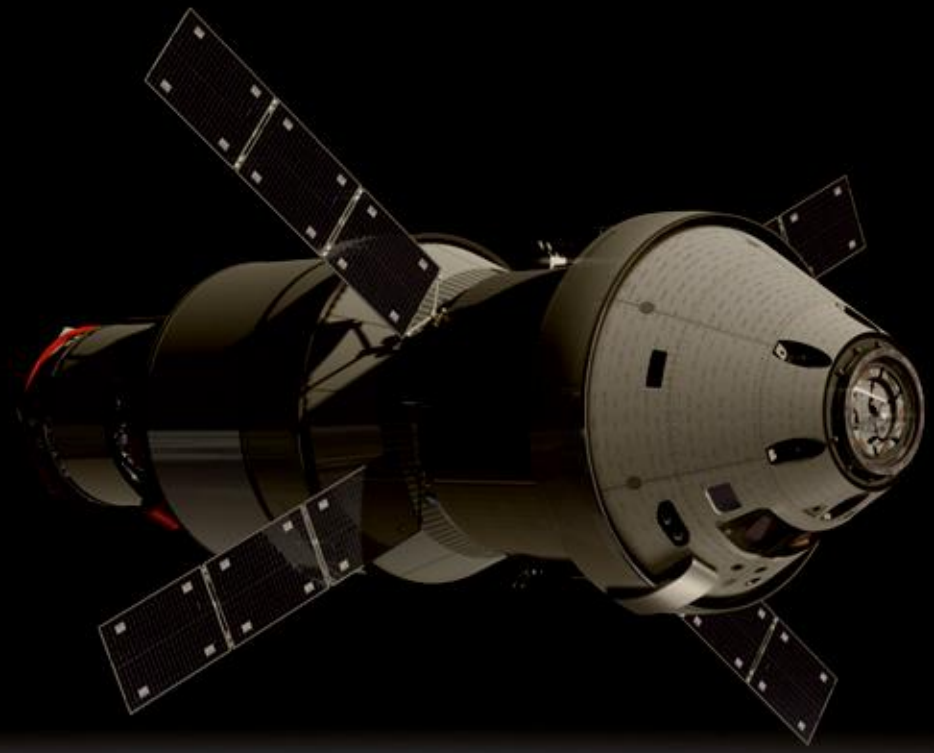
- **As Human Thermal Models have evolved, they have proven useful tools to predict human thermal response**
- **NASA has refined and used Human Thermal Models to design, develop, and test ECLSS (Environmental Control and Life Support Systems)**
- **Human Thermal Models could be used with Thermal Comfort Criteria may be used to assess effectiveness of Local Thermal Management Systems**

- **Questions/Comments?**

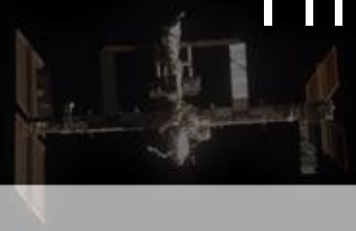
References

- Hensley, Mark, Abella, Netscher, Wissler, and Diller; “50 Years of Computer Simulation of the Human Thermoregulatory System”; *Journal of Biomechanical Engineering*, February 2013, Vol. 135
- Durrant and Fricker; “Exploration EVA Suit Thermal Performance in a Vairety of Environments”; 44th Internation Conferences on Environmental Systems; ICES-2014-271
- Cognata and Durrant; “3D Modeling of the Human Thermal Interaction in Complex Environments using the Wissler Human Thermal Model”; 44th Internation Conferences on Environmental Systems; ICES-2014-266
- Wissler; “A New Human Thermal Model”; Proc. 13th Int’l Conf. on Environmental Ergonomics, Aug 2-9, 2009, Boston, MA
- Bue; “Computer Program Documentation, 41-node Transient Metabolic Man Program”; CTSD-0425

BACKUP



Thermal Comfort Criteria



The Borg Scale

Colour	BORG	Explanation/percieved exertion
GREEN	6	Zero exertion
	7	Very easy
	8	Minimal recognition of effort
YELLOW	9	Very light (Comfortable walking pace)
	10	Can just start to hear your breathing
	11	Conversation is easy and you feel you could run for a while at this pace
	12	Light exertion - This is where you are deveopling your aerobic system
ORANGE	13	Somewhat Hard
	14	You can hear your breathing but you're not struggling
	15	You can talk but not in full sentences - You are still developing the aerobic system here but getting towards it's top end
	16	Hard work - This is probably just below your anaeoribic threshold
RED	17	Very hard - Starting to get uncomfortable and you're getting tired - This probably represents your anaerobic threshold
	18	You can no longer talk because your breathing is heavy
	19	Extremely hard. Your body is screaming at you to stop
	20	Max exertion