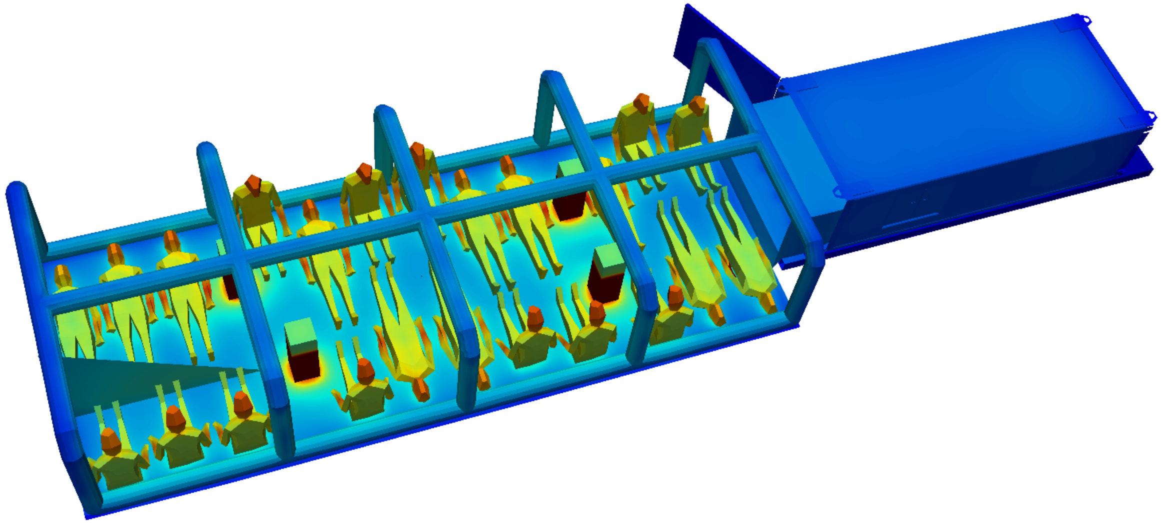
Miner Metabolic Heat Input and Thermoregulation for Refuge Alternative Conditions



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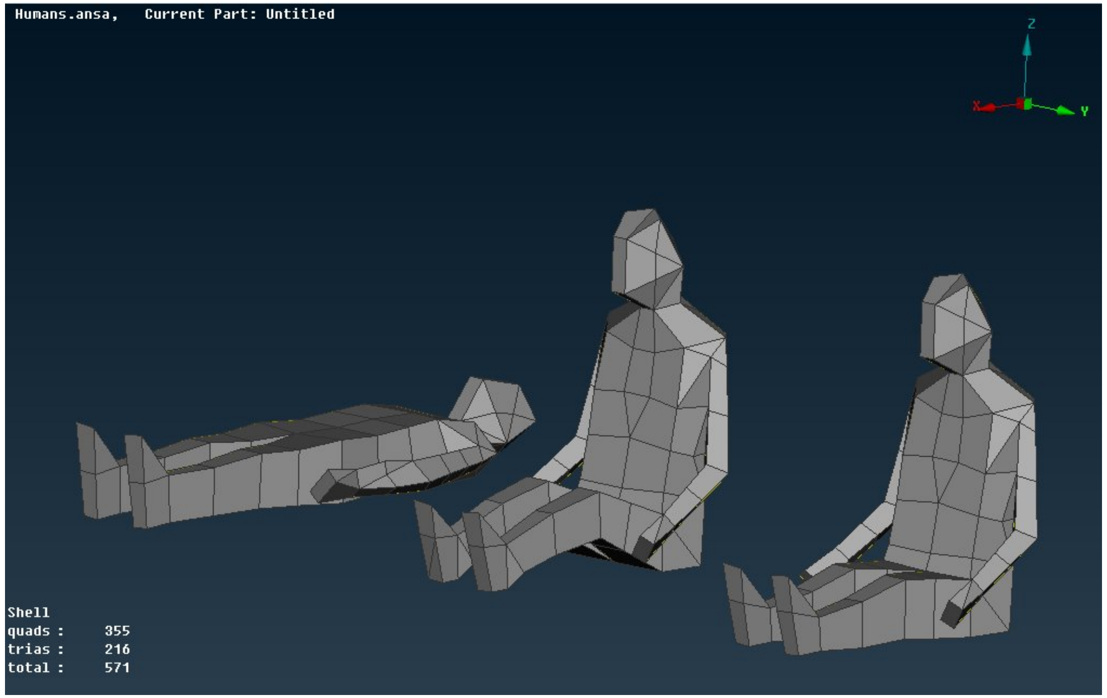
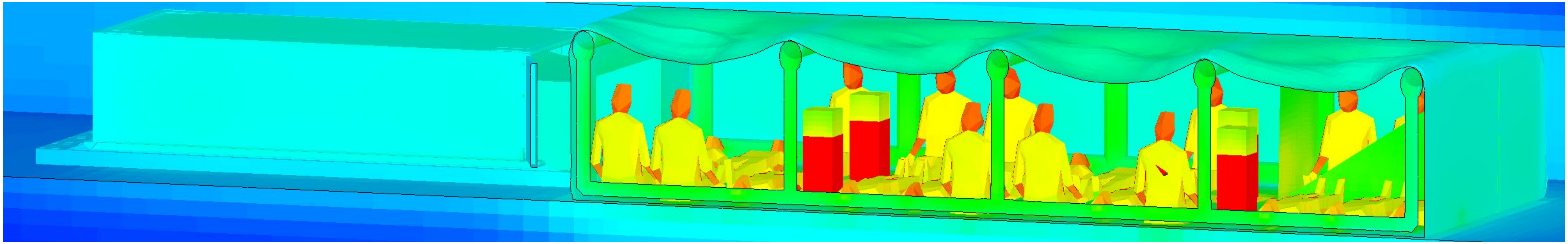
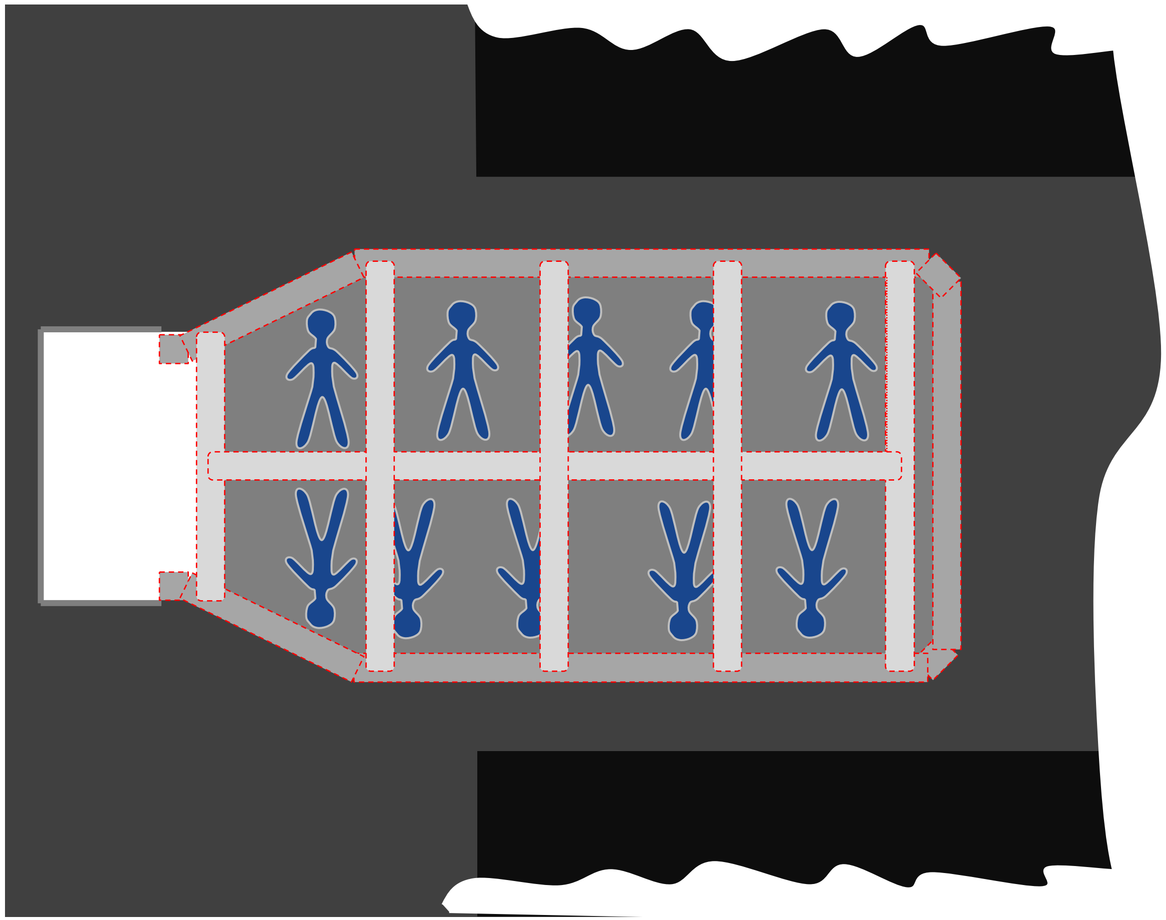
Outline

1. Introduction/background
2. Metabolic heat input contract
3. “Critical” apparent temperature contract
4. Summary & Conclusions





Heat buildup within an occupied RA is a serious concern.



- RAs must be designed to provide a livable environment for up to 96 hours
- RAs have a limited ability to dissipate heat
- Heat input to RA due to miner metabolic heat and carbon dioxide scrubber heat
- RA regulations mandate a maximum apparent temperature (AT) of 95 °F
- The AT is a metric that depends on both dry-bulb air temperature and relative humidity (RH)
- %RH in an RA will be ~90% or greater

Numerous metrics could be used to assess the RA internal conditions for heat stress.

- Wet-bulb Temperature - Haldane (1905)
- Effective Temperature - Houghton and Yaglou (1923)
- Equivalent temperature - Dufton (1929)
- Heat Stress Index - Belding and Hatch (1955)
- Wet-bulb Globe Temperature (WBGT) - Yaglou and Minard (1957)
- Discomfort Index - Thom (1959)
- Temperature Humidity Index - Ingram (1965)
- New Effective Temperature - Gagge (1972)
- Humidex - Masterson and Richardson (1979)
- *Sultriness Index - Steadman (1979)*
- *Apparent Temperature - Steadman (1984)*
- Heat Index - Rothfusz (1990)
- ISO 7243 WBGT - Parsons (2006)

See:
Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5
By J. R. Buzan, K. Oleson, and M. Huber

http://www.geosci-model-dev.net/8/151/2015/

Regardless of the metric that is used to assess RA thermal conditions, the body core temperature of the occupants is what really matters.

- Heat stroke is the most serious heat-related health problem
  - Body core temperature greater than 104°F
  - Occurs when the body's temperature regulation system fails
  - Medical emergency that may result in death
  - Signs & symptoms: confusion, loss of consciousness, seizures, cessation of sweating
- Heat exhaustion is the 2nd most serious heat-related health problem
  - Body core temperature greater than 100.4°F
  - Signs & symptoms: headache, nausea, dizziness, weakness, irritability, confusion, thirst, heavy sweating

https://www.osha.gov/OshDoc/data_Hurricane_Facts/heat_stress.pdf

Body core temperature is a function of activity level and thermal environment; heat stress is often assessed as a function of both.

Work/rest Regimen	Work Load		
	Light	Moderate	Heavy
Continuous work	30.0°C (86°F)	26.7°C (80°F)	25.0°C (77°F)
75% Work, 25% rest, each hour	30.6°C (87°F)	28.0°C (82°F)	25.9°C (78°F)
50% Work, 50% rest, each hour	31.4°C (89°F)	29.4°C (85°F)	27.9°C (82°F)
25% Work, 75% rest, each hour	32.2°C (90°F)	31.1°C (88°F)	30.0°C (86°F)
*Values are Wet-bulb Globe Temperature in °C and °F.			

American Conference of Governmental Industrial Hygienists (ACGIH). *Threshold Limit Values for chemical substances and physical agents. Biological Exposure Indices*. American Conference of Governmental Industrial Hygienists, Cincinnati, OH (1996).

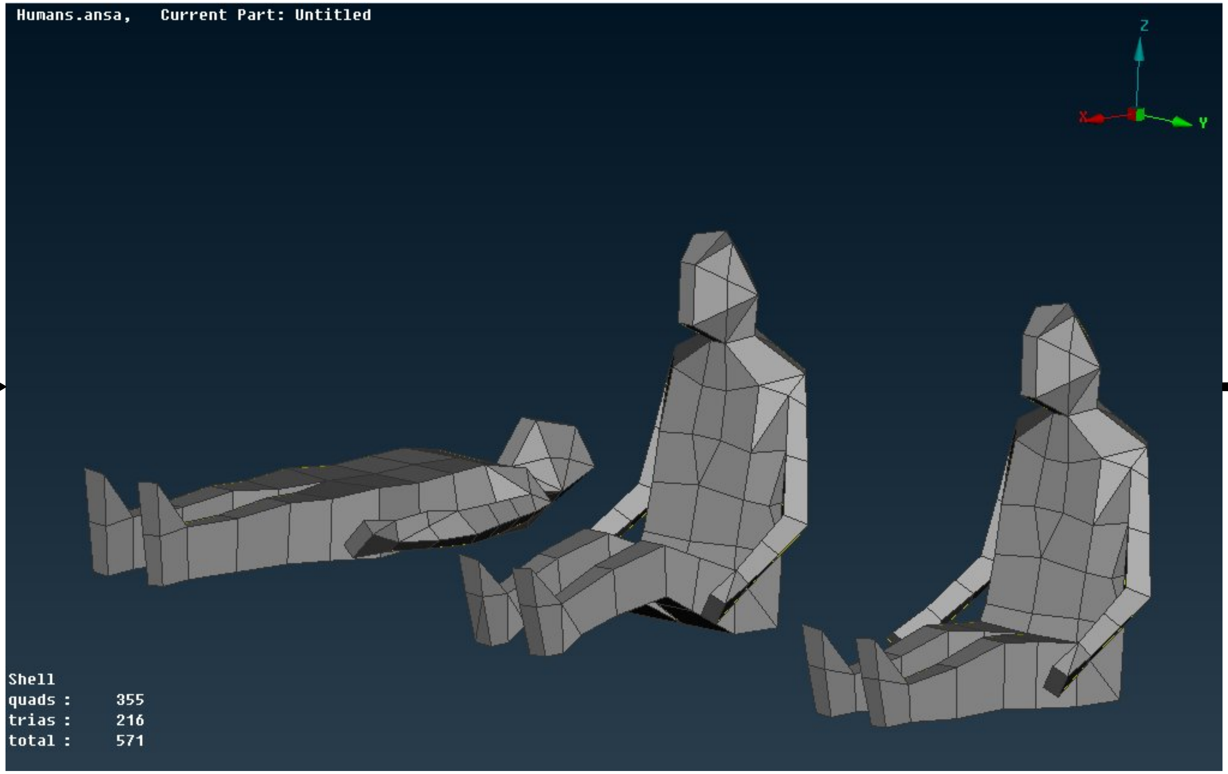
Parsons, K. Heat stress standard ISO 7243 and its global application. *Industrial Health*, **44**, 368-379 (2006).

PERMISSIBLE HEAT EXPOSURE THRESHOLD LIMIT VALUE from OSHA Technical Manual, Section III: Chapter 4

With respect to RAs, the miners' metabolic heat input is the main source of heat that could create an adverse thermal environment within an RA.

Metabolic heat input

- Activity Level
- Size & Age
- Posture
- Clothing
- Air Temperature
- Relative Humidity
- Floor Temperature
- Surroundings Temperature



- Core Temperature
- Skin Temperature
- Heat Loss Via Evaporation (sweat rate)
- Heat Loss Via Convection
- Heat Loss Via Conduction
- Heat Loss Via Radiation

Metabolic heat input, core temperature, and RA environmental conditions are linked!

There are a few key issues with assessment of RA heat stress.

- The metabolic heat input used to represent miners (117 W) is based on a “standard” 168-LB male with an 80% rest/20% moderate activity level
  - Must determine the height and weight of miners
  - Need to estimate activity level based on required tasks for in-use RAs
- Metabolic heat rate for testing/modeling must be based on realistic miner size and activity level for RAs
- Most heat stress standards apply to working in hot conditions for relatively short durations (~8 hours) at a light, moderate, or heavy workload
  - RA occupants could be in a hot environment for days at a very light workload
  - Need to determine the temperature/%RH that cause the body core temperature to increase to an unsafe level for these conditions
- Is the 95 °F apparent temperature limit protective?

NIOSH examined metabolic heat input and body core temperature of RA occupants using two research contracts.

- Metabolic Heat Estimation for Refuge Alternative Testing
  - University of South Florida (USF)
  - NIOSH Contract 200-2015-M-87466
  - T.E. Bernard, D.S. Yantek, and E.D. Thimons. 2018. Estimation of metabolic heat input for refuge alternative thermal testing and simulation. Min Eng. 2018 Aug;70(8):50-54. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6180326/.
- Determination of the Critical Temperature and Relative Humidity for Miners Entrapped in a Refuge Alternative used in Underground Coal Mines
  - ThermoAnalytics, Inc. (TAI)
  - NIOSH Contract 200-2015-M-63212
  - M. Klein, D.S. Yantek, M. Hepokoski, and L. Yan. 2017. Prediction of human core temperature rise and moisture loss in refuge alternatives for underground coal mines. Trans Soc Min Metall Explor Inc. 2017 Jan; 342: 29–35. https://doi.org/10.19150/trans.8105.

The USF contract consisted of three main tasks:

1. Characterize the anthropometric characteristics of miners
   - Recall that a “standard” 168-LB male has been used as the basis for RA occupant metabolic heat input
2. Determine the appropriate activity level for RA occupants
   - An 80% rest/20% moderate activity level has been used as recommended by Foster-Miller
3. Describe the metabolic rate profile of RA occupants
   - 117 W of metabolic heat has been used for RAs, this is based on assumptions for items 1 and 2 above

Five data sets were examined to characterize the size of miners.

- Texas Tech study of low coal - 1980
- Texas Tech study of medium and high coal - 1980
- ISO TR 7250-2:2010 Basic human body measurements for technological design -- Part 2: Statistical summaries of body measurements from individual ISO populations - 2010
- National Health and Nutrition Examination Survey (NHANES) - data for white non-Hispanic males - 2011
- UMWA convenience sample of 198 male miners - 2016

The "average" male coal miner for the UMWA sample was larger than a "standard" 168 LB person and the average for the other data sets.

Study	Mean			Standard Deviation			95th Percentile	
	HT (in)	WT (lb)	AGE (yrs)	HT (in)	WT (lb)	AGE (yrs)	HT (in)	WT (lb)
Texas Tech low coal - 1980	68.7	180.6	34.5	2.6	37.0	11.4	72.8	242.5
Texas Tech medium/high coal - 1980	68.6	177.3	31.6	2.7	26.9	9.3	73.2	222.7
ISO USA Males - 2010	69.7	183.4	39.3	3.2	38.4	11.9	74.8	246.9
NHANES non-Hispanic males - 2011	69.8	199.3	-	3.9	48.5	-	76.4	280.0
UMWA sample - 2016	70.9	221.6	45.5	3.2	43.0	11.0	76.0	293.2

Note: 95th percentile = mean + 1.64 SD HT & WT

Activity levels were found to be far less demanding than the assumed 80% rest/20% moderate activity level assumed in the Foster-Miller report.

- Activity level was estimated based on conversations with RA manufacturers about maintenance demands for in-use RAs
- Operation and maintenance of the RA during actual usage has low physical demand
  - Changing of carbon dioxide scrubber material
  - Monitoring oxygen levels and adjusting flow rate
  - Can be ignored in calculations
- *Only resting metabolic rate (RMR) needs to be used to estimate metabolic heat input for RAs*

Resting metabolic rate (RMR) for the average coal miner was calculated using five methods.

- Harris-Benedict (1919, amended 1984) – uses height, weight, and age
- Owen (1987) – uses weight
- WHO (1985) – uses weight
- WHO (1985) – uses height and weight
- Mifflin-St. Jeor (1990) – uses height, weight, and age

The calculated RMR for the average coal miner ranged from approximately 84 watts to 91 watts.

Equation	Mean RMR (W)	Std Dev of RMR (W)
Harris-Benedict	88.6	11.8
Owen	83.7	8.6
WHO w/o Height	89.3	9.8
WHO w/ Height	90.5	9.5
Mifflin-St Jeor	84.7	9.2

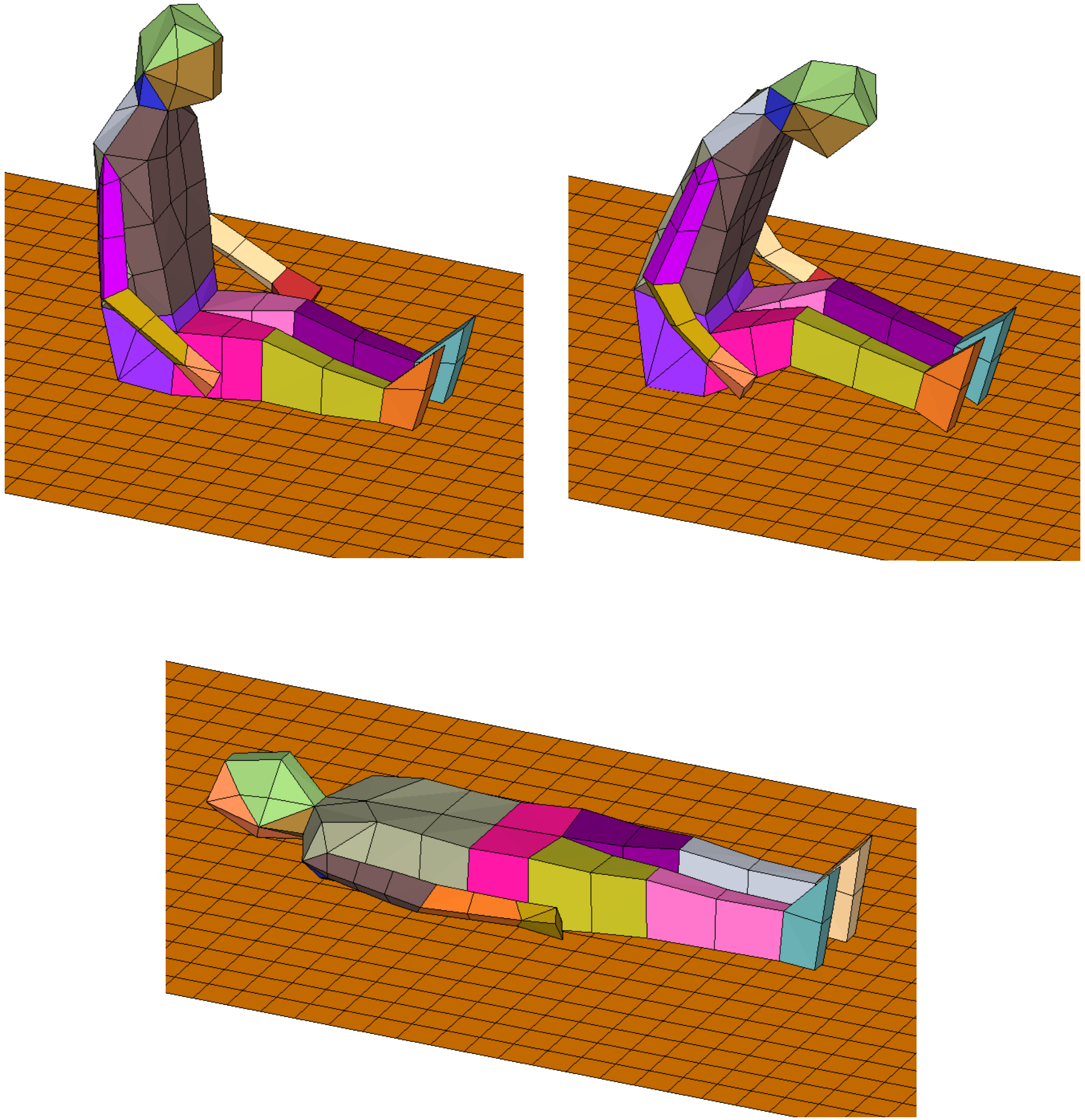
The average and standard deviation for the RMR were used to define heat input as a function of the number occupants.

# of Occupants	1.1*Highest RMR† (W)	Heat Input for RA Test/Analysis (W)
1	134.2	134 (95th %ile RMR)
2	126.6	126
3	123.2	123
4	121.2	121
5	119.9	120
10	116.5	116
15	115.0	115
20	114.0	114
25	113.5	113
30	113.1	113
35	112.8	113
† Highest value across all RMR estimates +10% to allow for an upper limit on the prediction error		

$$RMR_{95thmean} = RMR_{mean} + 1.64\ RMR_{sd} / \sqrt{n}$$

The TAI contract examined an RA occupant's core temperature and sweat rate as a function of apparent temperature.

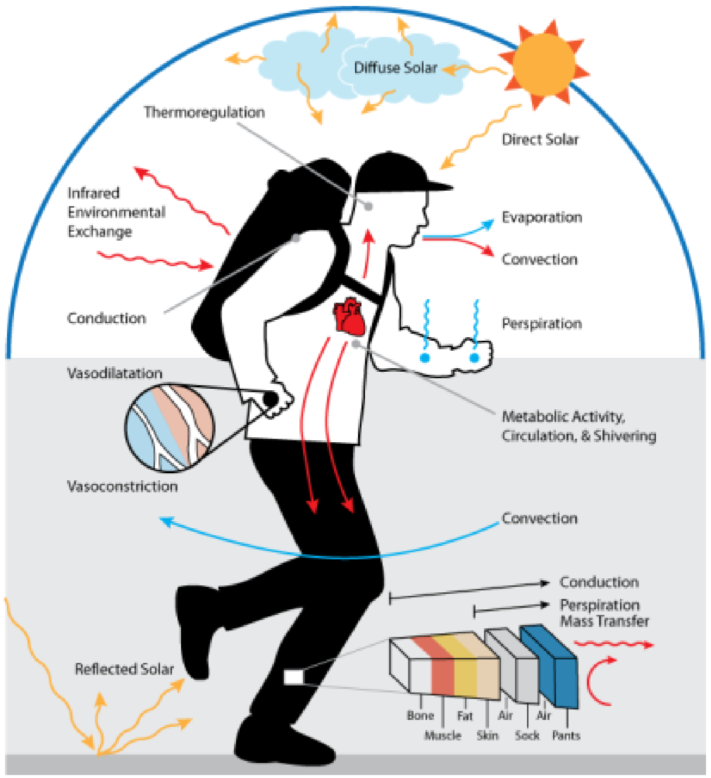
- Dry-bulb temperatures from 81°F to 90°F
- %Relative humidity from 90 %RH to 99 %RH
- Apparent temperatures between 88.5°F and 130.6°F
- Investigated the effects of
  - Posture (sitting or lying)
  - Activity level
  - Miner size

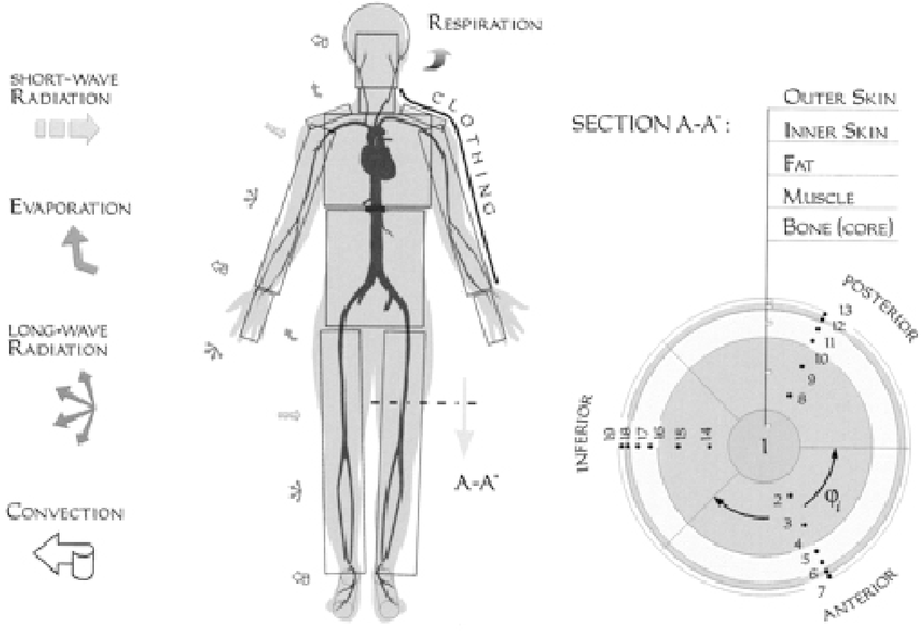


TAI used their TAITherm software and human thermal model in the analysis.

- Sophisticated thermo-physiological model based on Fiala et al.

  Fiala, D., Lomas, K. & Stohrer, M. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int J Biometeorol 45, 143–159 (2001)
- Simulates body processes used to maintain core temperature
- Includes shivering, sweating, and changes in skin blood flow
- Calculates surface and deep tissue temperatures within the human body
- Predicts body core temperature and sweat rate for transient, asymmetric environments

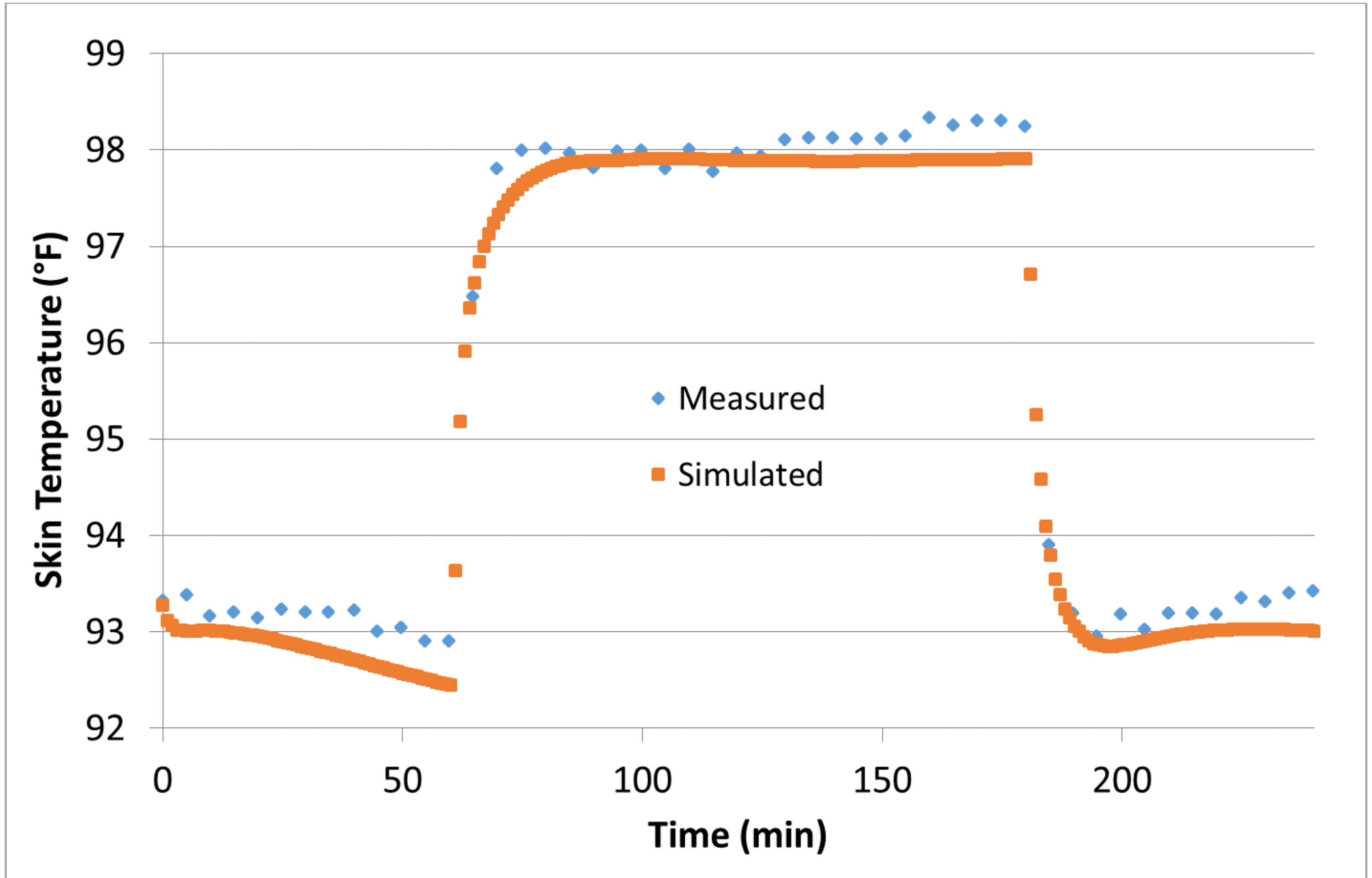




$$k_t \nabla^2 T + \dot{m}_b c_b \left(T_{art} - T\right) + \dot{q}_m + \dot{q}_{env} = \rho_t c_t \frac{\partial T}{\partial t}$$

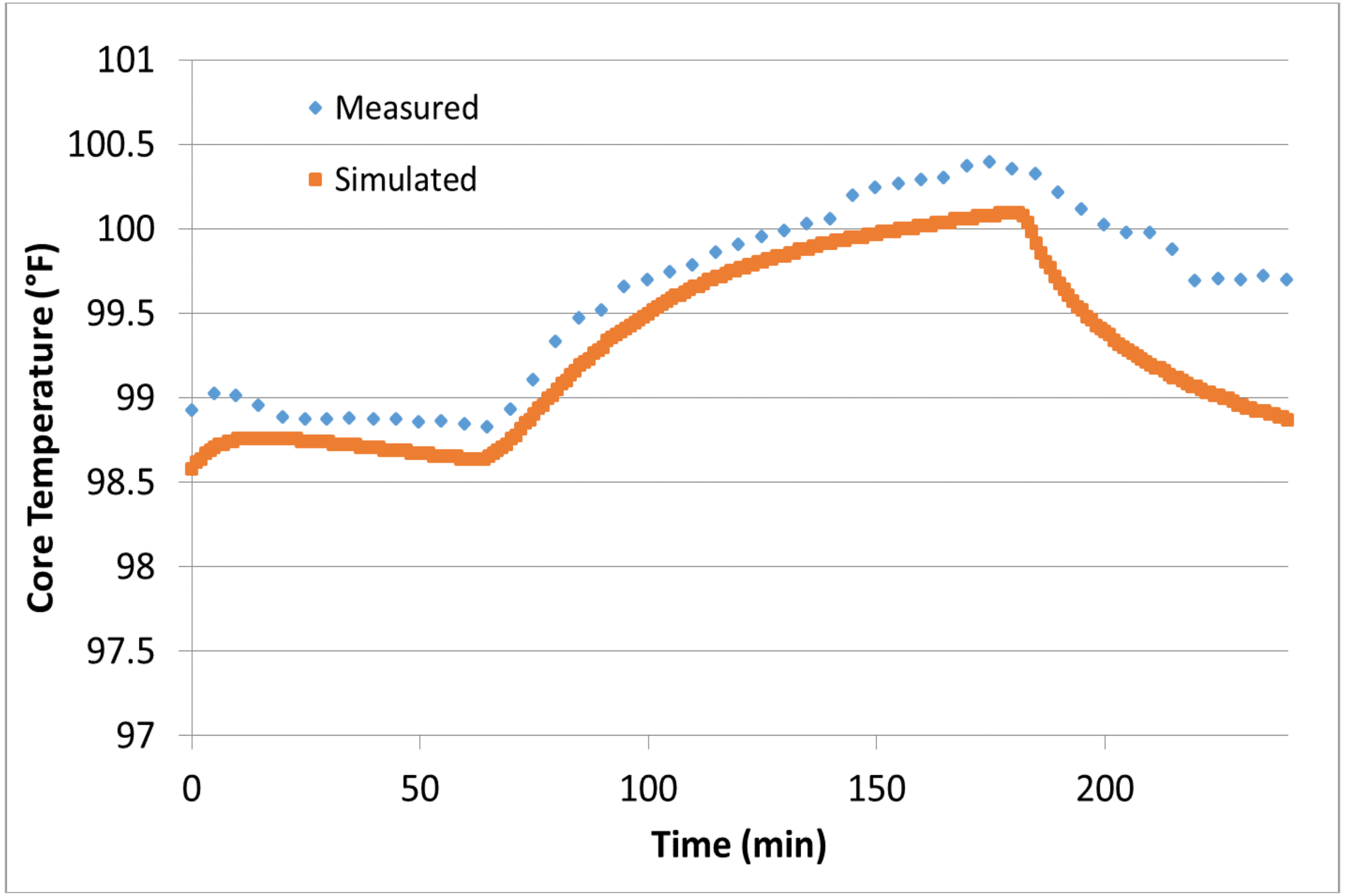
TAI's human thermal model (HTM) has been validated with published human subject test data.

- Skin temperature comparison: human subjects sitting quietly in a hot environment
- Ambient temperature started at 82.4 °F, then was raised to 118.4 °F for 120 minutes, and then returned to 82.4 °F



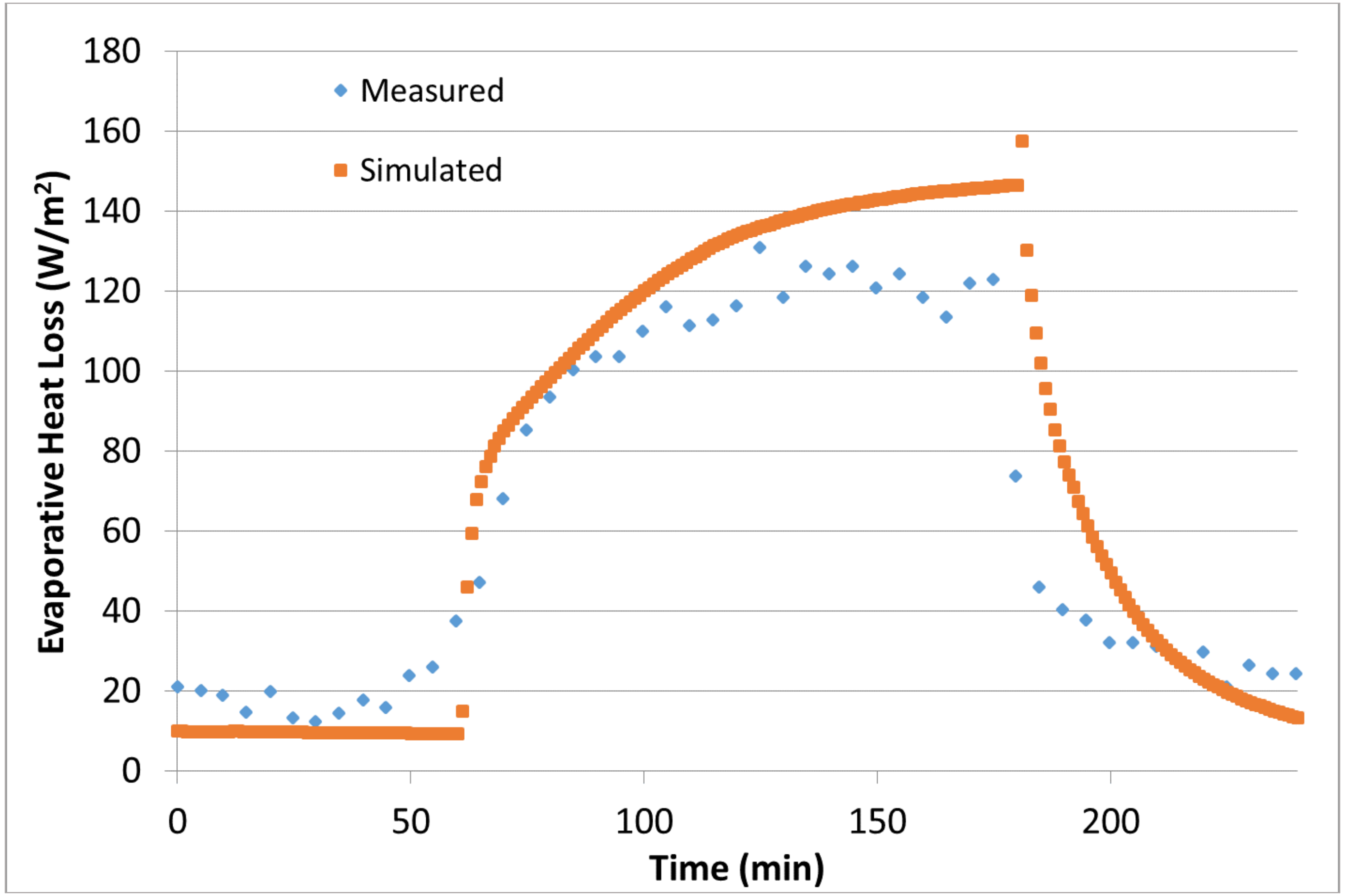
TAI's human thermal model (HTM) has been validated with published human subject test data.

- Core temperature comparison: active human subjects in a warm environment



TAI's human thermal model (HTM) has been validated with published human subject test data.

- Evaporative heat loss comparison: active subjects in a warm environment

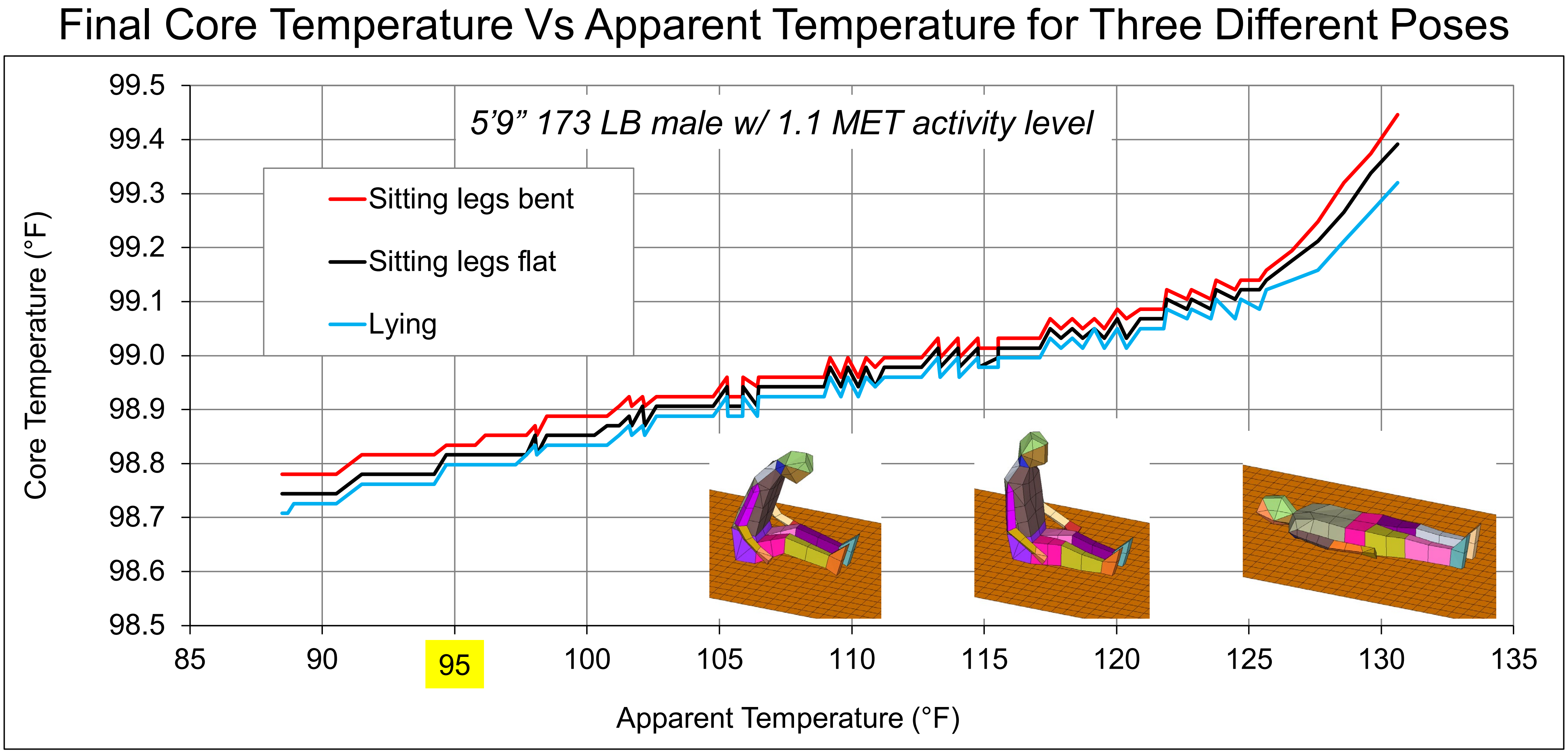


The main goal of the TAI contract was to find the “critical” apparent temperature that would cause the body core temperature to exceed 100.4°F.

From *Heat Stress Control and Heat Casualty Management*, TB MED 507/AFPAM 48-152 (I), US Army and Air Force:

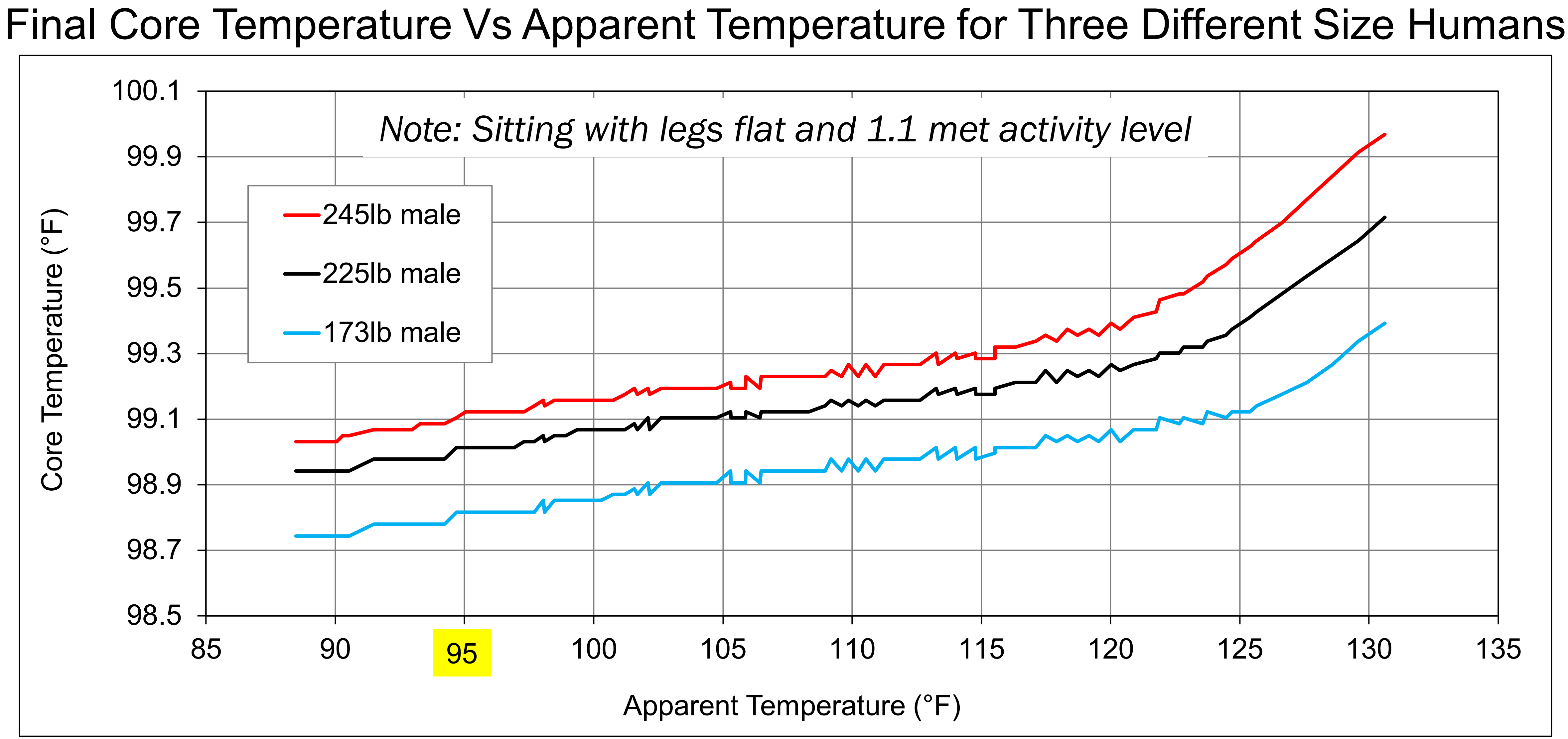
- The body's core temperature provides the “best” single physiological measure to estimate physical work capabilities during hot conditions
- Compensated heat stress
    - Heat lost by a person is in balance with their heat production, so a steady-state core temperature is maintained
    - Core temperature is proportional to metabolic rate
- Uncompensated heat stress
    - Evaporative cooling requirements exceed the evaporative cooling capacity
    - Skin temperatures are high, cardiovascular strain is increased
    - Threshold is defined as 100.4°F

Posture was found to have a negligible effect on core temperature.



The findings and conclusions in this report/presentation have not been formally disseminated by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention and should not be construed to represent any agency determination or policy.

Core temperature response versus apparent temperature has a consistent shape and core temperature increases slightly with miner weight.



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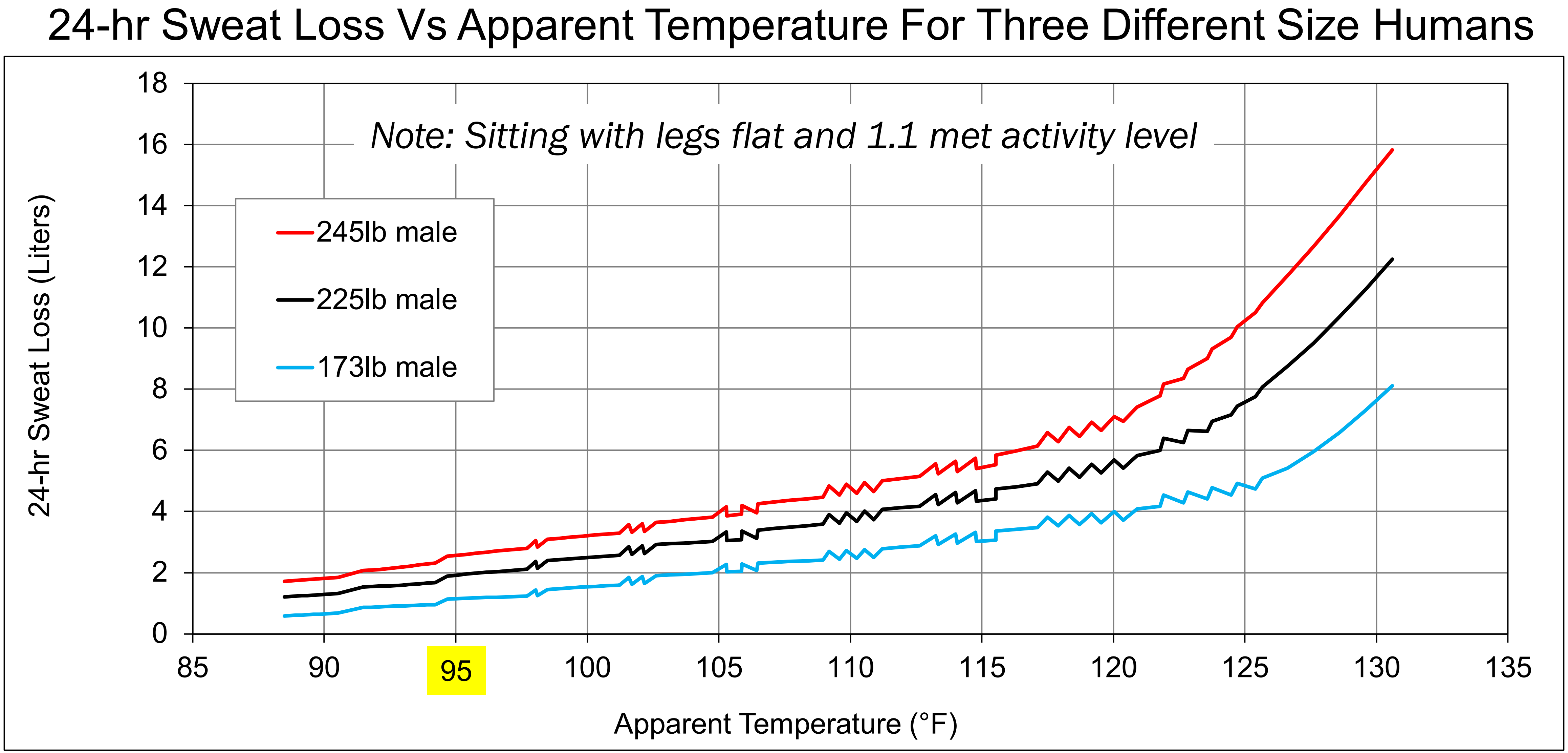
Sweat rates increase significantly with apparent temperature and miner size.



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Summary & Conclusions

- Average miner size found to be 5’11” 222 LB, larger than the “standard” male
- Maintenance demands of RAs are not a factor for heat input; resting metabolic rate should be used for calculating metabolic rate
- Heat input for test/analysis should be based on number of RA occupants
    - 135 W for a single occupant
    - 113 W for 25 or more occupants

Summary & Conclusions

- Posture (sitting vs lying) has little effect on body core temperature
- Miner size has a small effect on body core temperature
- Sweat loss increases with apparent temperature and miner weight
- RA occupants may need more than 2.25 quarts of water per day
- Body core temperature study shows “critical” apparent temperature would be higher than 120°F
- 95°F apparent temperature limit is protective

Questions?

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