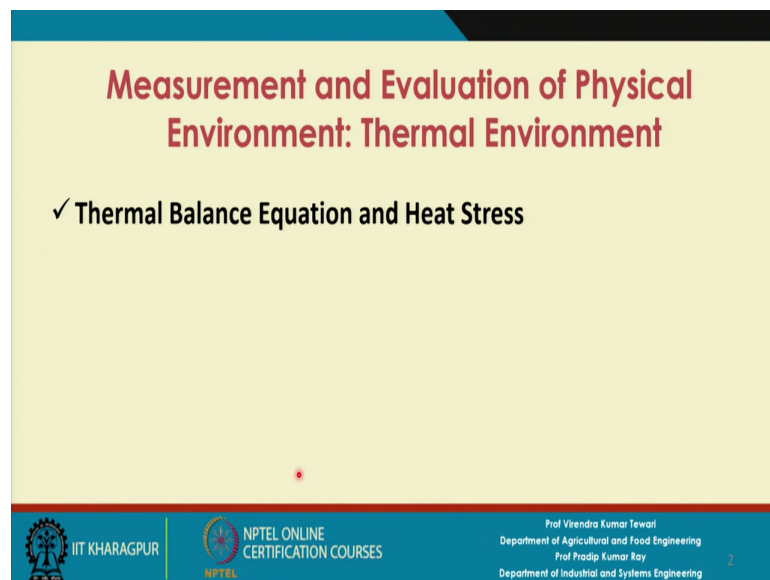


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**Lecture - 37**  
**Thermal Balance Equation and Heat Stress**

So, during the second lecture session of this week I will be discussing the Thermal Environment Design and its issues - Thermal Balance Equation and the Heat Stress.

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So, first I will discuss about thermal balance equation for human body and then I will also refer to the heat stress condition.

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**Thermal Balance Equation and Heat Stress**

- Level of heat stress or heat exposure is related to an equation of human thermal balance
- Human thermal balance equation is given by
$$S = M - E \pm R \pm C - W$$
where, S = heat gained or lost by body  
M = metabolic energy production  
E = heat dissipated through evaporation (sweating)  
R = radiant heat to or from environment  
C = convection to or from environment  
W = work done by worker

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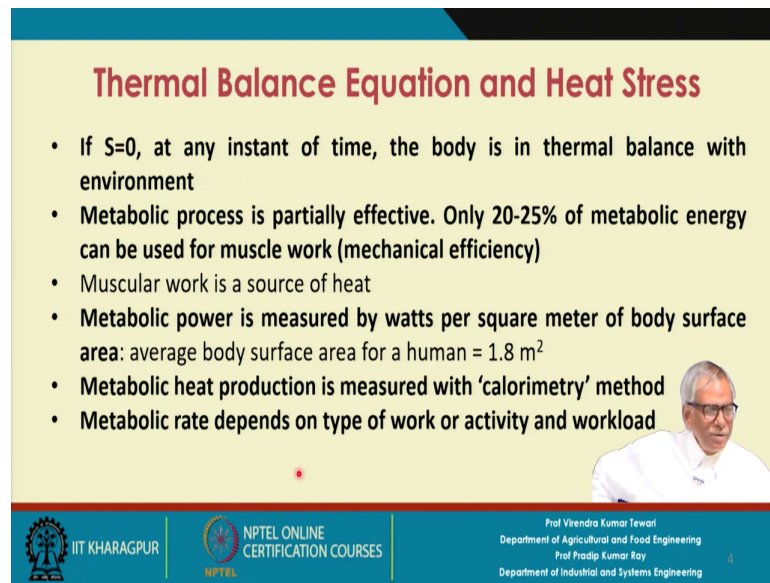
E = heat dissipated through evaporation (sweating)

R = radiant heat to or from environment

C = convection to or from environment

W = work done by worker

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**Thermal Balance Equation and Heat Stress**

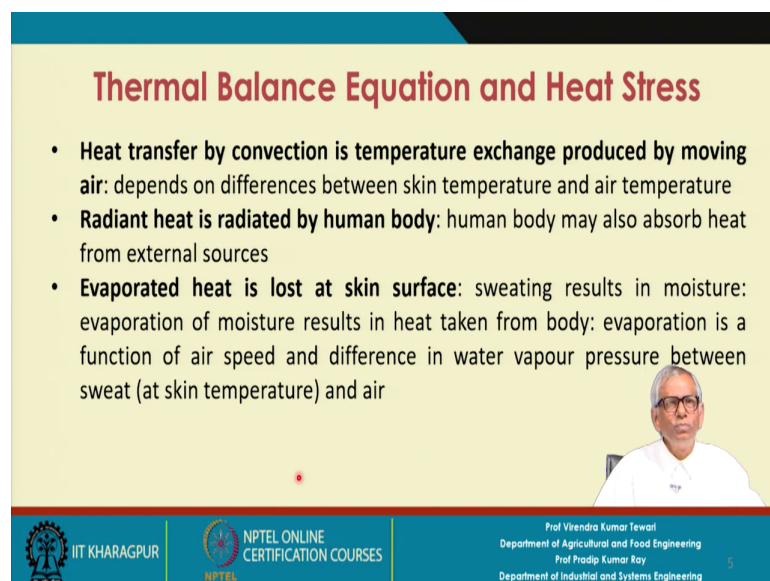
- If  $S=0$ , at any instant of time, the body is in thermal balance with environment
- Metabolic process is partially effective. Only 20-25% of metabolic energy can be used for muscle work (mechanical efficiency)
- Muscular work is a source of heat
- Metabolic power is measured by watts per square meter of body surface area: average body surface area for a human =  $1.8 \text{ m}^2$
- Metabolic heat production is measured with 'calorimetry' method
- Metabolic rate depends on type of work or activity and workload

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If  $S = 0$ , at any instant of time, the body is in thermal balance with environment. Metabolic process is partially effective. Only 20-25% of metabolic energy can be used for muscle work (mechanical efficiency). Muscular work is a source of heat. Metabolic power is measured by watts per square meter of body surface area: average body surface area for a human =  $1.8 \text{ m}^2$ . Metabolic heat production is measured with 'calorimetry' method. Metabolic rate depends on type of work or activity and workload.

(Refer Slide Time: 09:46)



**Thermal Balance Equation and Heat Stress**

- Heat transfer by convection is temperature exchange produced by moving air: depends on differences between skin temperature and air temperature
- Radiant heat is radiated by human body: human body may also absorb heat from external sources
- Evaporated heat is lost at skin surface: sweating results in moisture: evaporation of moisture results in heat taken from body: evaporation is a function of air speed and difference in water vapour pressure between sweat (at skin temperature) and air

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Now, the first one is the heat transfer by convection is temperature exchange ge produced by moving air. So, it depends on differences between the skin temperature and the air temperature or ambient temperature ambient air temperature.

Next one is the radiant heat is radiated by human body. So, human body may also absorb heat from external sources.

Evaporated heat is lost at skin surface; that means, sweating results in moisture: evaporation of moisture results in heat taken from body: evaporation is a function of air speed and difference in water vapour pressure between sweat (at skin temperature) and air.

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**Thermal Balance Equation and Heat Stress**

- In hot and humid environment, evaporated heat loss is limited: 100% humidity means no evaporation of sweat, and hence, no cooling of body
- In hot and dry environment, evaporated heat loss is restricted by perspiration rate of the worker: sweat disappears quickly from skin surface and absorbs by air
- Maximum sweat production rate by a person, on an average, is 1 liter per hour
- If  $S$  is large, effect may be heat stroke: there are many preventive measures

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In hot and humid environment, evaporated heat loss is limited: 100% humidity means no evaporation of sweat, and hence, no cooling of body. In hot and dry environment, evaporated heat loss is restricted by perspiration rate of the worker: sweat disappears quickly from skin surface and absorbs by air. Maximum sweat production rate by a person, on an average, is 1 litre per hour.

If  $S$  is large, effect may be heat stroke: there are many preventive measures.

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### Thermal Balance Equation and Heat Stress

Activity	Workload	Metabolic Rate (W/m <sup>2</sup> )
Seated	No load, resting	55 – 65
Standing, light work	Low	90 – 100
Standing, machining	Low	100 – 120
Heavy machine work	Moderate	150 – 170
Material handling (carrying heavy material)	High	220 – 240



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Workload is an important issue, there are activities, workload and metabolic rate give. In the typical seated activity- there is no workload and the metabolic rate is 55 to 65 watt per meter square. 2<sup>nd</sup> activity is standing, light work where workload is low and metabolic rate is 90-100 W/m<sup>2</sup>.

3<sup>rd</sup> activity is standing, machining where workload is low and metabolic rate is 100-120 W/m<sup>2</sup>.

4<sup>th</sup> activity is heavy machine work, where workload is moderate and metabolic rate is 150-170 W/m<sup>2</sup>.

5<sup>th</sup> activity is material handling where workload is high and metabolic rate is 220-240 W/m<sup>2</sup>.

We have noticed that metabolic rate increases when the workload increases.

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**Heat Stress Management: Measures to Minimize Heat Stress**

1. Reduce high relative humidity by using dehumidifiers
2. Increase air movement/speed by using fans or air conditioners
3. Decrease temperature by using air conditioners
4. Remove heavy clothing, use loose-fitting overalls/wide-clothing
5. Reduce work rate
6. Increase frequency of rest pauses
7. Introduce job rotation
8. Carry out outdoor work at cooler times, say early morning

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Now, our main concern is the heat stress and how to eliminate heat stress in a given condition and then only you say thermal involvement quality is excellent. In many workplaces the heat stress management is considered important and critical. It can be done in various way:

- a) Reduce high relative humidity by using dehumidifiers.
- b) Increase air movement/speed by using fans or air conditioners.
- c) Decrease temperature by using air conditioners.
- d) Remove heavy clothing, use loose-fitting overalls/wide-clothing.
- e) Reduce work rate.
- f) Increase frequency of rest pauses.
- g) Introduce job rotation.
- h) Carry out outdoor work at cooler times, say early morning.

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**Heat Stress Management: Measures to Minimize Heat Stress**

9. Select personnel who can tolerate extreme heat
10. Allow two weeks for acclimatization
11. Use cool, refrigerated vests (with cooling elements)
12. Install local cold spots (refrigerated room for rest breaks)
13. Provide shade to reduce radiant heat
14. Maintain hydration by drinking water and taking salt tablets

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- i) Select personnel who can tolerate extreme heat.
- j) Allow two weeks for acclimatization.
- k) Use cool, refrigerated vests (with cooling elements).
- l) Install local cold spots (refrigerated room for rest breaks).
- m) Provide shade to reduce radiant heat.
- n) Maintain hydration by drinking water and taking salt tablets.

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**Work in Hot Environment: Influencing Factors**

- Workers differ in their ability to tolerate heat stress
  - ✓ Hyper-heat tolerant person: no need for acclimatization
  - ✓ Heat intolerant person: never able to work safely
- Three Main Influencing Factors:
  1. Worker characteristics
    - Physiological heat
    - Heat tolerance
    - Physical fitness
    - Age and gender
    - Aerobic capacity
    - Degree of acclimatization

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Work in hot environment is unavoidable. So, even in a cold country, hot environment you have to create a manufacturing plant so, there you have to work. It is an artificial workplace.

Workers differ in their ability to tolerate heat stress, there will be individual difference. Now, there are two categories of persons you will come across, one type of person they are referred to as the hyper heat tolerant person and other one is heat intolerant person. There are three influencing factors which are as follow:

#### 1. Worker characteristics

- a) Physiological heat
- b) Heat tolerance
- c) Physical fitness
- d) Age and gender
- e) Aerobic capacity
- f) Degree of acclimatization



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**Work in Hot Environment: Influencing Factors**

**2. Thermal Environment**

- Relative humidity
- Globe temperature/radiant
- Heat shade
- Wind speed

**3. Task Requirements**

- Work rate
- Rest-period/pauses
- Protective clothing
- **Heat tolerant persons are to be selected for workplaces like underground mining, shot blasting, etc.**

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Next one is the, what kind of thermal environment and task requirement in which you have to work.

## 2. Thermal Environment

- a) Relative humidity
- b) Globe temperature/radiant
- c) Heat shade
- d) Wind speed

## 3. Task Requirements

- a) Work rate
- b) Rest-period/pauses
- c) Protective clothing
- d) Heat tolerant persons are to be selected for workplaces like underground mining, shot blasting, etc.

(Refer Slide Time: 31:14)

**Work in Cold Weather: Preventive Measures**

- **Suitable protective clothing:** body core temperature maintained (<math><33^{\circ}\text{C}</math> - disruption of central nervous system temperature control <math>\leq 29^{\circ}\text{C}</math> – breakdown of hypothalamic core temperature control- cooling of core tissues lowers metabolic rate/ heat production)
- **Adequate hydration**
- **Acclimatization to cold:** Increased blood flow through hand with repeated exposure to cold conditions
- **Injuries to fingers, toes, cheeks, and ears**

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Suitable protective clothing for maintaining body core temperature:

(<math><33^{\circ}\text{C}</math> - disruption of central nervous system temperature control <math>\leq 29^{\circ}\text{C}</math> – breakdown of hypothalamic core temperature control- cooling of core tissues lowers metabolic rate/ heat production). Adequate hydration. Acclimatization to cold: Increased blood flow through hand with repeated exposure to cold conditions. Injuries to fingers, toes, cheeks, and ears.

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**Work Rate, Work Efficiency, and Temperature:**

**Physical work limit or ability is affected by work rate and temperature,**

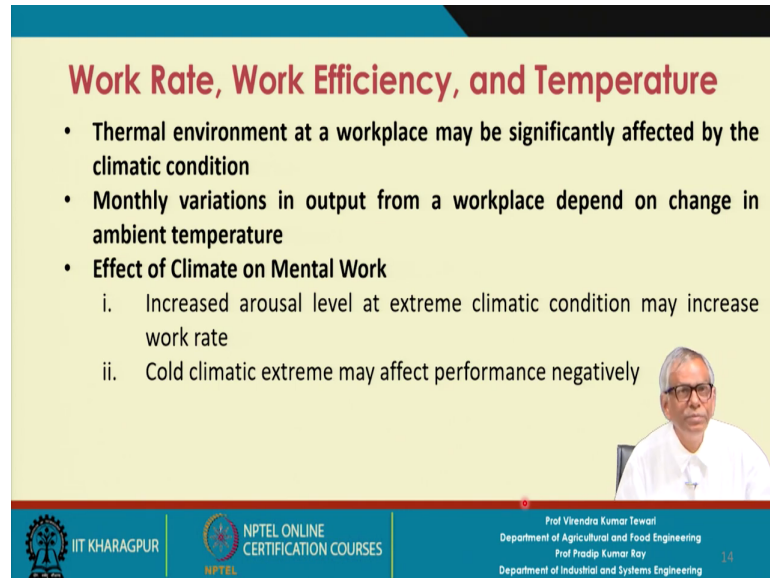
**Different tasks have different work rates**

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Now, work rate, work efficiency and the temperature these are interrelated. And as you come across different task or the jobs and they have different work rates. You cannot avoid this as this condition is imposed on the system.

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**Work Rate, Work Efficiency, and Temperature**

- Thermal environment at a workplace may be significantly affected by the climatic condition
- Monthly variations in output from a workplace depend on change in ambient temperature
- Effect of Climate on Mental Work
  - i. Increased arousal level at extreme climatic condition may increase work rate
  - ii. Cold climatic extreme may affect performance negatively

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So, the thermal environment at a workplace may be significantly affected by the climatic condition and Monthly variations in output from a workplace depend on change in ambient temperature.


Effect of Climate on Mental Work

1. Increased arousal level at extreme climatic condition may increase work rate
2. Cold climatic extreme may affect performance negatively

(Refer Slide Time: 34:13)

## Measurement and Evaluation of Heat Stress: WBGT Index

- Heat stress at a workplace for a given workload is measured by Wet Bulb Globe Temperature or WBGT index
- For a give workload, WBGT index is measured under two work environmental conditions:
  - i. Indoor or outdoor (with no sunshine), and
  - ii. Outdoor with sunshine (solar load)




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So, there is one the condition you have to maintain for different kinds of conditions. When you refer to the thermal balance equation, sometimes you work outside, sometimes you work inside, the indoor or outdoor so you should know how to measure these heat stress. Heat stress at a workplace for a given workload is measured by Wet Bulb Globe Temperature or WBGT index. For a give workload, WBGT index is measured under two work environmental conditions: Indoor or outdoor (with no sunshine), and Outdoor with sunshine (solar load).

(Refer Slide Time: 35:22)

## Measurement and Evaluation of Heat Stress: WBGT Index

1. Indoor/outdoor (without sunshine)
$$\text{WBGT} = 0.7 T_{\text{NW}} + 0.3 T_{\text{G}}$$
where,  $T_{\text{NW}}$  = Natural Wet Bulb Temperature  
 $T_{\text{G}}$  = Globe Temperature  
WBGT is measured in degree Celcius
2. Outdoor (with sunshine/ solar load)
$$\text{WBGT} = 0.7 T_{\text{NW}} + 0.2 T_{\text{G}} + 0.1 T_{\text{A}}$$
where,  $T_{\text{A}}$  = Natural Wet Bulb Temperature



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So, these two equations we have one is an indoor/outdoor without sunshine and outdoor with sunshine or the solar load.

1. Indoor/outdoor (without sunshine)

$$\text{WBGT} = 0.7 \text{ TNW} + 0.3 \text{ TG}$$

where, TNW = Natural Wet Bulb Temperature

TG = Globe Temperature

WBGT is measured in degree Celsius

2. Outdoor (with sunshine/ solar load)

$$\text{WBGT} = 0.7 \text{ TNW} + 0.2 \text{ TG} + 0.1 \text{ TA}$$

where, TA = Natural Wet Bulb Temperature

(Refer Slide Time: 36:10)

The slide features a yellow background with a red header and footer. The main title is 'Measurement and Evaluation of Heat Stress: WBGT Index' in red. Below it, a bullet point reads 'Measurement of  $T_{NW}$ ,  $T_G$ ,  $T_A$ '. A small video inset in the bottom right shows a man in a white shirt and glasses. The footer contains logos for IIT KHARAGPUR, NPTEL ONLINE CERTIFICATION COURSES, and the names of the professors: Prof. Virendra Kumar Tewari (Department of Agricultural and Food Engineering) and Prof. Pradip Kumar Ray (Department of Industrial and Systems Engineering). The slide number '17' is also present.

Measurement of  $T_{NW}$ ,  $T_G$ ,  $T_A$ .


(Refer Slide Time: 36:15)

## Work Activities (from light to heavy) and WBGT Index

- WBGT Index is measured against an activity for a person, based on two conditions: If the person is acclimatized or not
- An acclimatized person can tolerate higher values of WBGT index

Workload	Metabolism (M) (W/m <sup>2</sup> )	Reference Value of WBGT (Celsius)	
		Acclimatized	Not Acclimatized
Resting	<65	33	32
Low	65-130	30	29
Moderate	130-200	28	26
High	200-260	26	23
Very high	> 260	24	19

Adapted from International Standards Organization (1989).



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WBGT Index is measured against an activity for a person, based on two conditions: If the person is acclimatized or not.

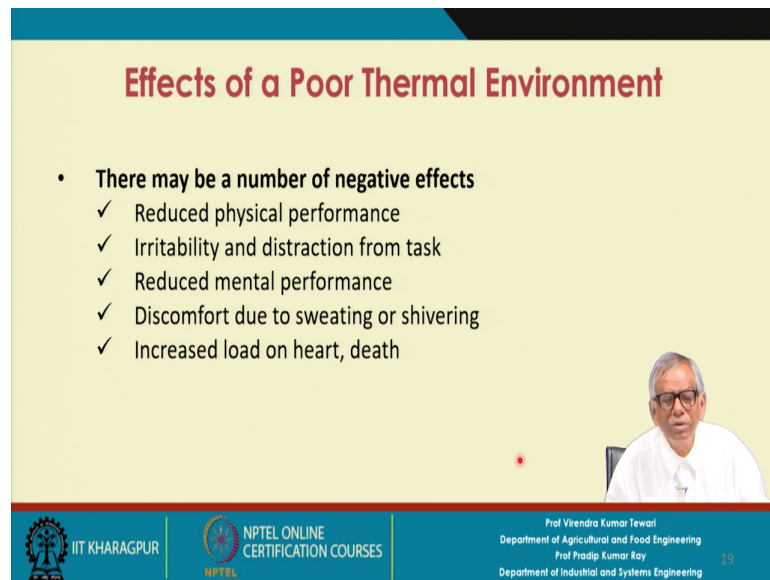
An acclimatized person can tolerate higher values of WBGT index.

Refer to table: So, here under different workload like resting, low, moderate, high, very heavy- these are the five categories we have.

So, metabolism rate is mentioned and acclimatized and non-acclimatized condition are also there.

After analysing we can conclude that work rate is dependent on the metabolism rate as well as the acclimatized condition or non-acclimatized condition.

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**Effects of a Poor Thermal Environment**

- **There may be a number of negative effects**
  - ✓ Reduced physical performance
  - ✓ Irritability and distraction from task
  - ✓ Reduced mental performance
  - ✓ Discomfort due to sweating or shivering
  - ✓ Increased load on heart, death

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There may be a number of negative effects:

1. Reduced physical performance.
2. Irritability and distraction from task.
3. Reduced mental performance.
4. Discomfort due to sweating or shivering.
5. Increased load on heart, death.

(Refer Slide Time: 38:08)

## List of Reference Textbooks

1. Sanders, M. S. and McCormick, E. J., Human Factors in Engineering and Design, McGraw-Hill, Sixth Edition
2. Bridger, R. S., Introduction to Ergonomics, Taylor and Francis Group, Third Edition
3. Helander M, A Guide to Human factors and Ergonomics, Taylor and Francis Group, Second Edition

