Thermal Conditions During Black Sky
The Physiological Responses to Thermal Extremes

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Centers for Disease Control
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Safety and Health

National Personal Protective Technology Laboratory

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Introduction

- Most research on the human response to thermal extremes has been conducted in outdoor environments or in occupations that expose workers to thermal extremes such as:
  - Firefighters (structural and wildland)
  - Foundry workers (steel mills)
  - Miners
  - Workers wearing encapsulating personal protective ensembles (healthcare workers, HAZMAT, etc.)
- This talk focuses on the physiological response to thermal extremes in workers who occupy buildings when the normal thermal environment cannot be maintained (loss of HVAC), including:
  - Buildings located in hot environments in which the ambient temperature is <u>increasing</u>
  - Buildings located in cold environments in which the ambient temperature is <u>decreasing</u>

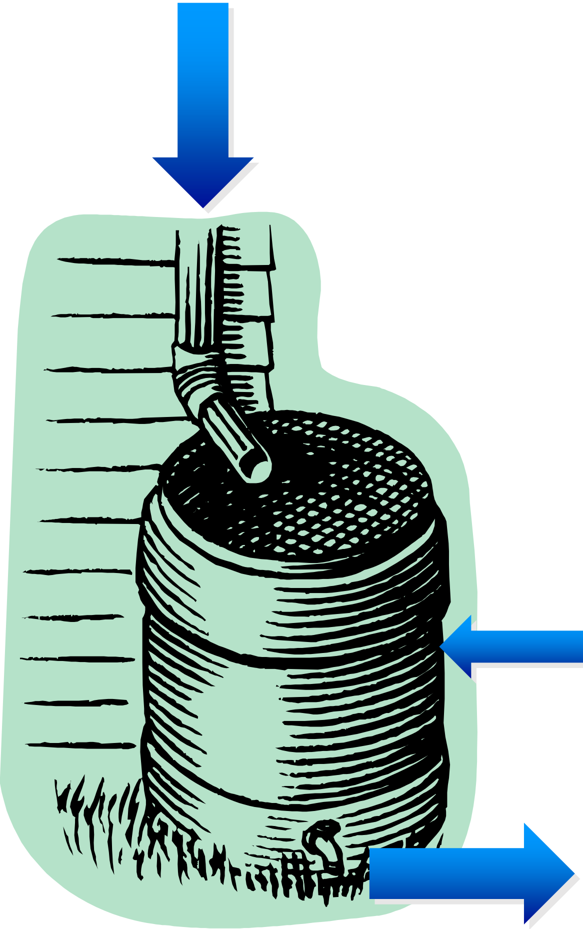
Introduction to Heat Stress in Humans*

- When it comes to heat transfer - we all must obey the laws of physics
  - Regulation of body temperature is a tight balance between heat production and heat loss (exchange with the environment)
  - The physiology of thermoregulation is a good example of the physics of thermodynamics
- The following discussion will review the physiological and biophysical mechanisms of the control of body temperature

Heat Balance Summary - Simple

Water (heat) inputs

Increased metabolism or environment heat or both



The balance is similar to water flow into and out of a rain barrel. If the flow into the barrel is equal to the flow out of the barrel, then the level of water (temperature) inside the barrel never changes. If the flow into the barrel is greater that the flow out of the barrel, then the water level (temperature) increases

If inflow equals outflow, then the water level (body temperature) does not change

Water (heat) outputs

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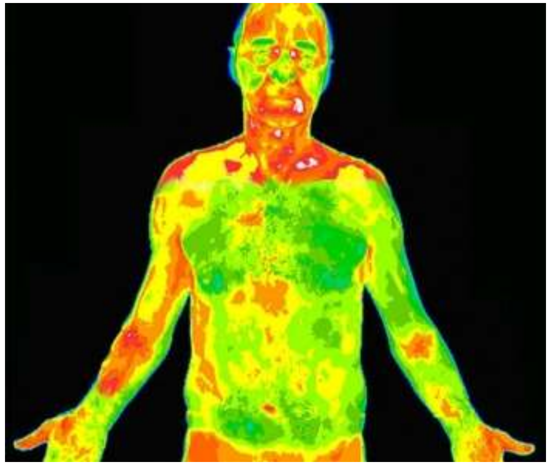
Heat Balance Equation - A Meld of Physics and Physiology*

- The heat balance equation allows the physiologist to determine whether there will be an increase (or decrease) in body temperature by taking into account the physical and physiological factors involved in either heat loss or gain:

  The equation follows the First Law of Thermodynamics that says:
  - 1) "..stored thermal energy (S) results from the balance among evaporation (E), conduction (K), radiation (R), and convection (C) thermal exchanges…" (loss of heat from body to the environment) and
  - 2) "… heat produced by metabolism (M) and exchanged when performing mechanical work (W)..." (gain of heat to the body from metabolism) and
  - 3) any heat absorbed into the body (sun, fire, other environmental sources)

Mechanisms of Transfer of Heat to the Environment (Physics)

- Conduction: direct contact with a colder object (leaning against a cold wall)
- Convection: movement of air across the skin surface which carries warmer air away from and cooler air closer to the body
- Radiation: direct emitting of electromagnetic heat waves from the body (can be visualized with an infrared camera)
- Evaporative heat loss: the most powerful and efficient means of heat transfer to the environment



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Heat Balance Equation for Sweat Evaporation*

- The heat balance equation takes into account several factors that determine whether the work rate, environment, or both will result in increased body temperature and the amount of heat transfer from sweat evaporation needed to maintain body temperature. The equation is as follows:
  - Equation 1: $E_{req} = H - E_{resp} \pm R \pm C$ [watts, W]
  - Where:
  - E_{req} = required evaporative cooling [W]
  - H = metabolic heat production (M – (±W)) [W]
  - E_{resp} = evaporation accompanying respiration [W]
  - R and C = heat transfer via radiation and convection [W]

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Magnitude of Heat Transfer from Evaporation of Sweat

- In humans, evaporation of sweat is an extremely efficient means of heat transfer over the large surface area of the skin
- Evaporation of sweat extracts 2436 kJ (580 kcal) of heat per liter of sweat
- A well acclimated individual may lose 12 L of sweat per day (at a rate of 1.0 liter per hour) exercising in the heat
- This translates into 29,232 kJ (6960 kcal) of total heat loss
- This is usually more than enough heat loss to maintain body temperature
- However, loss of fluid from sweating requires fluid replacement by drinking an adequate volume of water or sports drinks to maintain the process

Overall Heat Balance Equation*

- Put together, the equation is the following:
  - $S = M - (\pm W) - E \pm R \pm K \pm C$ (in W ·m^2 body surface area)
  - Thus, you may measure these factors in the equation and determine if energy (heat) is being stored in the body that, over time, will cause the core body temperature to increase (or decrease) taking into account the surface area of the body where heat exchange is occurring.
- This equation forms the basis of much of thermal physiology.

Behavioral Mechanisms to Control Body Heat – to Augment the Physics

- Doffing clothing (limited by social convention!)
- Using air conditioning (if available), moving indoors on a hot day (not relevant to our purposes)
- Moving into a shaded area (reduce radiant heat exposure) (not relevant to our purposes)
- Drinking fluids (aids in sweat evaporation by providing replacement fluids)
- Take a rest break – reduce heat produced by physical exertion (not relevant to our purposes)

Heat Imbalance = Physiological Heat Strain

- Humans have evolved physiological and behavioral mechanisms that allow survival within a range of environmental temperatures
- These mechanisms allow internal body temperatures to be tightly regulated to within a vary narrow range 36.5-37°C (97.7-98.6°F)
- However, humans can acclimatize to hot environments (heat stress) only up to a point
- Heat strain (physiological response) occurs in hot environments (heat stress) when humans experience an increase in deep tissue (body core) temperature above 37°C (98.6°F) because of a reduced ability to transfer that heat away from the body to the environment

Sources of Heat Stress*

- Exertional (or metabolic):
  - Generation of internal body heat by working muscles
  - Can cause heat stress/injury even in a relatively mild environmental temperature and relative humidity
- **Although an important source of heat, this topic will not be addressed here because the focus is on <u>environmental</u> heat.**
- Environmental:
  - High air temperature may add heat to the body and/or high humidity defeats sweat evaporation
  - Radiant energy (direct sun, fire, hot machinery, etc.) adds heat to the body (not relevant to people working in built structures shielded from radiant energy)
  - Use of encapsulating PPE (not generally relevant to workers in office buildings)
- The increase in body temperature from environmental heat stress can result in increased core body temperatures leading to heat strain and decrease in ability to work.

Physiological Responses to Heat Stress

- Environmental heat is sensed by thermal sensors (free nerve endings) in the skin which send signals to the brain (hypothalamus).
- When the deep body core temperature increases, the hypothalamus protects against overheating by:
  - Moving warm blood from the deep body tissues to the skin for exchange with the environment via conduction, convection, and radiation
  - Increased sweating and moisture from the respiratory tract which is then evaporated taking a large amount of heat away from the body.
- These mechanisms are extremely effective in maintaining a constant internal body temperature

Physiological Responses (continued)

- Since sweat evaporation is the most effective means of heat transfer to the environment, it is the most important means of heat transfer in hot environments.
- Sweat evaporation depends on being well hydrated - NOT under-hydrated
  - For shorter duration activity (~1-2 hours) – water
  - For longer duration (>2 hours) – electrolyte/carbohydrate containing "sports" drinks
- Acclimatization to heat involves recruitment of inactive sweat glands – this results in more water loss and a greater need to hydrate

Physiological Responses (continued)

- For the present purposes, the thermal stress experienced by workers in the office setting will be limited to a combination of air temperature and relative humidity.
  - This combination of environmental factors has been organized into the NOAA Heat Index chart
  - This chart neglects the factors of radiant heat gain and convective heat loss due to air movement
- Since convective heat loss and radiant heat gain may be absent from the office environment, then the heat index chart may be used effectively to determine the heat stress imposed on the office worker

Heat Index Chart

Commonly used to determine heat stress imposed by a combination of air temperature and humidity

NOAA's National Weather Service

Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	118	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	126	130					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | External Danger

Conclusion

- Through both physical, physiological, and behavioral mechanisms, humans strongly defend internal body temperature against a wide range of environmental temperatures
- Humans can acclimate to hot environments by increasing sweating and through other mechanisms
- However, hot and humid environments, poor hydration and other factors can defeat the physical and physiological mechanisms used to maintain core body temperature
- Uncompensated heat stress can lead to heat injury and death if specific intervention is delayed

Introduction to Cold Stress*

- Cold Stress
  - Each year nearly 700 people in the U.S. die of hypothermia.
  - 37% (~259) of hypothermia-related deaths in the U.S. between 1999-2000 were work-related
  - Cold environmental temperatures may produce extreme discomfort prior to any damaging health effects
  - A person working in a cold environment may actually experience heat stress until the work ceases and the person becomes cold.

Physiological Responses to Cold Stress

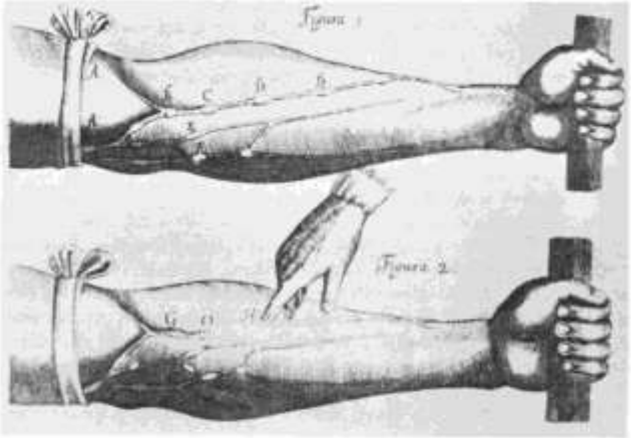
- When the deep body core temperature decreases, the hypothalamus protects against overcooling by:
  - Moving warm blood from the cutaneous tissues to the core to reduce heat exchange with the environment via conduction, convection, and radiation
  - Increased metabolism and shivering thermogenesis to produce heat within the body.
- These mechanisms are extremely effective in maintaining a constant internal body temperature

Physiological Response to Cold Stress

- Cold stress can induce several physiological responses in order to conserve and/or generate heat
- The overall result is that core body temperature is maintained
- A significant decrease in core body temperature may be dangerous or even fatal if not mitigated.

Physiological Response to Cold Stress

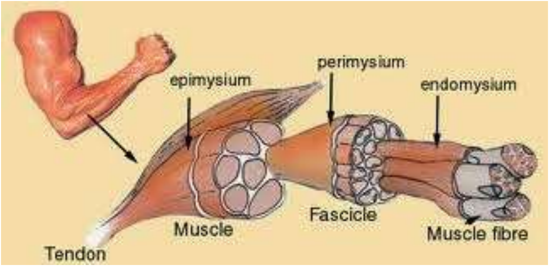
- Upon exposure to cold environments, heat is lost from the body through the physical mechanisms already discussed.
- To limit this loss, one of the first physiological responses is vasoconstriction of the blood vessels in the skin.
  - Limits the flow of warm blood to the body shell and reduces heat exchange with the environment.



Wikipedia: photo public domain. From Wm. Harvey, De Motu Cordis, 1628

Physiological Response to Cold Stress

- A second physiological response is to increase metabolic heat production
  - Shivering thermogenesis is a very effective means to increase core body temperature.
  - Accomplished through the asynchronous firing of muscle fibers which produces heat but not physical work
  - Further cooling will result in a synchronous firing of muscle (10-12 Hz oscillations) to produce shivering



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Physiological Response to Cold Stress*

- Shivering can result in a 6-fold increase in heat production above resting levels for short periods and a 2-fold increase for longer periods
- Shivering entails a metabolic oxygen cost
  - Estimates show that shivering may increase oxygen consumption up to 50% of $\dot{V}O_{2max}$
- Shivering may result is some heat loss from skin but heat is also transferred to the body core
- Exercise inhibits shivering but will also produce metabolic heat

Physiological Response to Cold Stress

- The physiological responses are triggered by changes in core body temperature (T_{core})
  - T_{core} = 98.6°F (37°C) – normal
  - T_{core} = 96.6 °F (36°C) – increase metabolic rate to compensate for heat loss
  - T_{core} = 95°F (35°C) – maximal shivering to compensate for heat loss
- Below 91.4 °F (34°C) – severe hypothermia

Physiological Acclimatization to Cold

- Human behavioral responses to cold have allowed for survival in cold environments

- Physiological adaptation to cold is, therefore, difficult to document
  - With protective clothing, the microclimate within the clothing is warm compared to the environment.
  - Therefore, whether cold adaptation does not really occur from a physiological standpoint is unclear.
  - Exercise increases metabolic heat production to increase T_{core} but this is not necessarily an adaptation but an activity

Physiological Acclimatization to Cold

- If cold acclimatization does occur, there are three possible physiological mechanisms:
  - Hypothermic: allowing the T_{core} to decrease thereby limiting heat loss
  - Insulative: enhanced insulation hence preventing cooling
  - Metabolic: Increased heat production (non-shivering thermogensis)
- Some evidence for these adaptations but still inconclusive.

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Behavioral Mechanisms to Control Body Heat – to Augment the Physics

- Donning or Doffing clothing
- Moving indoors on a cold day (not relevant to our purposes)
- Drinking hot fluids (if available)
- Increase physical activity (heat produced by physical exertion) (limited in an indoor setting)

Hypothermia – Early Stages

- Early Symptoms
  - Shivering – attempt to generate heat
  - Fatigue
  - Loss of coordination
  - Confusion and disorientation
- May be treated using basic first aid technics
  - Remove from cold
- Should workers exhibit these signs/symptoms, they should be moved to a warmer area if possible. If not, the building environment is not clement for effective work.

EMERGENCY OPERATING CONDITIONS (BLACK SKIES)

Assumptions Regarding the Building Status During a Black Skies Event

- The building environmental control systems fail and cannot be restored over a period of hours to days.
- The occupants of the building must stay in that building to perform their jobs (i.e., cannot leave to move to more comfortable conditions).
- The building occupants do not have access to clothing that can provide anything more than minimal protection against either cold or hot conditions (at most a clo ≤ 1.0).
  - One clo is equal to the thermal insulation required to keep a sedentary person thermally comfortable in an ambient temperature of 21˚C (underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes).
    - 0.75 clo (underpants, shirt, trousers, socks, shoes) – thermal comfort in warm conditions
    - 2.55 clo (Underwear with long sleeves and legs, thermojacket + trousers, parka with heavy quilting, overalls with heavy quilting, socks, shoes, cap, gloves) – thermal comfort in cold conditions
- The building occupants are generally healthy with the normal physiological responses to deviations in environmental conditions.
- The workers remain inside the building and perform minimal physical work (nearly at rest, 1.2-1.5 MET where 1.0 MET is equivalent to the oxygen consumption [metabolic rate], and therefore activity level, at rest). At this minimal workload, the metabolic heat produced will be minimal (slightly above that produced at rest).

Black Skies Event Continued

Assumptions:

- Factors such as convection and direct radiation from the sun will be considered negligible.
- Air movement in the building occupied zone is below 0.7 ft/min (0.2 m/min) and, as such, there is little convective heat transfer.
- Building is lit using either fluorescent, or LED lighting, which results in a negligible radiant heat from lighting fixtures.
- The building environmental conditions will be affected as a result of the function of the HVAC system in an indoor setting, and the environmental stressors are the dry air temperature (Dry Bulb or T_{db}) and humidity or wet bulb temperature (T_{wb}) with other environmental factors such as air velocity and radiant heat being negligible.

Physiological/psychological signs and symptoms of thermal strain (not comprehensive).

Hypothermia (T_{core} <96.8 °F (< 36 °C))	Hyperthermia (T_{core} >100.4 °F (>38 °C))
Extreme discomfort	Skin vasodilation (flushing)
Numbness (tactile sensitivity, manual dexterity decreases)	Sweating (>1 $L \cdot h^{-1}$ in the extreme)
Shivering	Dehydration (thirst not a good indicator of hydration status)
Skin vasoconstriction (blanching)	Eventual decrease in sweating (hidromeiosis)
Cold becomes a distraction	Increase in heart rate
Muscle stiffness	Fatigue (heat exhaustion)
Cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.)	Cognitive changes (decreased situational awareness, poor judgement)
Loss of sensory information (blurred vision)	Mental confusion
Cardiovascular effects	Behavioral changes
Loss of consciousness	**Collapse – heat stroke**

Building Environmental Conditions - Hot

- Loss of HVAC may result in building office space becoming uncomfortably hot/humid
  - Most workers can function in a hot environment up to a point
    - However, some of the mechanisms for transfer of heat from body depend on a thermal gradient which can be overcome if the environment exceeds core body temperature
    - Sweating normally transfers body heat efficiently but can be defeated in a humid environment that prevents sweat evaporation
  - Should ambient temperatures increase above 75 °F (24 °C) for workers performing sedentary work (1 MET) with normal indoor clothing (1.0 Clo) resulted in the following performance decrements:
    - the rate of accidents rose sharply by 50% at 77°F (25 °C),
    - mental performance decreased by 40% between 68 °F and 86 °F (20 °C and 30 °C)
    - and the work rate declines sharply (by 55%) between 68°F and 80.6°F (20 °C and 27 °C)

Building Environmental Conditions-Cold

- Loss of HVAC may result in building office space becoming uncomfortably cold
  - Most workers can function in a cold environment up to a point
  - However, some of the mechanisms for transfer of heat from body depend on a thermal gradient which can be significant if the environment decreases below core body temperature
    - The worker may begin to lose body heat to the point where core body temperature decreases and indicate the decline in ability to perform light work (1.2 Met) with light clothing (0.6 Clo)
    - At ambient temperatures below 60.8°F (16 °C) indoor climate (down to 50°F [10 °C]):
      - the rate of accidents rose sharply by 40%
      - manual dexterity rapidly declined by 20%
      - speed and sensitivity of fingers declined by 50%
  - These effects suggest that the ability of workers performing critical tasks is significantly impaired at a temperature below 60.8 °F (16 °C).

Summary

Building Thermal Environment is Important to Worker Health and Productivity

Therefore,

- In emergency situations, reduction of indoor air temperature with mission critical buildings operating below 60.8 °F (16 °C) [ACGIH 2018] and
- An increase in Wet Bulb Globe Temperature (WBGT) above 87.8 °F (31 °C)[ACGIH 2017]) is not recommended since it will impair performance of mission operators.
- Should these conditions persist for hours or without a reasonable anticipation of HVAC repair, the workers should be relocated to more comfortable thermal environments.

*Reference:

This presentation was developed using the following reference work:

Parsons K. Human Thermal Environments (2nd Edition). Taylor and Francis, London, 2003.

Thanks!

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