Advanced Building Science

- Thermal Comfort
  - Parameters of physiological comfort
  - Interior design conditions

- Readings
  - HF: Chapter 9 => 9.1 – 9.23

Thermal Comfort

- Conditions for Comfort
  - Physiological principles
- Indoor Design Conditions
  - temperatures
  - moisture and humidity

Thermal Comfort

Physiological Principles

- Human comfort
  - temperature
    - air
    - mean radiant
  - humidity
  - air distribution
    - velocity
  - air cleanliness
    - odors
    - acoustical

Thermal Comfort

Thermal Body Interaction with the Environment

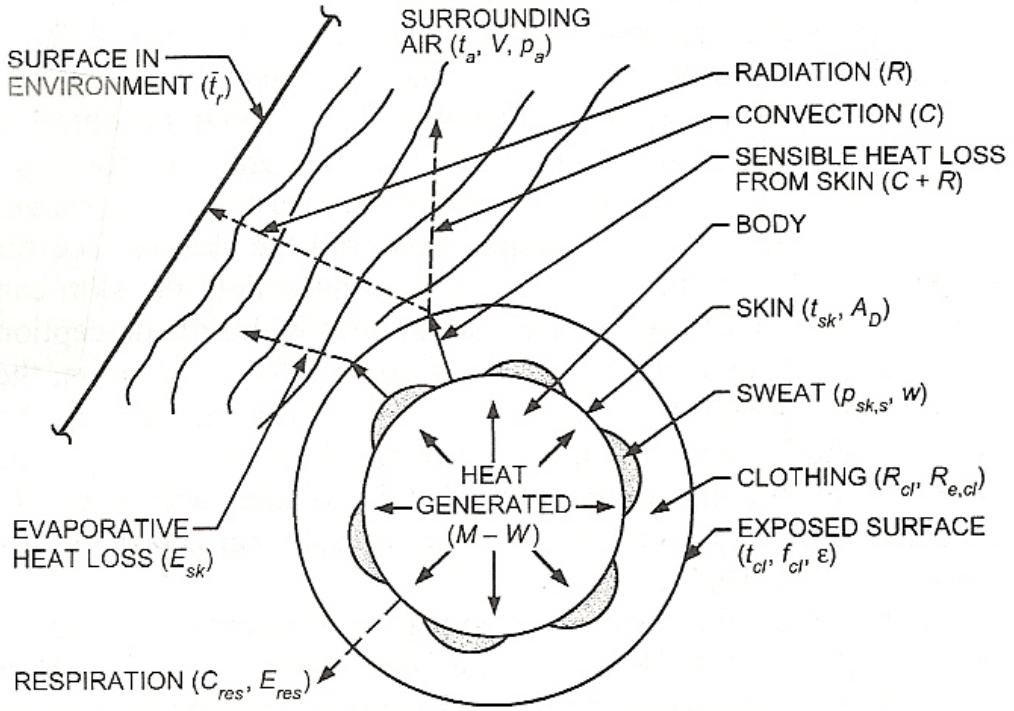

Fig. 1 Thermal Interaction of Human Body and Environment

https://www.researchgate.net/publication/223669260_Thermal_comfort_A_review_paper/figures?lo=1

Thermal Comfort

Thermal Exchanges with the Environment

- Body surface area

- Heat loss
  - sensible loss from the skin
    - predominantly convective and radiative
    - conduction is usually small
  - evaporative losses from the skin
  - respiratory losses

Thermal Comfort

Environmental Parameters

- Directly measured parameters
  - dry-bulb temperature
  - wet-bulb temperature, dew-point temperature, relative humidity, and humidity ratio
  - total atmospheric pressure
  - air movement
  - radiant temperature

- Calculated parameters
  - mean radiant temperature
  - plane radiant temperature
  - radiant temperature asymmetry

Thermal Comfort

Environmental Indices

- Operative Temperature => ambient temperature & MRT
- Effective Temperature => ambient temperature at 50% RH
- Humid Operative Temperature => ET at 100% RH
- Heat Stress Index
- Index of Skin Wettedness
- Wet-Bulb Globe Temperature => wet bulb and MRT
- Wet Globe Temperature => a direct measure of WBGT
- Wind Chill Index => temperature and wind velocity
  - used to calculate the wind chill factor

Thermal Comfort

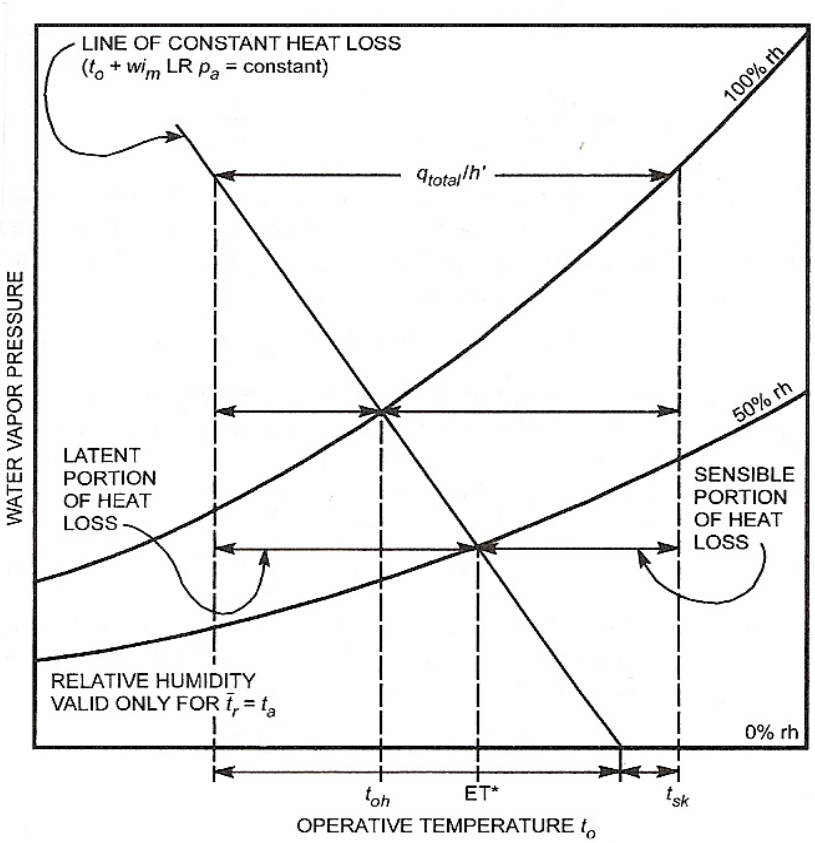

Fig. 2 Constant Skin Heat Loss Line and Its Relationship to t_{oh} and ET*

https://www.researchgate.net/publication/223669260_Thermal_comfort_A_review_paper/figures?lo=1

Thermal Comfort

- Metabolic Rate
  - Function of surface area
    - $A = 0.108 * m^{0.425} * l^{0.725}$
    - m = mass in lb.; l = ht. in in.
  - Activity
    - met = 18.4 Btu/(h-ft^2)
- Clothing Level
  - Clo symbol is "I"
  - R = 0.88 I

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9.6

Table 4 Typical Metabolic Heat Generation for Various Activities

	Btu/h·ft^2	met*
Resting		
Sleeping	13	0.7
Reclining	15	0.8
Seated, quiet	18	1.0
Standing, relaxed	22	1.2
Walking (on level surface)		
2.9 fps (2 mph)	37	2.0
4.4 fps (3 mph)	48	2.6
5.9 fps (4 mph)	70	3.8
Office Activities		
Reading, seated	18	1.0
Writing	18	1.0
Typing	20	1.1
Filing, seated	22	1.2
Filing, standing	26	1.4
Walking about	31	1.7
Lifting/packing	39	2.1
Driving/Flying		
Car	18 to 37	1.0 to 2.0
Aircraft, routine	22	1.2
Aircraft, instrument landing	33	1.8
Aircraft, combat	44	2.4
Heavy vehicle	59	3.2
Miscellaneous Occupational Activities		
Cooking	29 to 37	1.6 to 2.0
Housecleaning	37 to 63	2.0 to 3.4
Seated, heavy limb movement	41	2.2
Machine work		
sawing (table saw)	33	1.8
light (electrical industry)	37 to 44	2.0 to 2.4
heavy	74	4.0
Handling 110 lb bags	74	4.0
Pick and shovel work	74 to 88	4.0 to 4.8
Miscellaneous Leisure Activities		
Dancing, social	44 to 81	2.4 to 4.4
Calisthenics/exercise	55 to 74	3.0 to 4.0
Tennis, singles	66 to 74	3.6 to 4.0
Basketball	90 to 140	5.0 to 7.6
Wrestling, competitive	130 to 160	7.0 to 8.7

Sources: Compiled from various sources. For additional information, see Buskirk (1960), Passmore and Durnin (1967), and Webb (1964).
*1 met = 18.4 Btu/h·ft^2

Thermal Comfort

Predicting Thermal Sensation and Comfort

- For temperature and vapor pressure
- Exposure time
- Male vs. female

Table 9 Equations for Predicting Thermal Sensation (Y) of Men, Women, and Men and Women Combined

Exposure Period, h	Subjects	Regression Equations[a, b] t = dry-bulb temperature, °F p = vapor pressure, psi
1.0	Men	$Y = 0.122\,t + 1.61\,p - 9.584$
	Women	$Y = 0.151\,t + 1.71\,p - 12.080$
	Both	$Y = 0.136\,t + 1.71\,p - 10.880$
2.0	Men	$Y = 0.123\,t + 1.86\,p - 9.953$
	Women	$Y = 0.157\,t + 1.45\,p - 12.725$
	Both	$Y = 0.140\,t + 1.65\,p - 11.339$
3.0	Men	$Y = 0.118\,t + 2.02\,p - 9.718$
	Women	$Y = 0.153\,t + 1.76\,p - 13.511$
	Both	$Y = 0.135\,t + 1.92\,p - 11.122$

[a] Y values refer to the ASHRAE thermal sensation scale.
[b] For young adult subjects with sedentary activity and wearing clothing with a thermal resistance of approximately 0.5 clo, $\bar{t}_r \approx \bar{t}_a$ and air velocities < 40 fpm.

Source: 2013 ASHRAE Handbook Fundamentals, Chapter 9

Thermal Comfort

Conditions for Thermal Comfort

- ASHRAE Comfort Zone
  - sedentary activity
  - typical clothing
- Based on satisfaction scores
  - 80% find the environment thermally acceptable
- Adjustments for Clothing / Activity Levels
  - shift the comfort zone
  - Fanger adjustments

Thermal Comfort

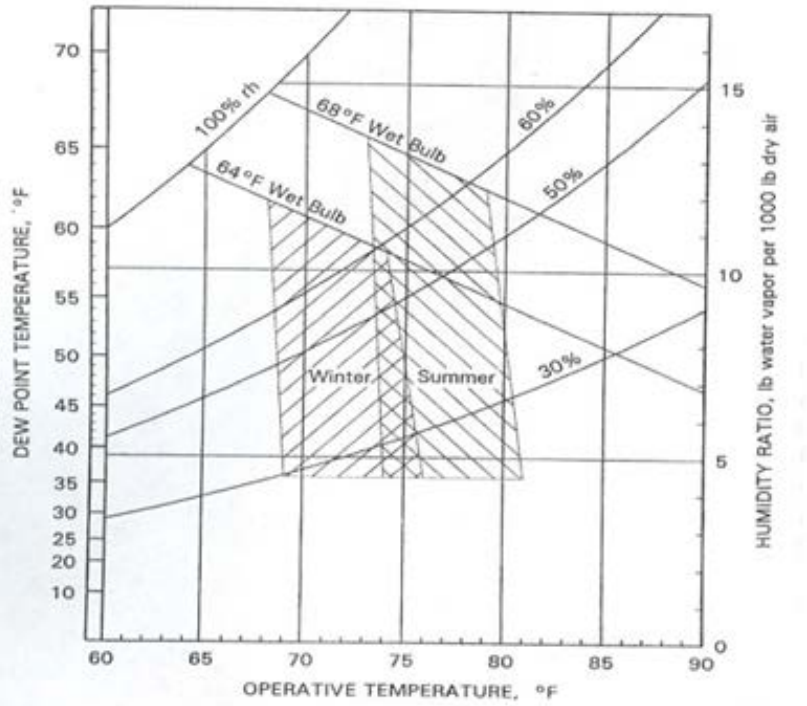

Fig. 5 ASHRAE Summer and Winter Comfort Zones
(Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.)

Source: ASHRAE Handbook Fundamentals 2005, Chapter 8.12

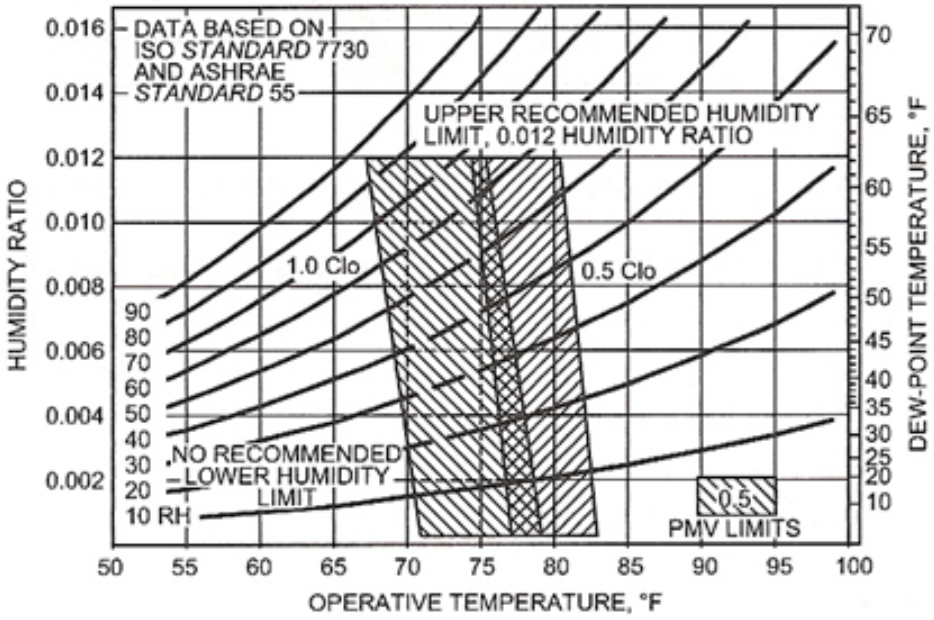

Fig. 5 ASHRAE Summer and Winter Comfort Zones
[Acceptable ranges of operative temperature and humidity with air speed ≤ 40 fpm for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met).]

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9.12

Thermal Comfort

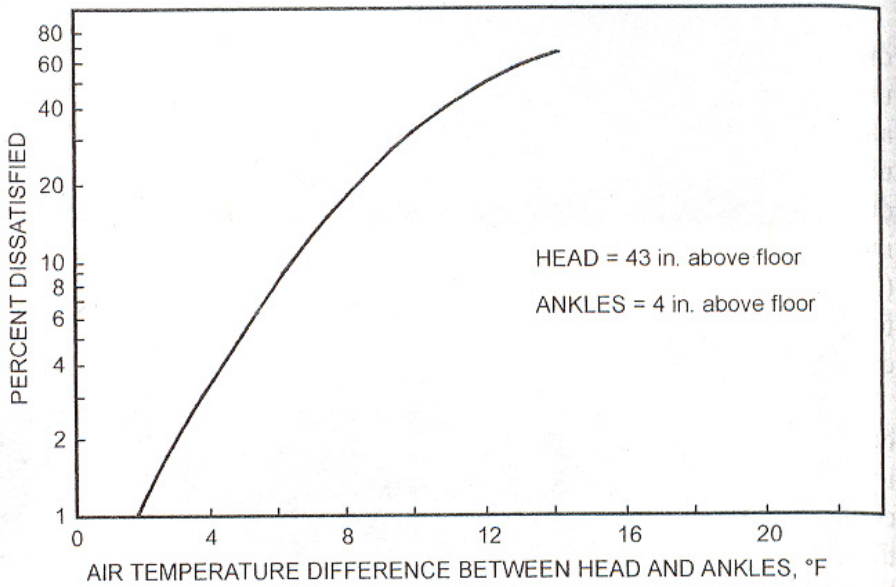

Fig. 9 Percentage of Seated People Dissatisfied as Function of Air Temperature Difference Between Head and Ankles

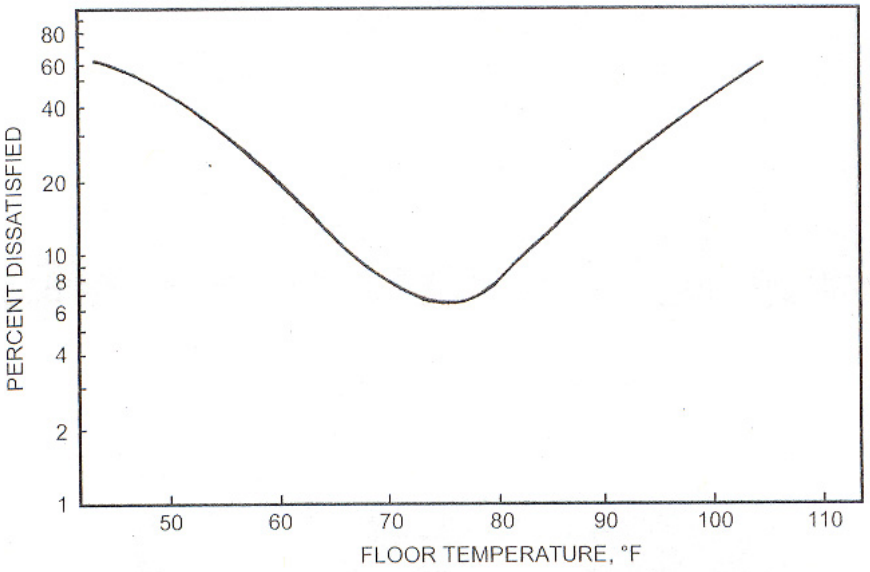

Fig. 10 Percentage of People Dissatisfied as Function of Floor Temperature

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9.12, Figures 12 and 13

Thermal Comfort

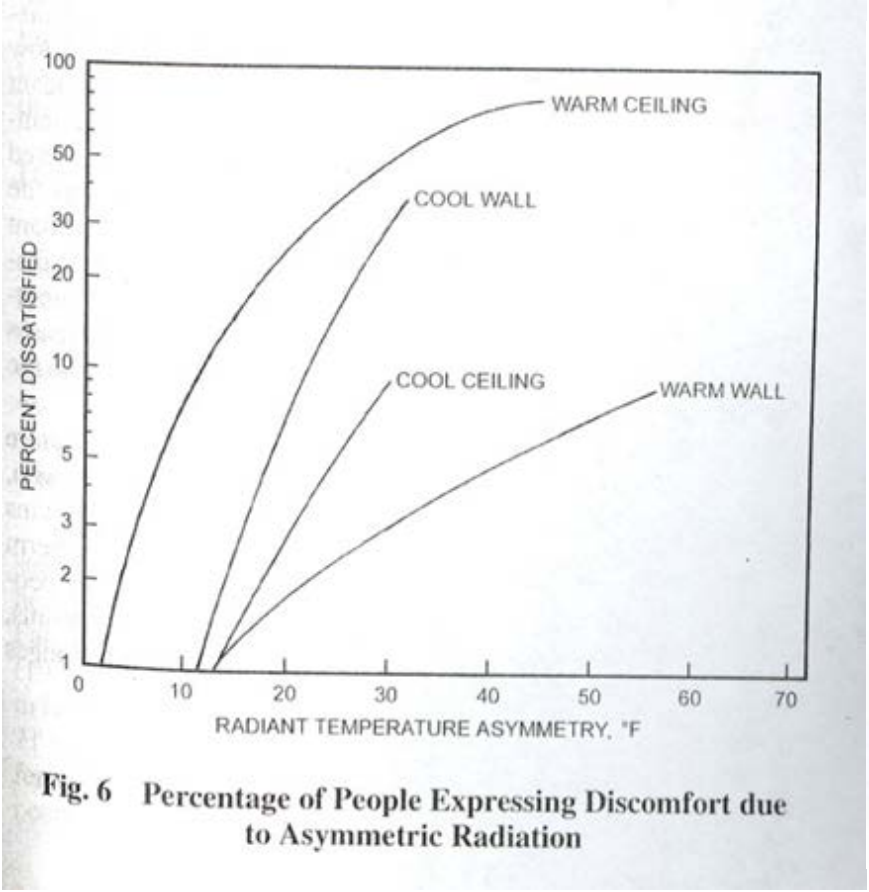

Fig. 6 Percentage of People Expressing Discomfort due to Asymmetric Radiation

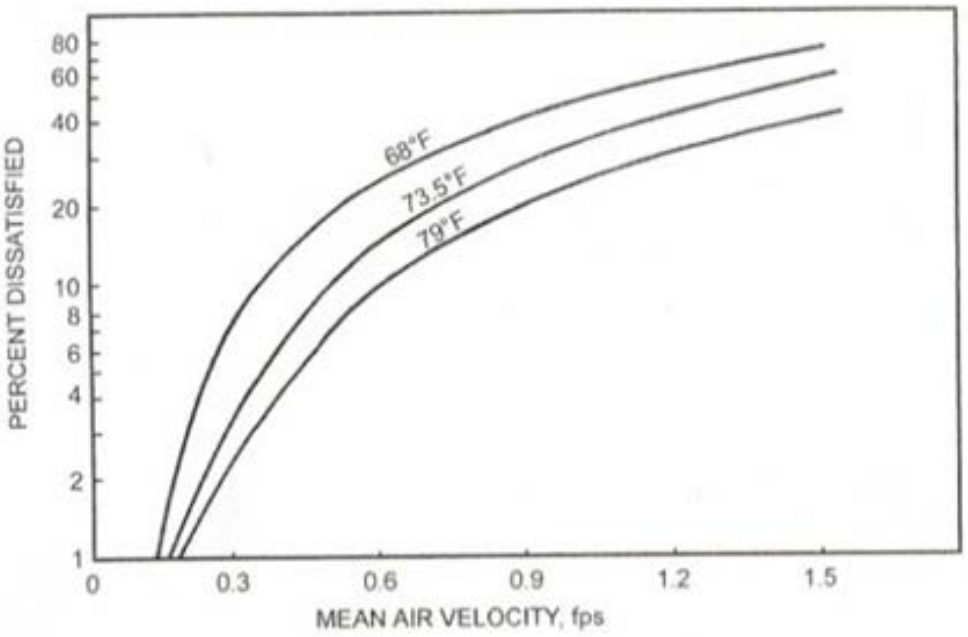

Fig. 7 Percentage of People Dissatisfied as Function of Mean Air Velocity

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9, Figures 9 and 10

Thermal Comfort

Thermal Stress

- Heat and humidity
- Wet-bulb globe temperature
  - 70% naturally ventilated wet bulb
  - 20% black globe
  - 10% ambient

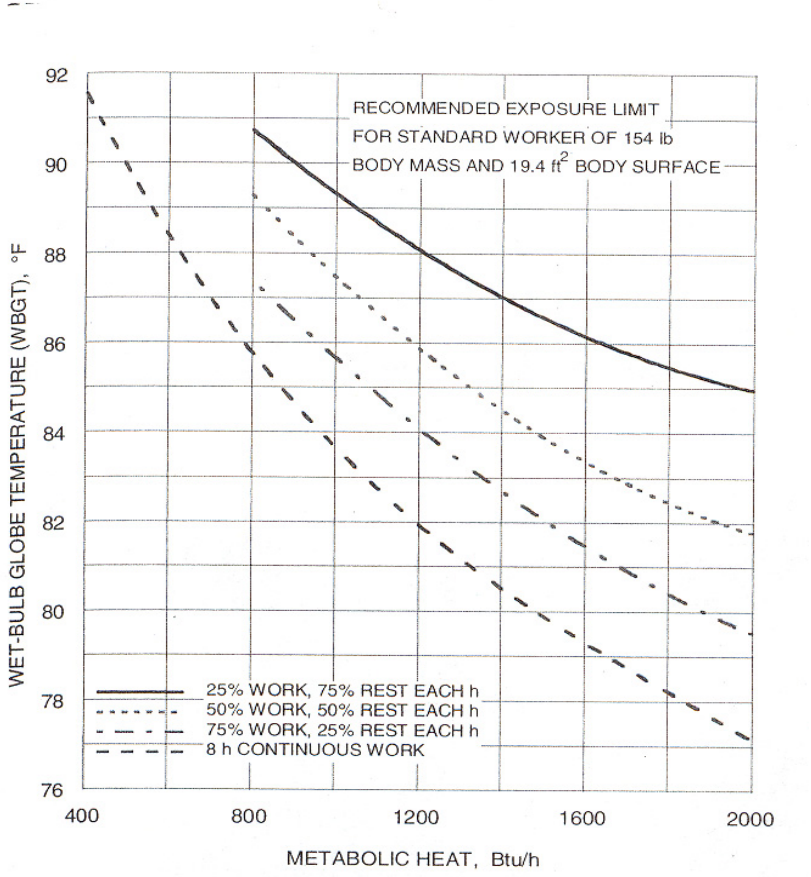

Fig. 17 Recommended Heat Stress Exposure Limits for Heat Acclimatized Workers
[Adapted from NIOSH (1986)]

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9, Figure 20

Thermal Comfort

Thermal Stress – Wind Chill

Table 11 Equivalent Wind Chill Temperatures of Cold Environments

Wind Speed, mph	Actual Thermometer Reading, °F											
	50	40	30	20	10	0	−10	−20	−30	−40	−50	−60
	Equivalent Wind Chill Temperature, °F											
0	50	40	30	20	10	0	−10	−20	−30	−40	−50	−60
5	48	37	27	16	6	−5	−15	−26	−36	−47	−57	−68
10	40	28	16	3	−9	−21	−34	−46	−58	−71	−83	−95
15	36	22	9	−5	−18	−32	−45	−59	−72	−86	−99	−113
20	32	18	4	−11	−25	−39	−53	−68	−82	−96	−110	−125
25	30	15	0	−15	−30	−44	−59	−74	−89	−104	−119	−134
30	28	13	−3	−18	−33	−48	−64	−79	−94	−110	−125	−140
35	27	11	−4	−20	−36	−51	−67	−83	−98	−114	−129	−145
40	26	10	−6	−22	−38	−53	−69	−85	−101	−117	−133	−148
Little danger: In less than 5 h, with dry skin. Maximum danger from false sense of security. (WCI < 1400)					**Increasing danger:** Danger of freezing exposed flesh within 1 min. (1400 ≤ WCI ≤ 2000)			**Great danger:** Flesh may freeze within 30 s. (WCI > 2000)				

Source: U.S. Army Research Institute of Environmental Medicine.
Notes: Cooling power of environment expressed as an equivalent temperature under calm conditions [Equation (81)]. Winds greater than 43 mph have little added chilling effect.

Source: ASHRAE Handbook Fundamentals 2013, Chapter 9, Table 12

Thermal Comfort

Moisture and Humidity

- Human comfort
  - 30% to 70%
- Static electricity
  - varies => generally less than 45%
- Prevention & treatment of disease
  - 50% maximum mortality for influenza virus
- Visible condensation
  - primarily windows
- Concealed condensation

Thermal Comfort

Interior Humidity => Pat's Guide

- Occupant 40 to 60%
- Furnishings & Finishes 35 to 45%
  - woodwork
  - fine art, piano, etc.
- Building 20 to ?? %
  - surface condensation (windows, cold corners, etc.)
    - component characteristics
    - outdoor temperature dependent
  - cavity condensation (attic, walls, rim joists, etc.)
    - envelope characteristics
    - outdoor temperature dependent

In Summary

Questions and Discussion

Preview for Next Class

- Intro to Air Exchange
  - Basic concepts
  - Terminology

- Readings
  - HPE: Chapter 3.2
  - HPE: Appendix B.11