Thermal Environment
Concepts and Principles

Objective and Subjective

Objective
(measured)

Subjective
(perceived)

Stress and Strain

Imposed force
Stress

Triggered reaction
Strain

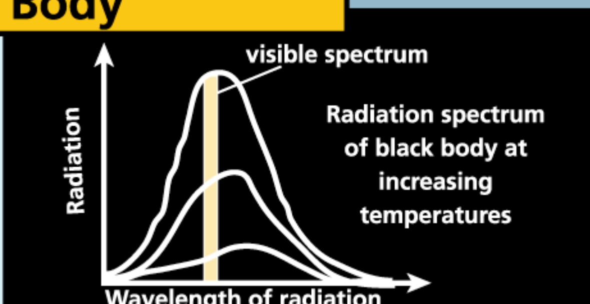
Sensible and Latent Heat

Sensible
(Temperatue rises until water boils.)

Latent
(Temperature stays at 212˚F while water evaporates.)

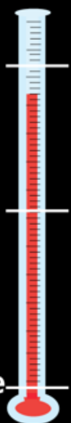
Black Body

Absorption
(idealized concept)
Perfect absorber of all incident radiation (emissivety = 1)



Thermal Environment
Units of Measurement

Temperature



Boiling Point — +212° F (100° C; 373 K)

Freezing Point — + 32° F (0° C; 273 K)

Absolute Temperature — -460° F (-273° C; 0 K)

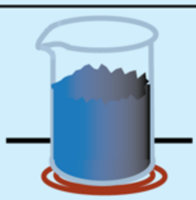
Centigrade (Celsius)
$°C = 5/9\ (°F - 32)$

Fahrenheit
$°F = 9/5\ °C + 32$

Kelvin
$K = °C + 273$
$K = 5/9\ (°F - 32) + 273$

Thermal Energy

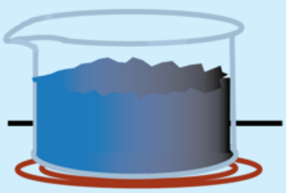
British Thermal Unit (BTU)



(temperature increases from 63° F to 64° F)

1 BTU = Heat (energy) required to raise the temperature of 1 LB of water by 1°F.

Calorie (and calorie)



(temperature increases from 14.5° C to 15.5°C)

1 Calorie = Heat (energy) required to raise the temperature of 1KG of water by 1°C.

1 calorie = Heat (energy) required to raise the temperature of 1g of water by 1°C.

Thermal Environment

Human Body as a Heat Engine

The human body is a form of heat engine that derives its energy from the combustion of food (i.e., metabolism).

- Thermal comfort depends on heat transfer between human body and environment.
- Heat loss may occur through outward radiation (to sky and colder surroundings), evaporation (from breathing and perspiration), and outward convection (air below skin temperature) or conduction (feet on cold floor).
- Direct solar radiation may exceed 300 BTU/SF/HR on a horizontal surface.
- Deep body temperature (i.e., temperature of blood) is approximately 98.6˚F (skin temperature is about 92˚F).

Thermal Environment

Adaptation to Environmental Conditions

Environmental temperature is one of the most critical factors governing human comfort and survival.

- Our ability to survive in environmental temperatures ranging from -60˚F to 130˚F is due to our technical skills (shelter and clothing).
- Our deep body temperature must not vary by more than ± 1% for thermal comfort and -2˚F to +6˚F for health and survival.
- Clothing is an effective mechanism for insulating the body in cold climates and for providing some individual control under most conditions.

Thermal Environment

Human Body: Vaso-Motor Control

Deep body temperature is regulated by the control of blood flow in the skin and underlying tissue (i.e., vaso-motor control).

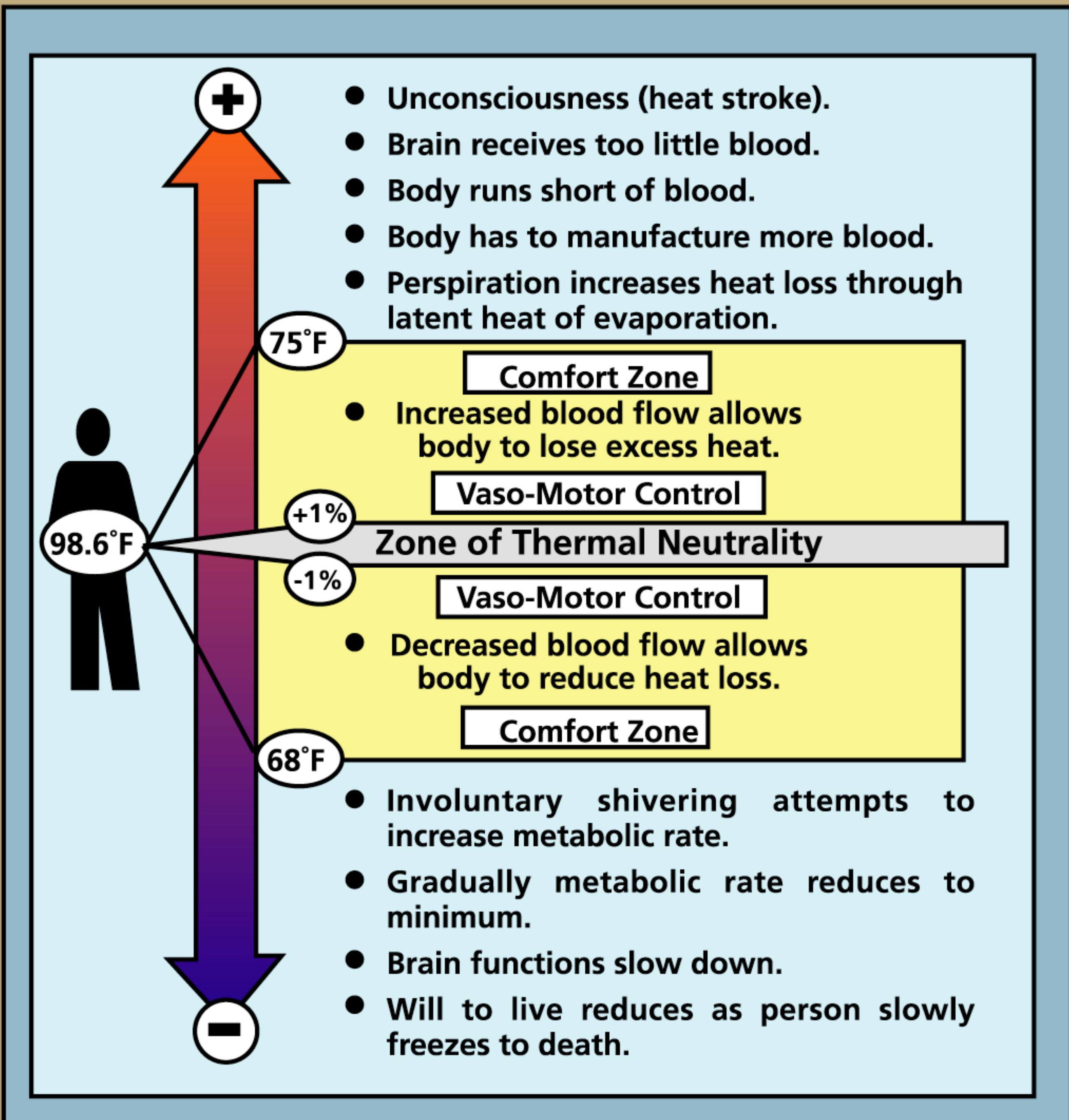
- **Colder Environment**
  Vaso-Motor Control will constrict blood vessels to reduce the flow of blood and in this way reduce heat loss.

- **Warmer Environment**
  Vaso-Motor Control will dilate blood vessels to increase the flow of blood and heat loss.

- Control of the rate of blood flow also controls the metabolic rate of the human body (or vice versa).

Thermal Environment

Human Body: Reaction to Temperature Changes



Thermal Environment

Vaso-Motor Control Equation

$$M = E \pm C \pm R \pm S$$

- **M** — Heat produced by metabolism.
- **E** — 20% Heat lost by evaporation.
- **C** — 40% Heat exchanged by conduction.
- **R** — 40% Heat exchanged by radiation.
- **S** — Heat added to or taken out of storage.

- **Both perspiration and shivering are wasteful of the body's intake of water/salt and food, respectively.**

Thermal Environment

Vaso-Motor Control Implications

Building orientation, insulation, sun shading devices, window openings, material selection, and space layout, are primary architectural design tools.

- Rate of metabolism is normally determined by physical work performed.
- Perspiration is uncomfortable and should be avoided where possible.
- However, perspiration can be facilitated through air movement to decrease discomfort under hot/humid conditions.
- Air movement under hot/dry conditions dries out the skin (e.g., dermatitis) and should be minimized.

Thermal Environment
Subjective Comfort Factors

Desirable Conditions

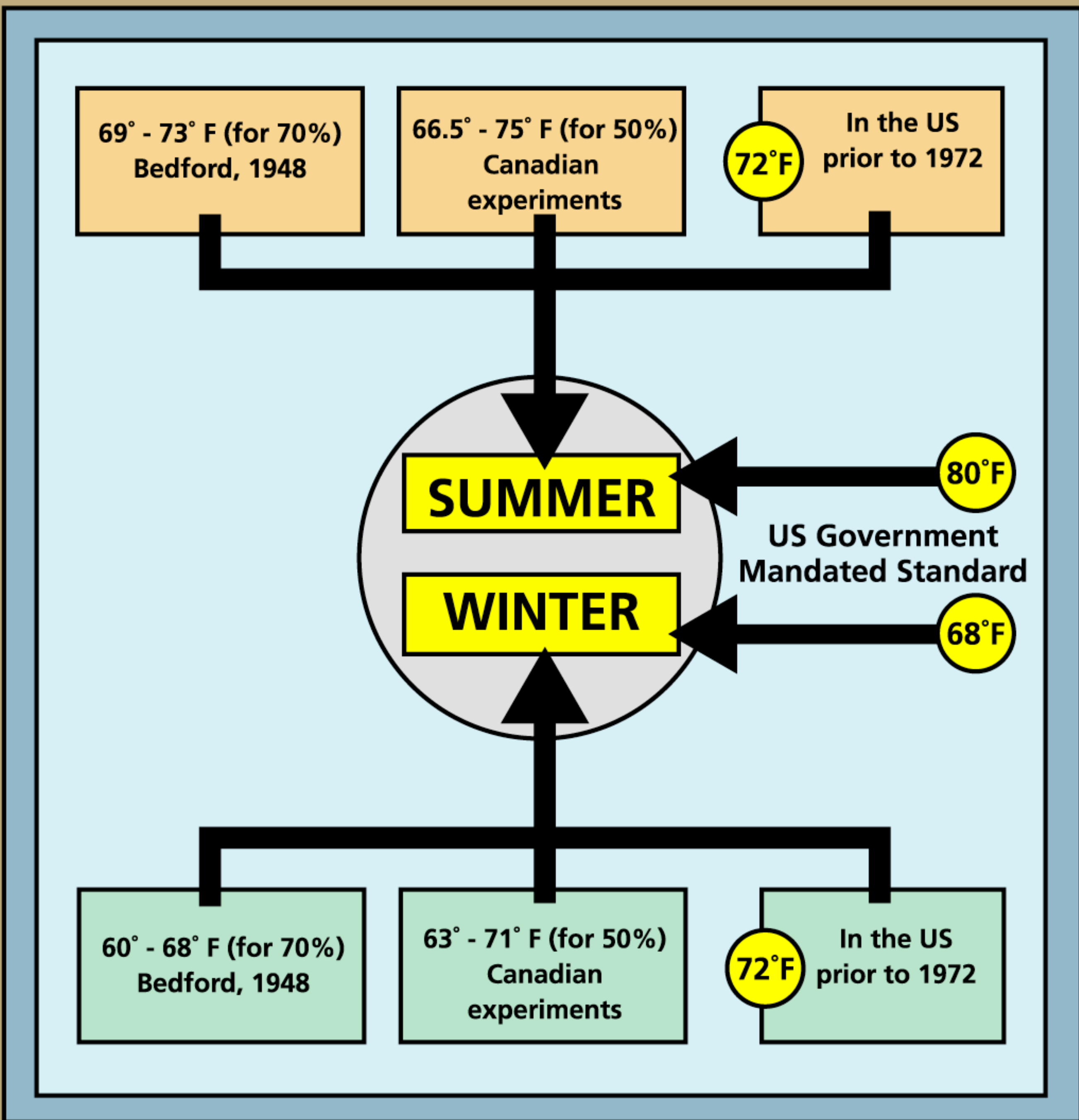
- Air temperature as cool as acceptable.
- Relative humidity between 30% and 70%.
- Adequate air movement.
- FRESHNESS: coolness, no unpleasant odors, slight air movement, and low density of occupation.

Undesirable Conditions

- High air temperature with or without high relative humidity.
- Elevated air temperature with high relative humidity.
- Excessive local heat (e.g., radiation).
- Insufficient air movement.
- Cold surfaces (e.g., floor).
- STUFFINESS: hotness, odor, lack of air movement, high density of occupation.

Thermal Environment

What is a Comfortable Temperature?



Thermal Environment

How About Individual Differences?

The desire of women for slightly warmer conditions in both winter and summer is due to differences in clothing.

Age: The elderly are particularly sensitive to extremes in temperature.

Diet: Very high and very low calorie diets appear to slightly reduce heat tolerance.

Health: Any infection will reduce the ability to resist thermal stress.

Work Efficiency: The amount of muscular activity is directly related to individual heat tolerance. This is the most important factor contributing to individual differences.

Acclimatization: Appears to be due to behavioral adjustments (e.g., greater work efficiency) and not due to physiological changes.

Thermal Environment

Hooke's Law

According to Hooke's law, strain (e.g., physiological reactions) is proportional to stress (e.g., temperature).

- **Stresses are usually cumulative (e.g., temperature, noise, glare, distractions) so that even low levels of a number of environmental stresses may cause discomfort, even though any one of these factors by itself may be quite tolerable.**

- **Strain is the physiological reaction of the human body to any imposed stress (e.g., shivering, perspiration, pulse rate, blood pressure, headache).**

Thermal Environment

Assessment Measures

To date no single measurement scale that combines the six thermal comfort parameters into one index of thermal stress has been devised.

Air Temperature: The temperature of the air measured with a thermometer in the shade.

Humidity: The moisture content of the air typically expressed as a percentage in terms of relative humidity.

Air Movement: The speed at which air moves across the human body greatly influences thermal comfort.

Mean Radiant Temperature: The radiation that is received from surrounding surfaces (note: radiation is not influenced by air movement).

Rate of Work Performed: Muscular activity directly impacts the metabolic rate (and therefore the heat production).

Clothing Worn: The insulating characteristics of clothing inhibit heat loss from the human body.

Thermal Environment
Stress and Strain

Stress

- Typically only low levels of thermal stress occur in buildings.
- Currently comfort zones are established mainly on the basis of only four of the six thermal parameters (i.e., air temperature, humidity, air movement, and rate of work performed).

Strain

- Physiological strain factors include heart rate, blood pressure, rate of respiration, oxygen consumption, fatigue level, body temperature, and survival time.
- These measures of physiological strain are really only useful when the level of thermal stress is very high.

Thermal Environment

Three Basic Groups of Indices

Indices based on physical factors.

e.g.,
- Dry-Bulb Temperature
- Wet-Bulb Temperature
- Equivalent Temperature

Provide no direct measure of the physiological effect of the environment.

Indices based on physiological strain.

e.g.,
- Effective Temperature
- Predicted 4-Hour Sweat Rate

Based on Hook's Law, which states that conditions of equal environmental stress produce equal physiological strain.

Indices based on heat exchange calculations.

e.g., Indices that attempt to calculate the heat exchange between the human body and its surroundings.

Potentially the most promising approach to the development of a single thermal comfort index, but depends on the ability to accurately model the human body.

Thermal Environment

How To Choose The Appropriate Index

Rule 1: The index must cover the correct range of temperatures (e.g., Equivalent Temperature does not extend above 75˚F, P4SR applies only to those conditions where sweating occurs).

Rule 2: If two environments are to be compared then the index does not need to include thermal parameters that are the same in each environment. (e.g., there may be no air movement in an office environment).

Rule 3: If there is a choice of indices then always select the simpler index (e.g., in air-conditioned offices the Dry-Bulb Temperature index will suffice).

Thermal Environment
Comfort Requirements

General Thermal Effects

- Mainly governed by air temperature, relative humidity, and air movement.
- Space should be as cool as possible, have adequate air movement, and have a relative humidity between 30% and 70%.

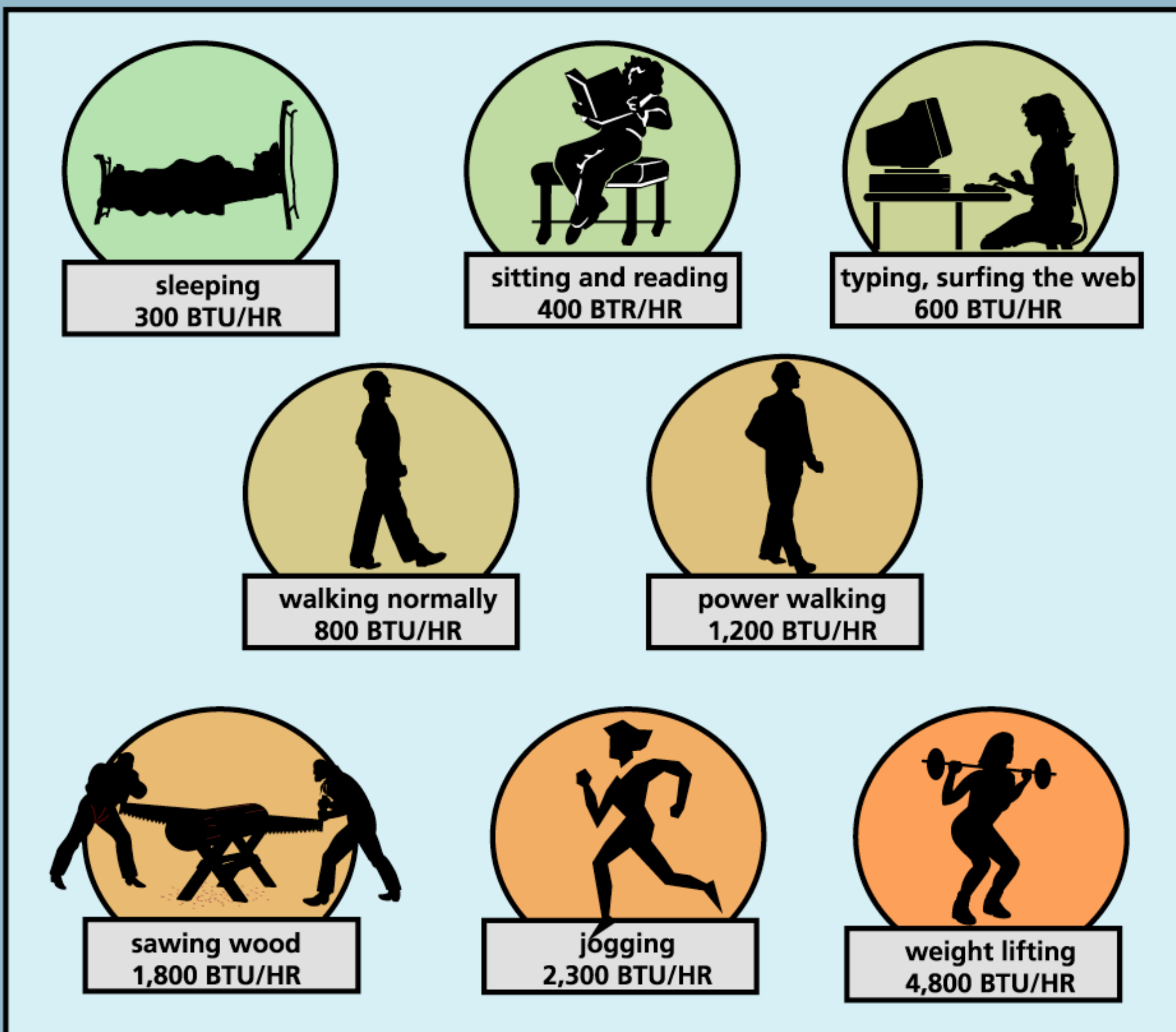
Local Thermal Effects

- Avoid excessive local heat and vertical temperature gradients.
- Warmer ceilings should be avoided, but warmer floors are acceptable.
- Density of occupation can have a significant impact on thermal comfort (e.g., perception of stuffiness and hotness).

Thermal Environment

Impact of Activity Level

Muscular activity increases the metabolic rate, which produces heat.



Thermal Building Design

Thermal Stress: Acceptability Limits

Hot and dry conditions

88°F *(sedentary tasks)*

Hot and humid conditions

82°F *(sedentary tasks)*

Cold conditions

60°F *(sedentary tasks)*

Thermal Building Design

Design Principles: Hot-Dry Climate

Climatic Characteristics

Temperature:
- Very hot during daytime (100(+) ˚F)
- Cooler nights (80(+) ˚F)

Humidity:
- Very dry (RH < 30%)

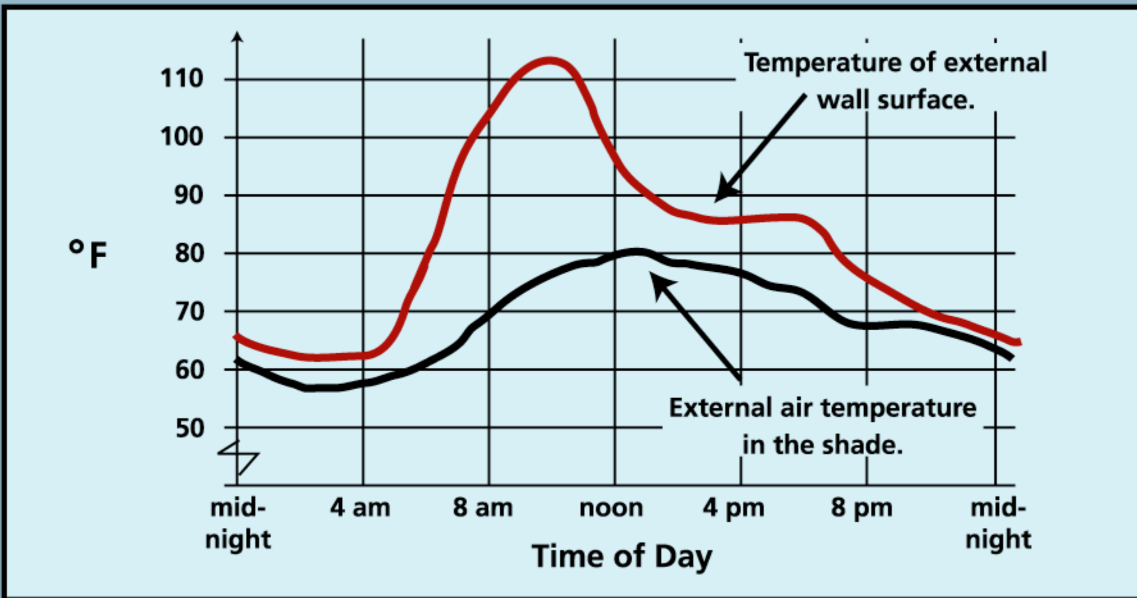
Design Strategies

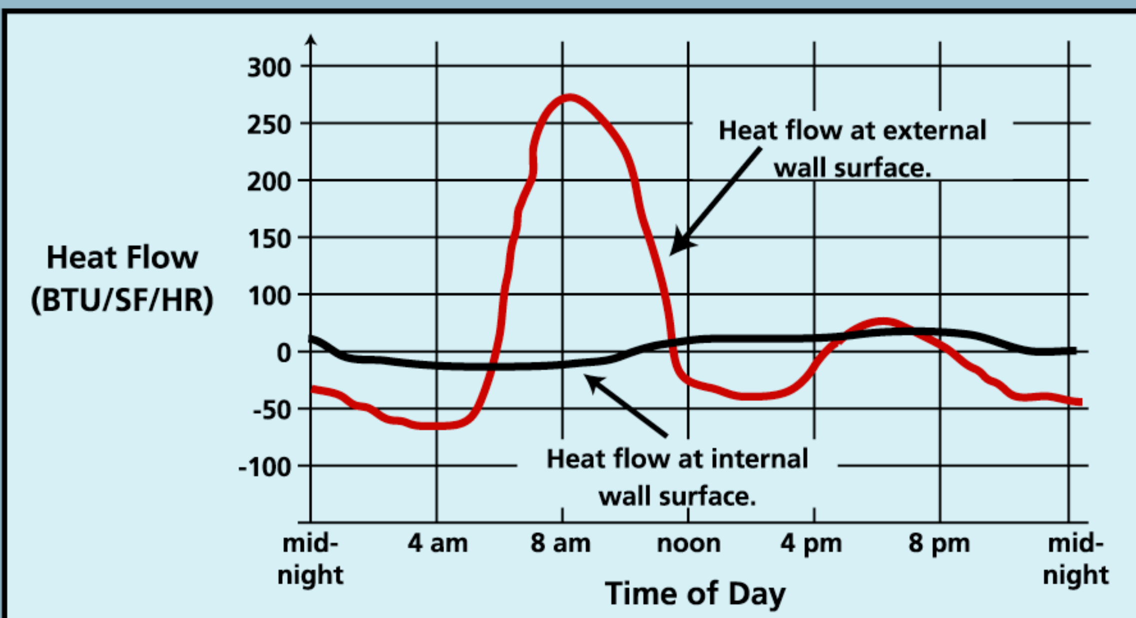
Utilize the building envelope as a buffer and heat sink. Seal the building during the day and open it up at night to cool the envelope from the inside and the outside. Then repeat the cycle at sunrise.

- Heavy construction with high heat capacity for walls and roof.
- Small windows deeply recessed into the walls.
- Reflective external envelope (surfaces).
- Thermal insulation in walls (inside surface) and roof (also reflective foil).

Thermal Building Design

Thermal Capacity of Building Envelope





(Source: Roux, A., J. Visser and P. Minnaar (1951); 'Periodic Heat Flow Through Building Components; National Building Research Institute, Report #DR-9, South Africa.)

Thermal Building Design

Design Principles: Hot-Humid Climate

Climatic Characteristics

Temperature:
- Hot during daytime (90(+) ˚F)
- Little cool-down at night (80(+) ˚F)

Humidity:
- Very humid (RH > 80%)

Design Strategies

Single-banked building plan with large openings to maximize air-movement at the occupant level. Typically an elongated plan on an east-west axis.

- Since external air is used for cooling purposes the internal building temperature cannot be lower than the external air temperature in the shade.
- Lightweight construction with more than 50% of wall openings.
- Thermal insulation is required only in surfaces exposed to direct solar radiation (east, west and roof).
- Sun shading devices are recommended for south walls. (north walls in Southern Hemisphere).

Thermal Building Design

Design Principles: Cold Climate

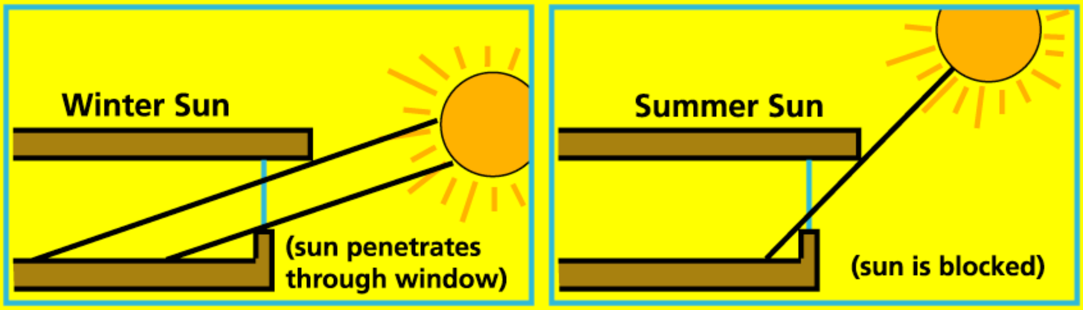
Climatic Characteristics

Temperature:
- Cold during daytime (<60 ˚F)
- Warmer in sunshine.

Wind:
- Windchill factor may be severe.

Design Strategies

Substantial thermal insulation for all external surfaces including roof and footings. Allow controlled solar radiation to penetrate openings when available.

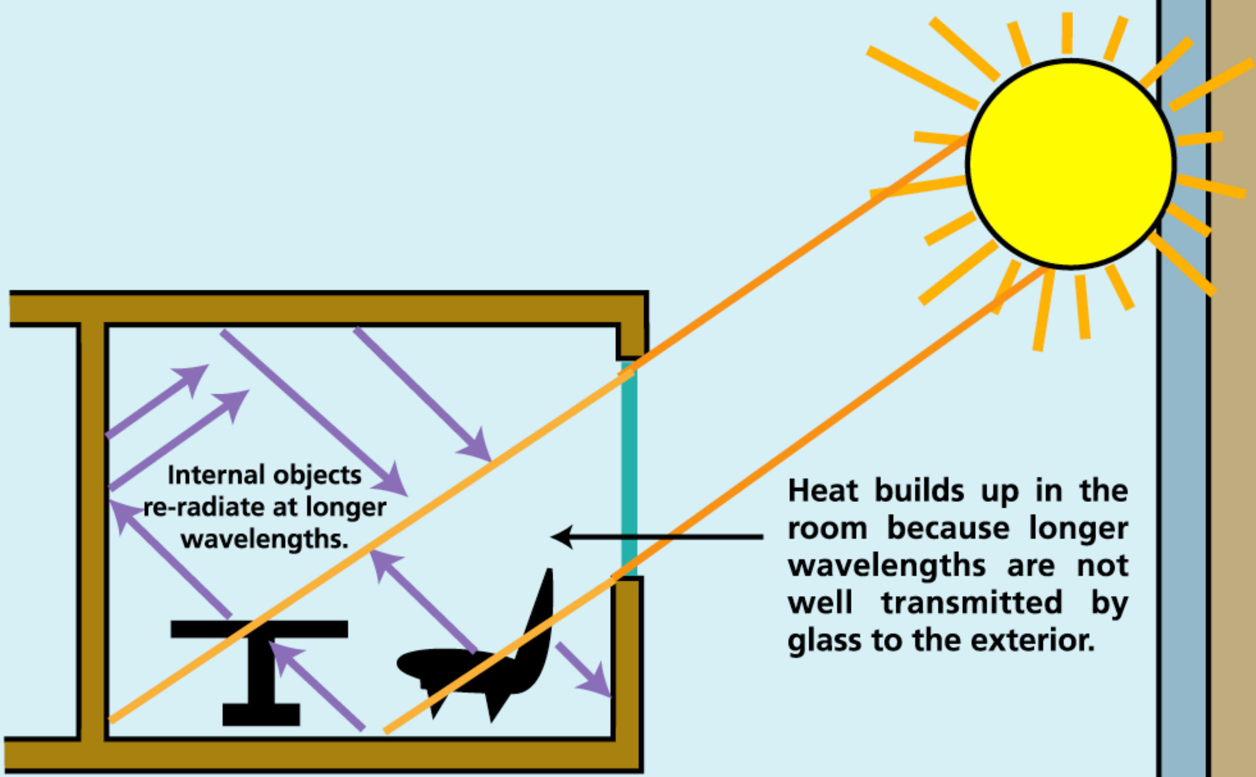


- Double-glazed windows reduce heat loss.
- Windows and doors should be well sealed with weather stripping.
- Some form of non-natural heating will be required.

Thermal Building Design

The Greenhouse Effect

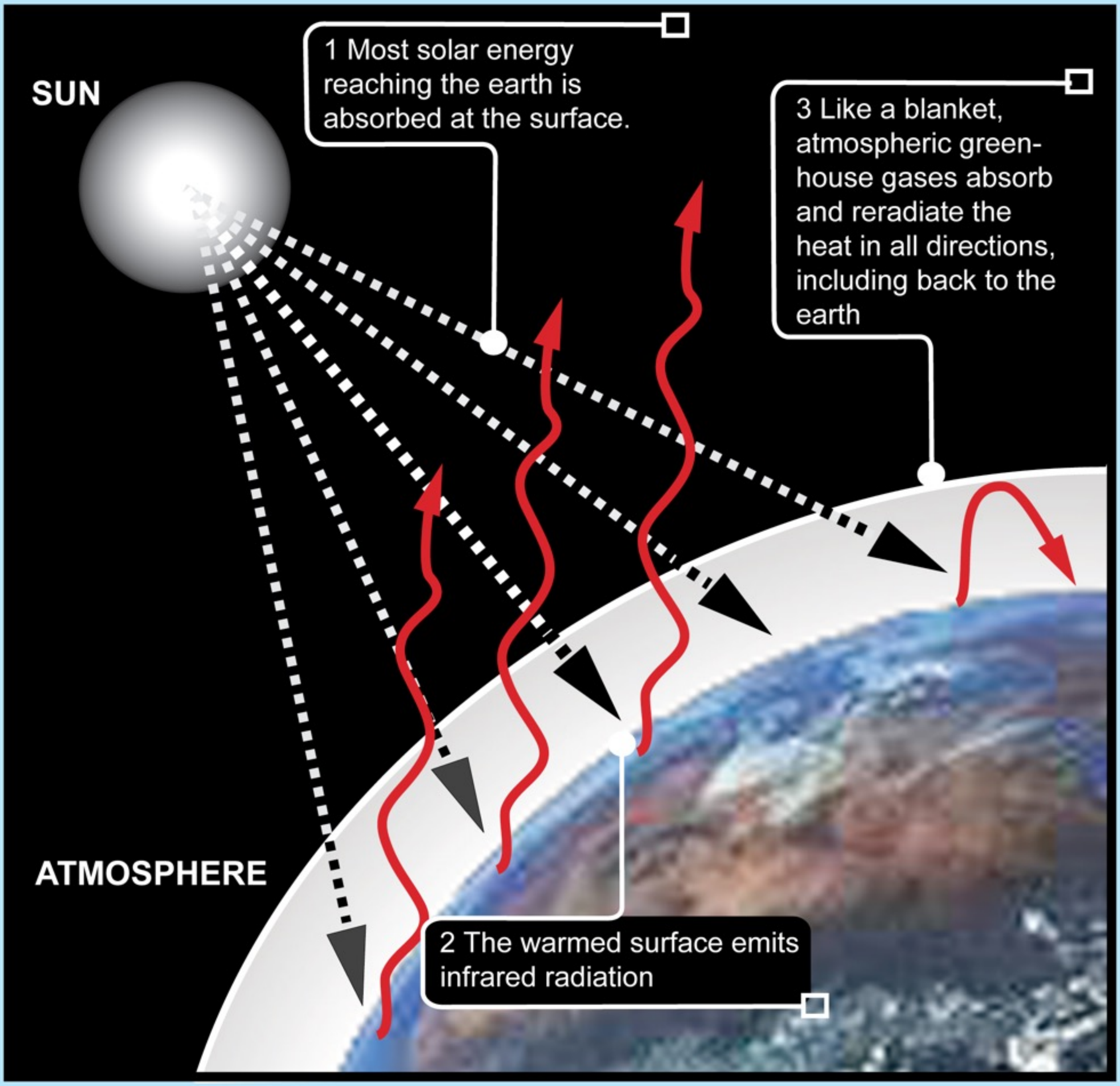
After solar radiation passes through a window (glass) it is absorbed by the objects inside the building space. These objects heat up and re-radiate heat at a longer wavelength that is partially blocked by the window glass.



Climate Trends

Global Greenhouse Effect (1/2)

A prerequisite for life on earth, the greenhouse effect occurs when infrared radiation (heat) is retained within the atmosphere.

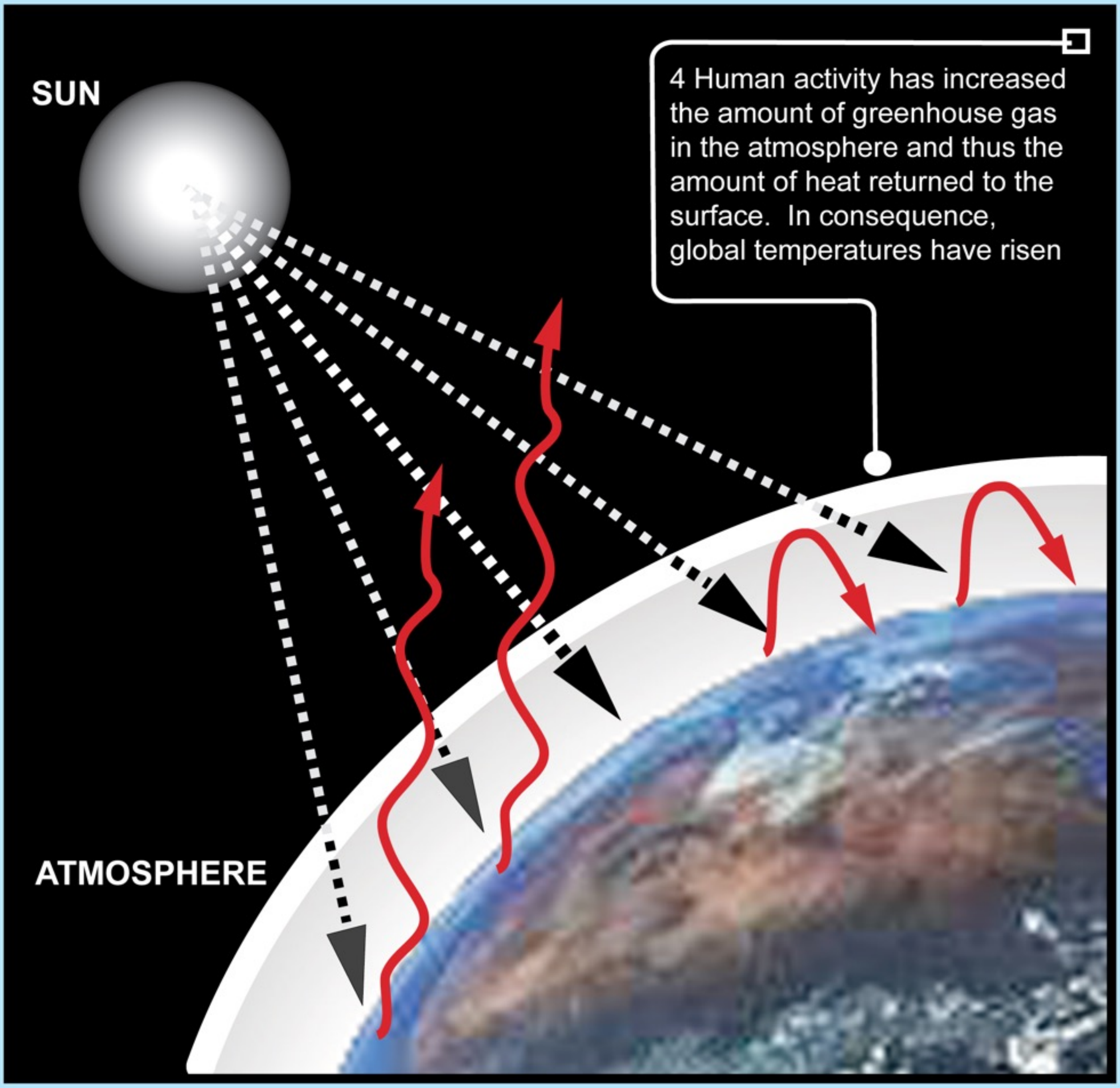


Source: Stix, Gary, "A Climate Repair Manual" Scientific American, September 2006, pg. 48

Climate Trends

Global Greenhouse Effect (2/2)

A prerequisite for life on earth, the greenhouse effect occurs when infrared radiation (heat) is retained within the atmosphere.



Source: Stix, Gary, "A Climate Repair Manual" Scientific American, September 2006, pg. 48

Climate Trends

Disappearance of Glaciers (Sunset Glacier, Alaska)

1939

2004

Source: Stix, Gary, “A Climate Repair Manual” Scientific American, September 2006, pg. 49

Thermal Building Design

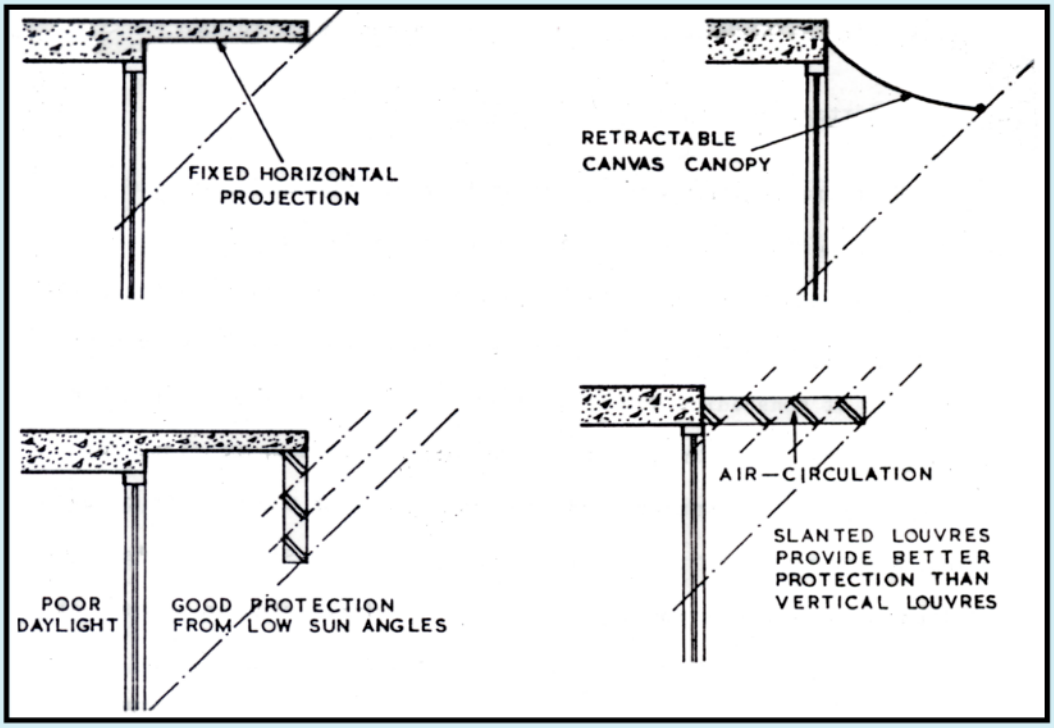
Sun Shading: Principles

- The altitude of the sun is much lower during the winter (about 30° at noon) than in summer (about 70° at noon).
- Heat transmission through glass (single-glazing) is virtually instantaneous.
- External sun shading devices are the most efficient form of solar heat protection.
- However, external sun shading devices interfere with interior daylighting (and possibly air movement).
- External sun shading devices should have a reflective finish and allow free air flow over their surface, because they can become a heat source.

Thermal Building Design

Sun Shading: South Orientation

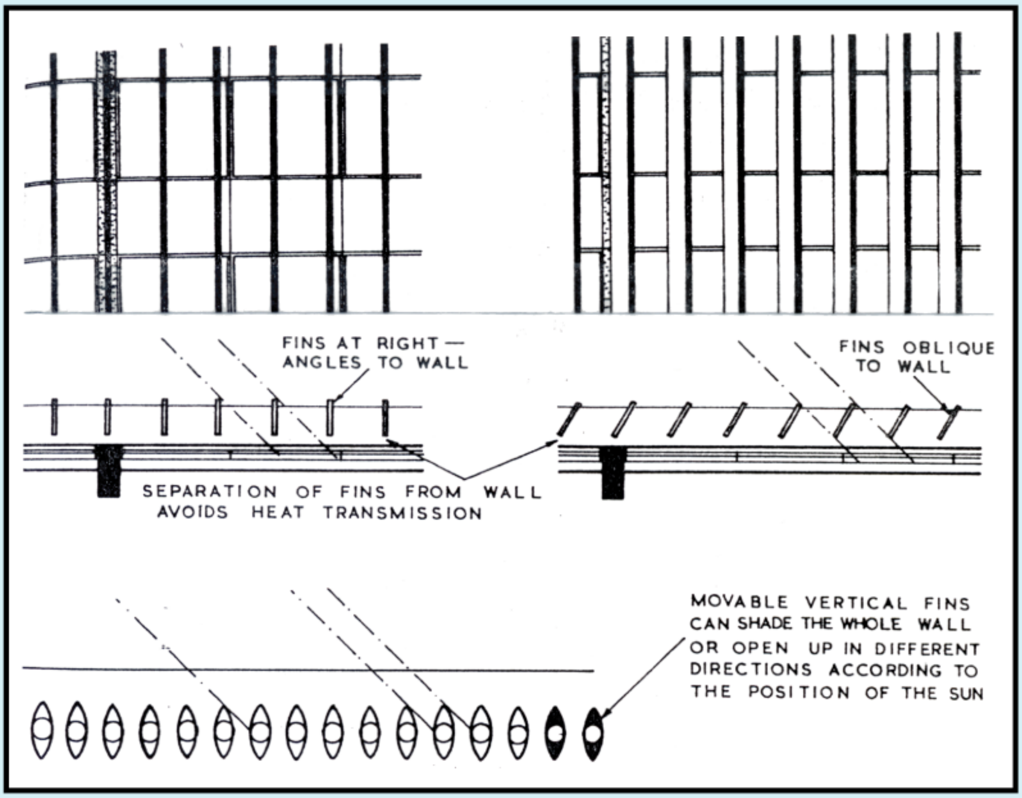
Fixed horizontal sun shading devices can be used to advantage in SOUTH orientations because the altitude of the sun is high.



Thermal Building Design

Sun Shading: East and West Orientation

Movable vertical sun shading devices can effectively block solar penetration on EAST and WEST orientations where the altitude of the sun is low.



Thermal Building Design

Sun Shading: Other Devices

Internal shading devices are only as effective as the relative amount of direct solar radiation that they are capable of reflecting back through the window glass.

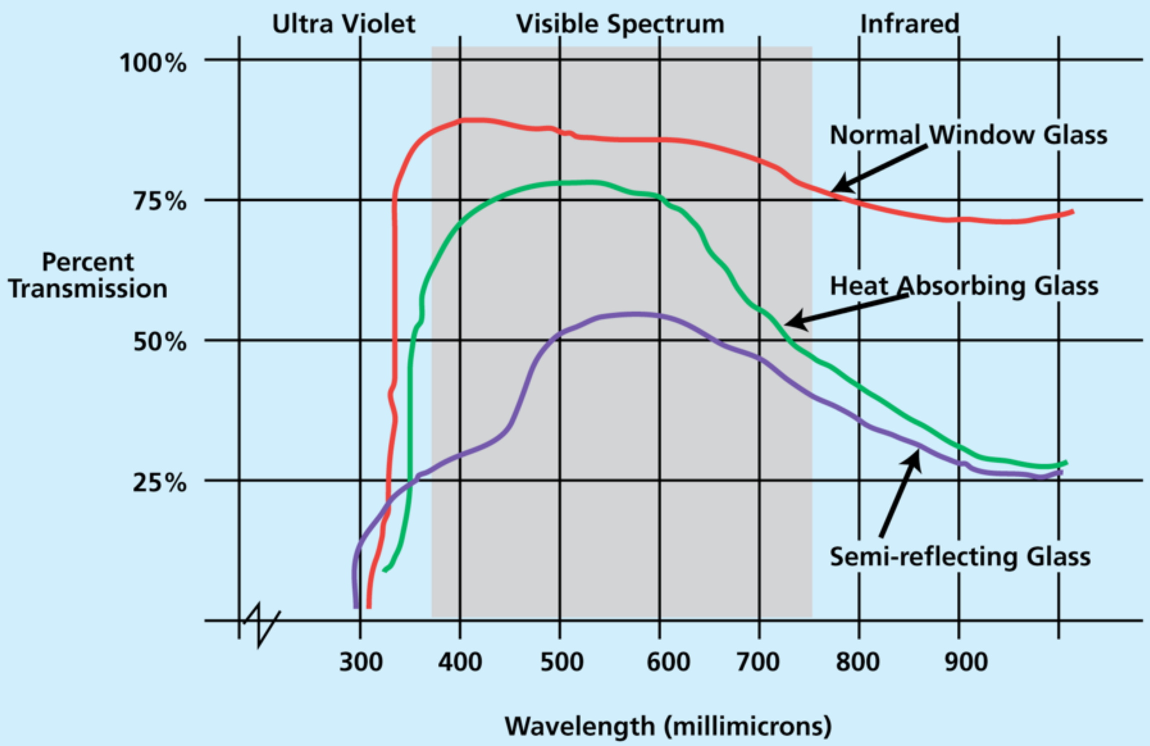
Approximate reduction in heat transfer due to selected internal and external shading devices:

Internal curtains		10% to 20%
Internal roller shades	(dark color)	20%
	(light color)	60%
Internal Venetian blinds	(dark color)	25%
	(light color)	45%
External canvas awnings	(with sides)	65%
	(without sides)	75%
External louvers	(light color)	85%

Thermal Building Design

Sun Shading: Special Glass

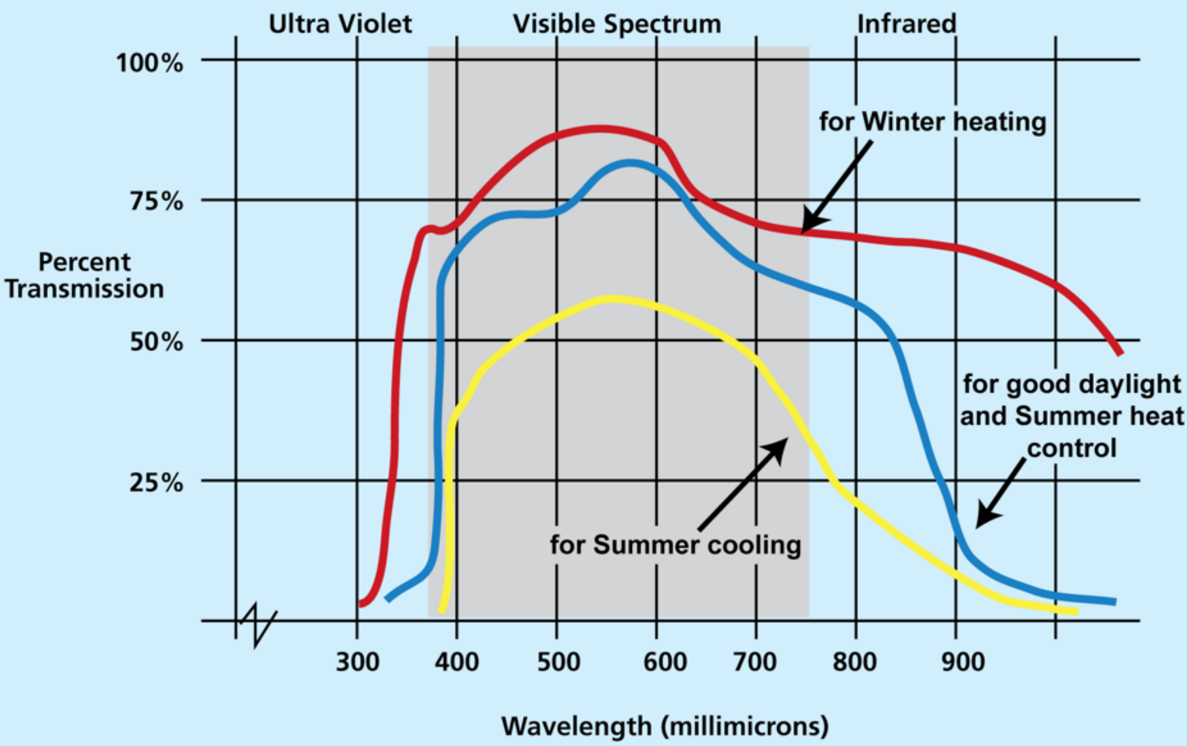
Heat absorbing glass can be a severe radiator unless it is installed as a double-glazed unit with ordinary glass on the inside and a ventilated cavity.



Thermal Building Design

Sun Shading: Low-E Glass

Hard-coat E-films are durable and less expensive, but thermally less effective. **Soft-coat E-films** are less durable and more expensive, but thermally more effective.



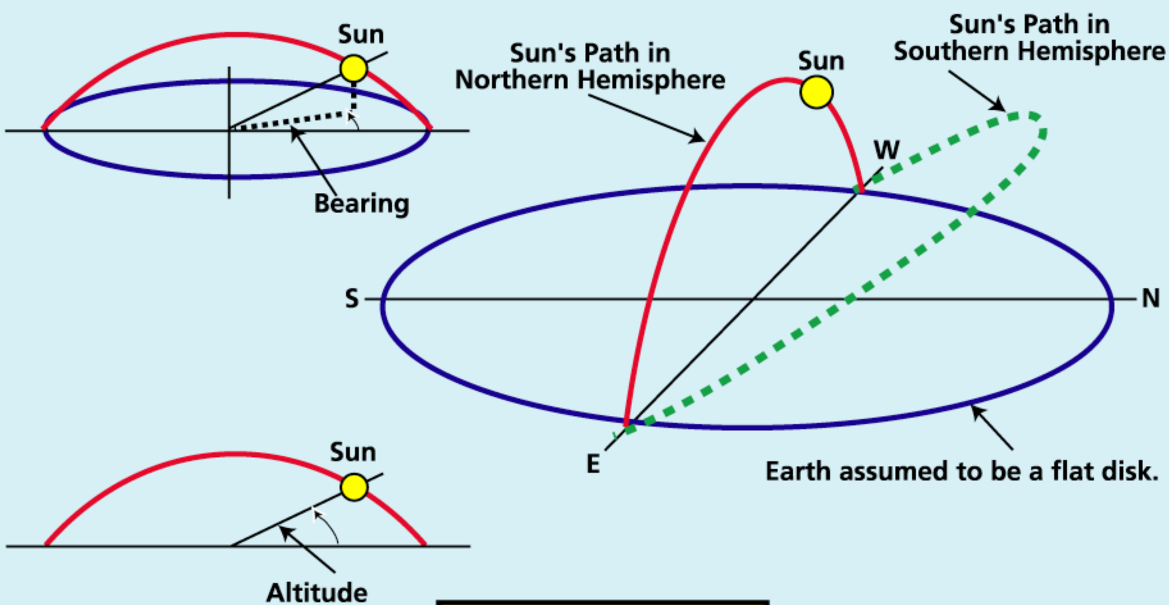
Low-E coatings are normally applied to one glass surface facing an air space between multiple glazings.

Thermal Building Design

Sun Position: Principles

Solar radiation intensity received on a surface depends on:

1. Altitude of sun due to the season.
2. Position of sun due to time of day.
3. Inclination of the receiving surface.



Assumptions

The earth is a flat plane.

The sun rotates around the earth.

Thermal Building Design

Sun Control: Design Steps

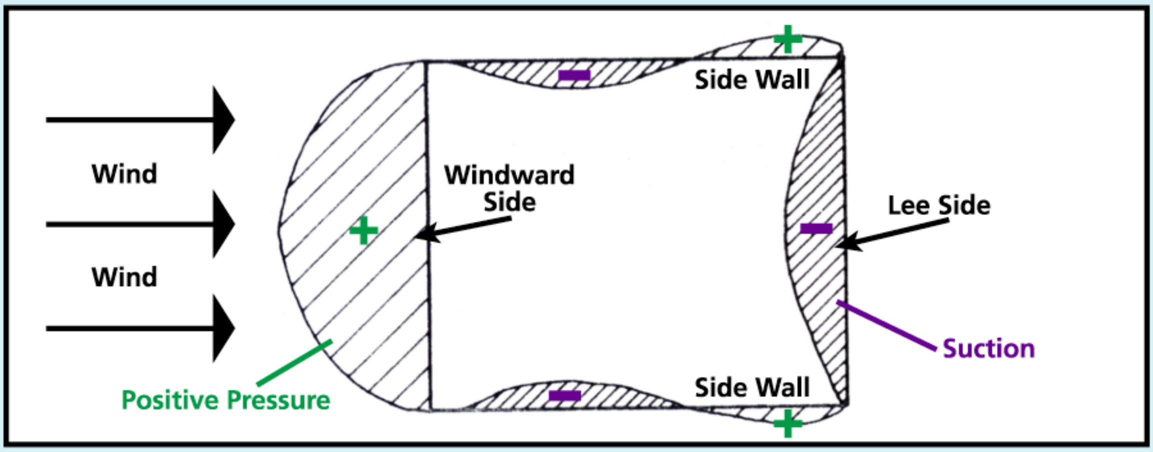
The inclusion or exclusion of the sun is an important building design consideration.

1. What type and degree of solar control will be required (e.g., part or complete exclusion, reflection, diffusion)?
2. What are the building orientation and layout alternatives?
3. What should be the size and location of the window areas? Considerations include need for air movement, daylight, heat gain or loss requirements, and avoidance of glare.
4. What are the most suitable shading devices? (e.g., inclined or movable vertical louvers for East and West, horizontal shades for South, and combinations of horizontal and vertical shades for South-East and South-West)?

Thermal Building Design

Air Movement: Principles

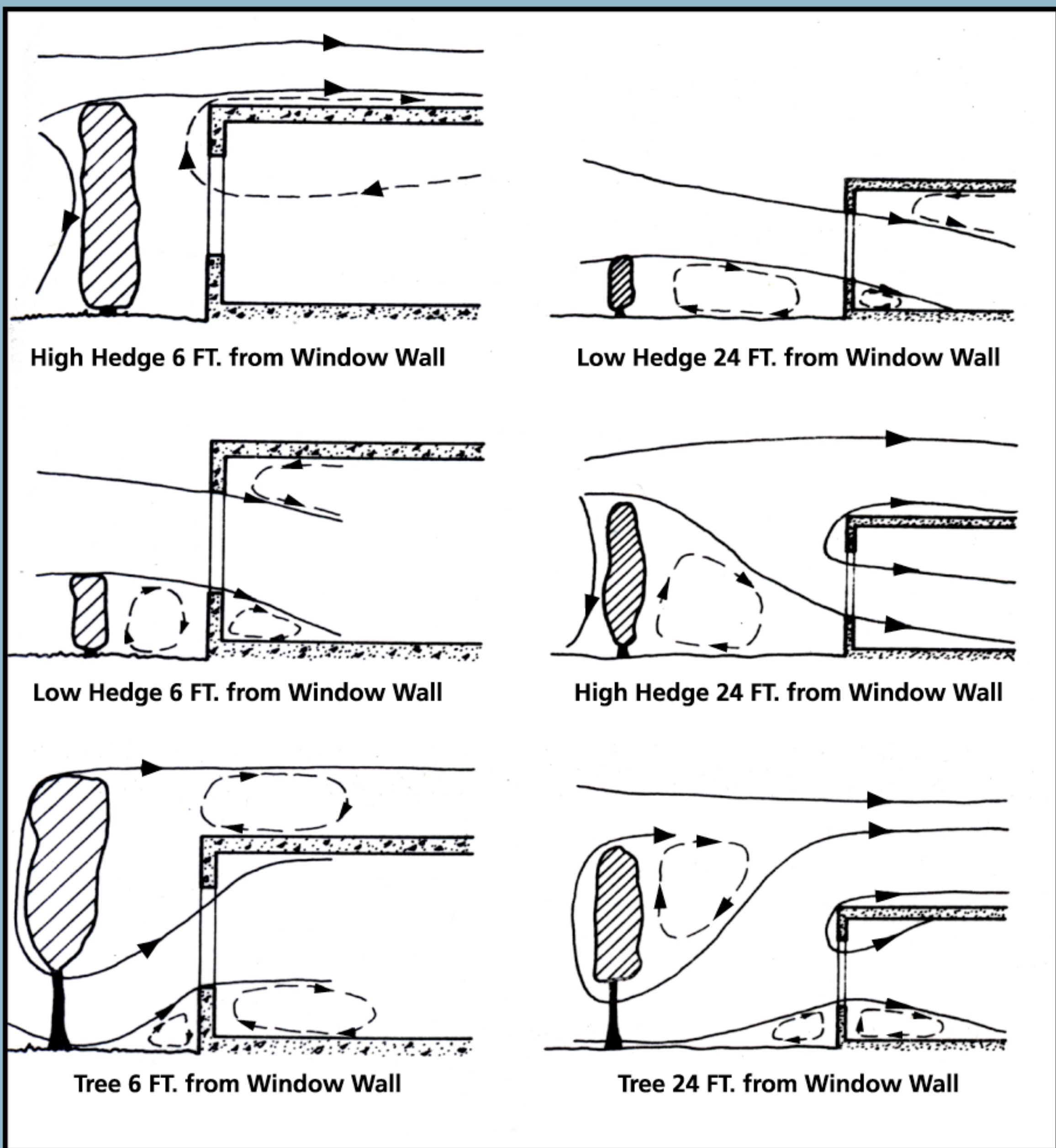
- Air is sucked rather than pushed through a building.
- Air movement at low speeds (< 8 mph) is easily obstructed.



- For efficient summer cooling the air must pass over the occupants.
- For maximum air flow the inlets and outlets should be of equal size.
- Each opening and bend will produce a disproportionate reduction in air flow.

Thermal Building Design

Air Movement: Effects of Landscaping



Source: White R.; 'Effects of Landscaping on Natural Ventilation of Buildings and Their Adjacent Areas'; Texas Engineering Experiment Station, Report #45, 1954.

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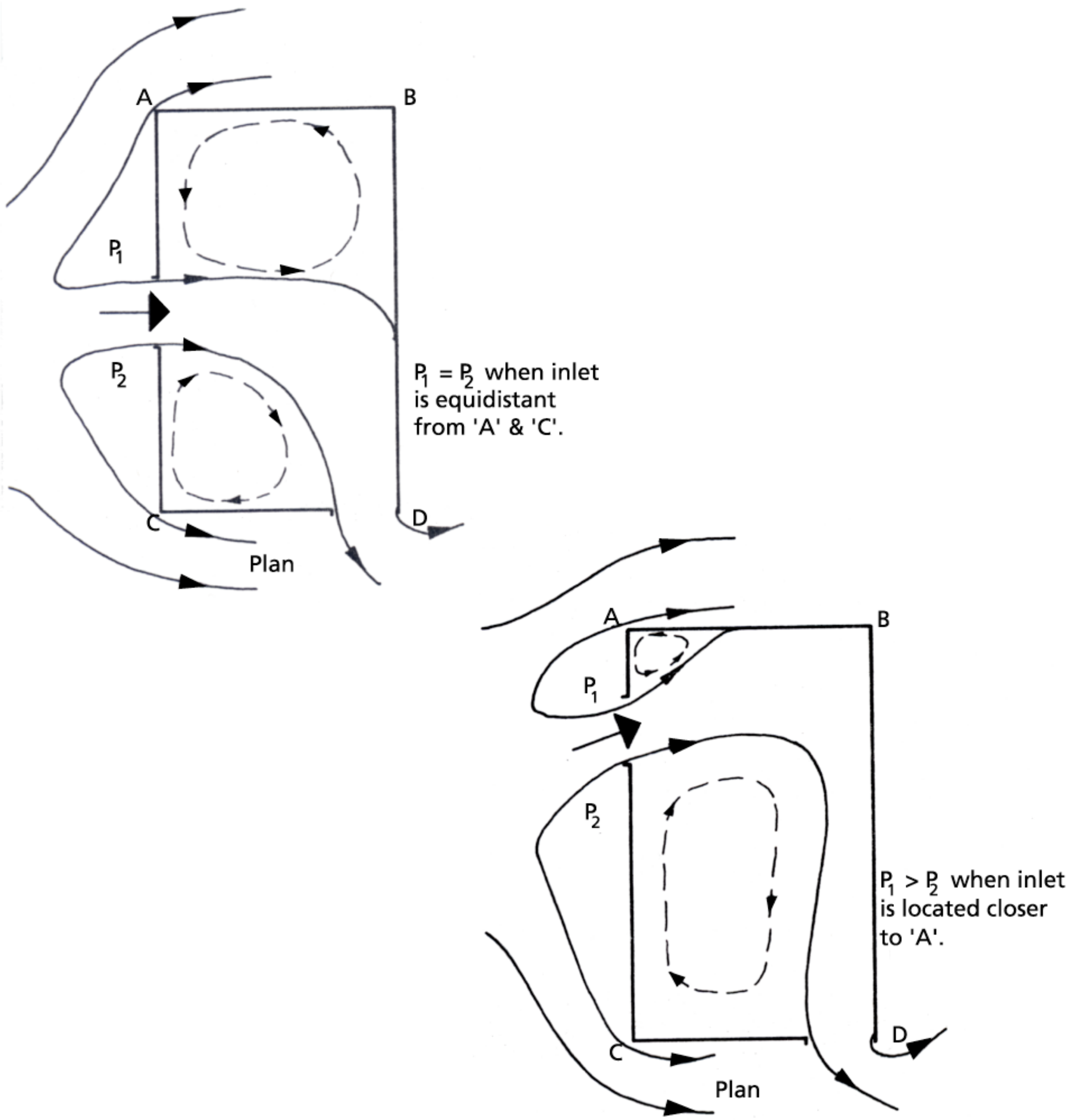
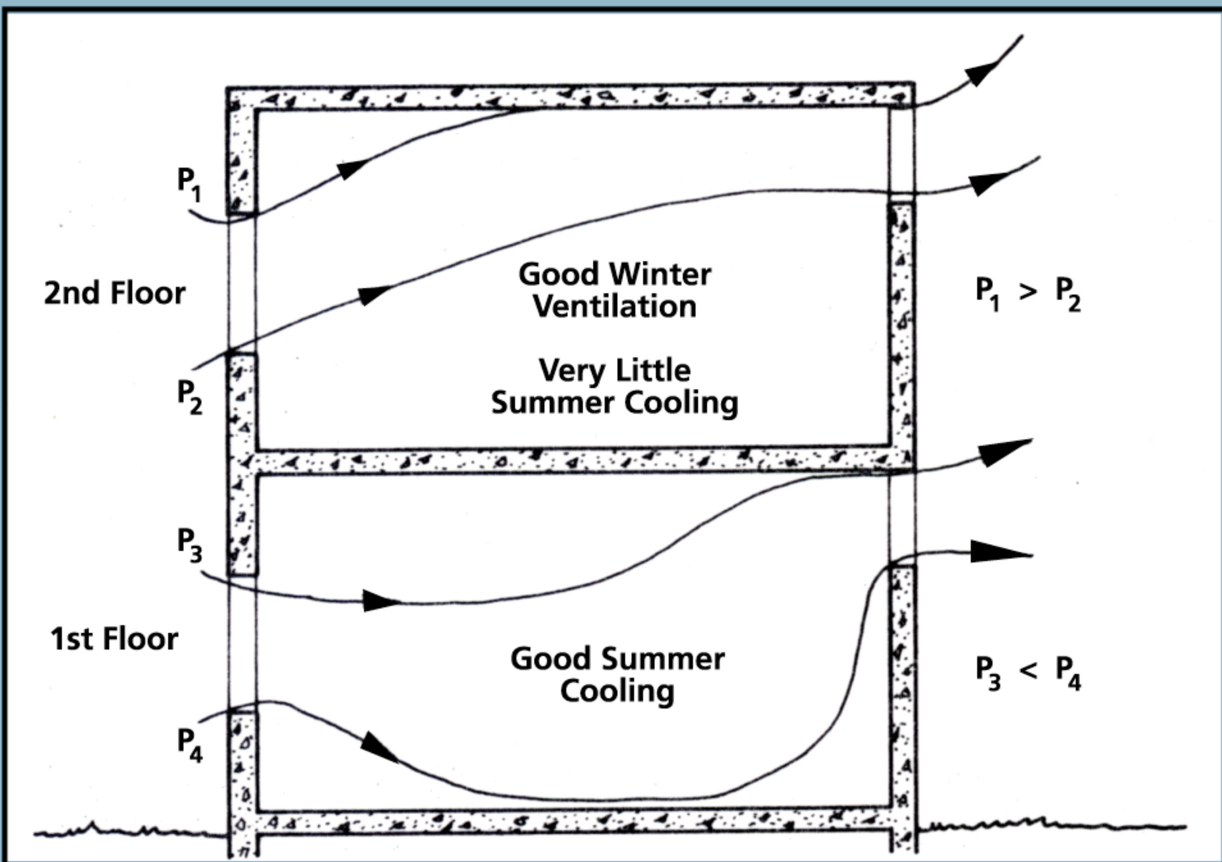
Thermal Building Design

Air Movement: Effect of Inlet Location



Thermal Building Design

Air Movement: Effect of Height of Inlet



Thermal Building Design

Heat Removal by Ventilation (Equation)

The ventilation rate (V CF/HR) required to remove a heat load (Q BTU/HR) is given by:

$$V = \frac{Q}{PS(T_1 - T_2)} \quad \text{(CF/HR)}$$

where: P = average air density (approx. 0.075 LB/CF at an indoor temperature of 70˚F)

S = specific heat of air (0.24 BTU/LB/˚F)

T_1 = indoor temperature (˚F)

T_2 = temperature of ventilation air (˚F)

Thermal Building Design

Heat Removal by Ventilation (Example)

Problem

Determine the required ventilation rate for:

Volume of room (v) = 1,345 CF
Indoor temperature (T) = 70° F
Outdoor temperature (T) = 65° F
Heat load to be removed (Q) = 12,000 BTU/HR

Ventilation Rate

Required ventilation rate is calculated as:

$$V = \frac{Q}{PS\,(T_1 - T_2)} \quad \text{(CF/HR)}$$

$$V = \frac{12{,}000}{0.075 \times 0.24\,(70 - 65)} \quad \text{(CF/HR)}$$

$$V = 133{,}333 \quad \text{(CF/HR)}$$

Air Changes

Number of air changes per hour are given by:

$$A = \frac{\text{ventilation rate}}{\text{room volume}} \qquad A = \frac{133{,}333}{1{,}345}$$

$$A = 99 \text{ (air changes per hour)}$$