Energy Conservation

Status (1970s) and Strategies

Lifespan Building Energy Usage

Energy Usage Category	Building Type		
	Residential	Commercial	Offices
Construction	3%	3%	3%
Space Heating	55%	45%	52%
Air Conditioning	4%	13%	6%
Refrigeration	6%	8%	(N.A.)
Hot Water	15%	8%	3%
Lighting	(N.A.)	(N.A.)	23%
Other	17%	23%	13%

(Source: AIA; 'Energy and the Built Environment'; American Institute of Architects, Washington, DC, 1974.)

Strategies

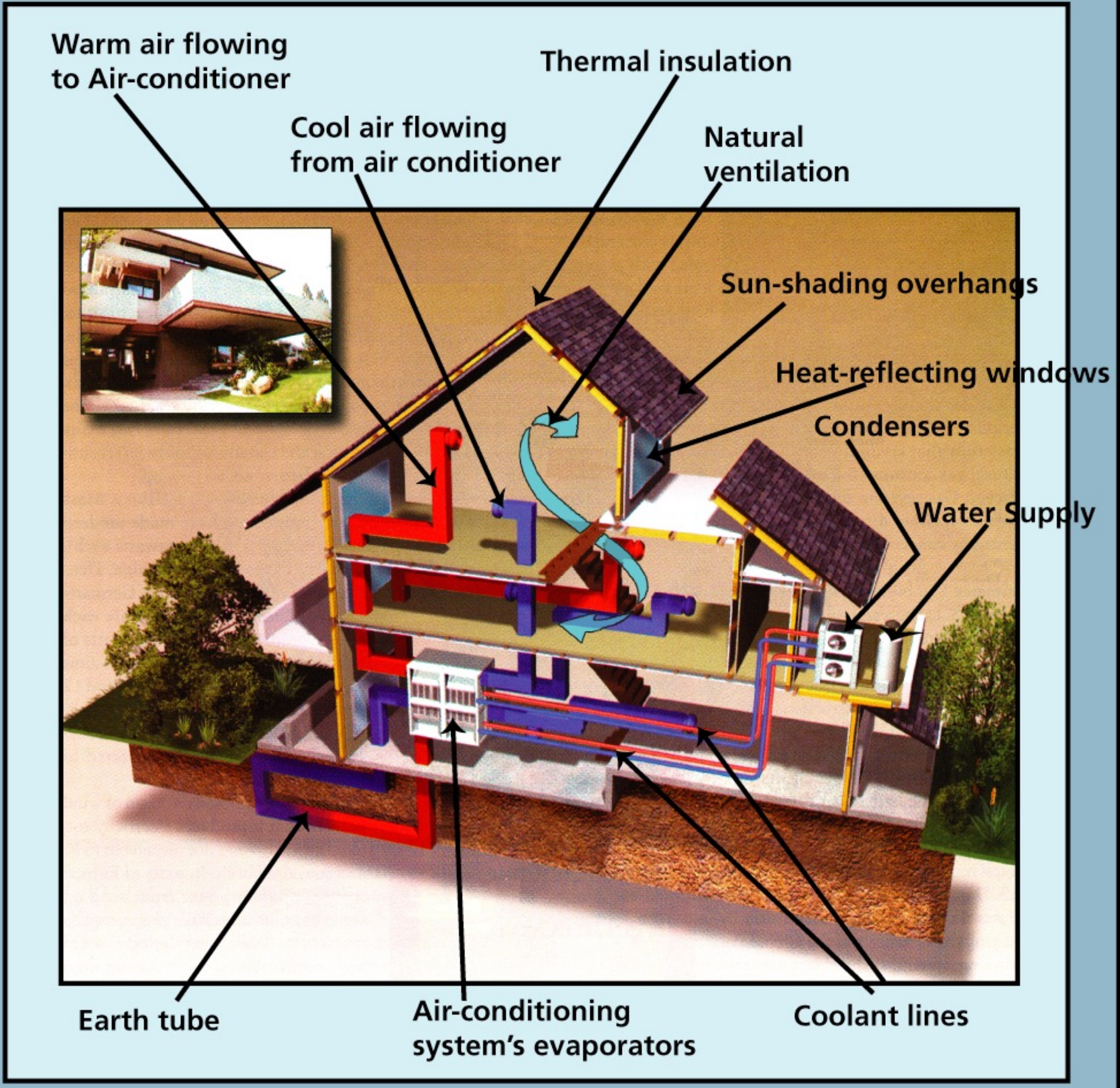
1 *Utilize energy efficiently:* Maximize thermal insulation and improve efficiency of heating systems (e.g., fireplaces and resistance heaters).

2 *Utilize less energy:* Maximize daylighting, reevaluate comfort standards, and adhere to better planning and design principles.

3 *Utilize alternative energy sources:* Apply solar energy, wind energy, photovoltaic, and other natural energy sources.

Energy Conservation

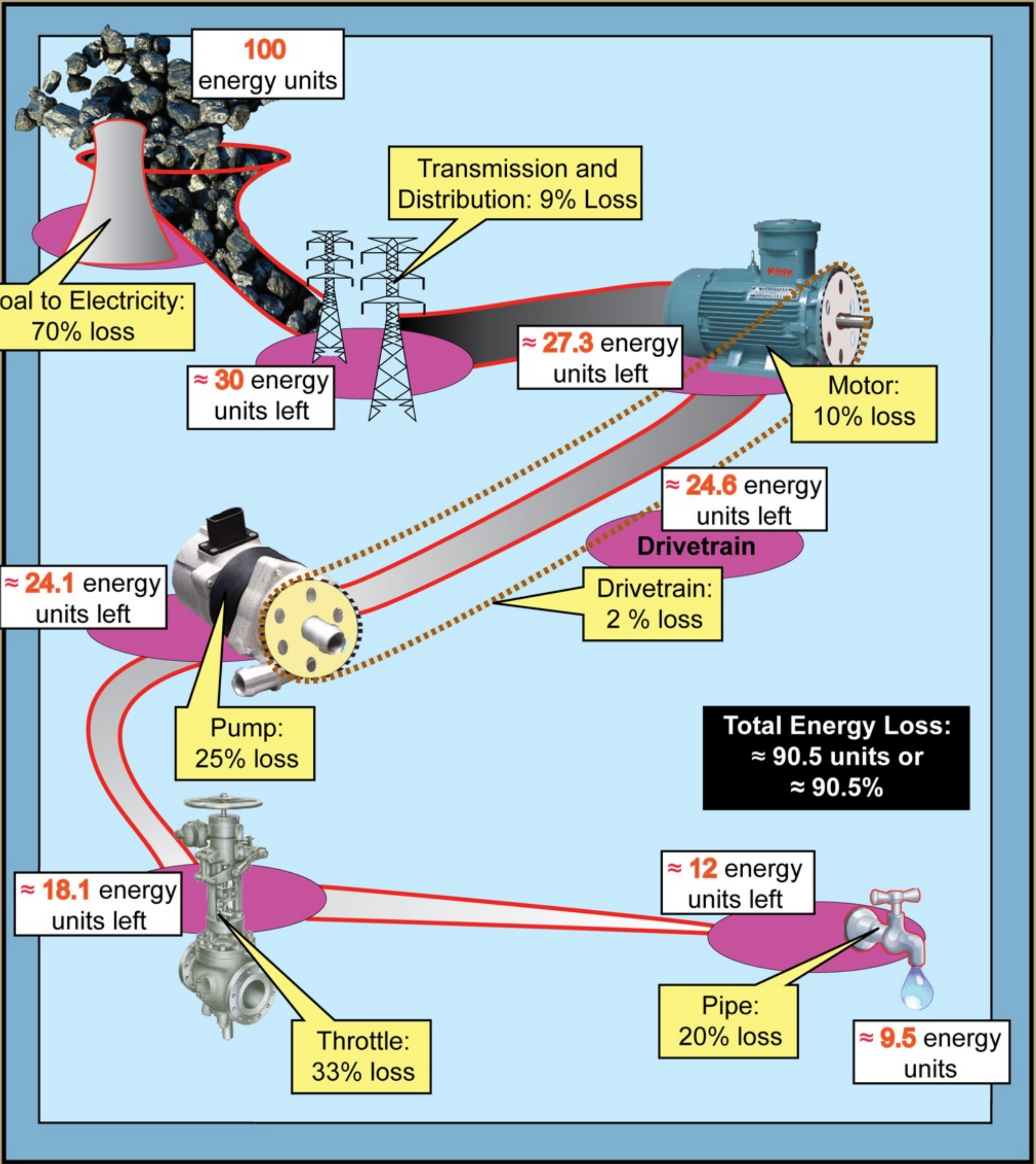
Building Design Opportunities



A.B. Lovins; "More Profit with Less Carbon"; Scientific American, Sept. 2005, pg. 79.

Energy Conservation

Energy Production Losses



100 energy units

Coal to Electricity: 70% loss

≈ **30** energy units left

Transmission and Distribution: 9% Loss

≈ **27.3** energy units left

Motor: 10% loss

≈ **24.6** energy units left

Drivetrain

Drivetrain: 2 % loss

≈ **24.1** energy units left

Pump: 25% loss

≈ **18.1** energy units left

Throttle: 33% loss

≈ **12** energy units left

Pipe: 20% loss

≈ **9.5** energy units

Total Energy Loss:
≈ 90.5 units or
≈ 90.5%

Energy Conservation

Heat Flow: Principles

Heat flow always occurs from regions of higher temperature to regions of lower temperature.

- Heat is a form of energy and may appear either as sensible heat (which is perceived as a change in temperature) or as latent heat (which is used up during a change of state).
- The concepts of heat and temperature are closely interrelated. Two bodies are at the same temperature if they remain in thermal equilibrium when brought into contact with each other (i.e., there is no heat flow between them).
- Heat flow can occur by conduction, convection, and radiation.

Energy Conservation
Heat Flow: Conduction

Thermal conduction is the direct transmission of heat through a material or between two materials that are in contact with each other.

The rate of heat transfer by conduction (Q_C) depends on the thermal conductivity of the material(s):

$$Q_C = \frac{\left[\begin{array}{c}\text{thermal}\\ \text{conductivity}\end{array}\right] \times \left[\begin{array}{c}\text{surface}\\ \text{area}\end{array}\right] \times \left[\begin{array}{c}\text{temperature}\\ \text{difference}\end{array}\right]}{[\text{ material thickness }]} \text{ (BTU/HR)}$$

- Assumes that all of the heat is transferred through the material, while in fact some of the heat is absorbed and the temperature of the material is raised.
- The amount of heat stored depends mainly on the specific heat and mass of the material.

Energy Conservation

Heat Flow: Convection

Heat is transferred by convection in liquids and gases as a result of circulation.

The rate of heat transfer by convection (Q_E) depends on the surface coefficient of heat transfer, the degree of air movement, the configuration of the surface(s) and the temperature difference.

$$Q_E = \left[\begin{array}{c}\text{surface}\\ \text{coefficient}\\ \text{of}\\ \text{heat transfer}\end{array}\right] \times \left[\begin{array}{c}\text{temperature}\\ \text{difference}\end{array}\right]^{5/4} \quad \text{(BTU/HR)}$$

- Typical surface coefficients of heat transfer:
  - horizontal surface (face up) = 0.4
  - horizontal surface (face down) = 0.2
  - vertical surface = 0.3
- Most hot air and hot water heating systems operate on the basis of convection currents.

Energy Conservation

Heat Flow: Radiation

In radiant heat transfer heat energy is converted into electro-magnetic radiation and reconverted to heat through absorption by another substance in its path.

The rate of heat transfer by radiation (Q_R) depends on the emissivities of the surfaces involved and the temperature difference between the surfaces.

$$Q_R = \left[\begin{array}{c}\text{emissivity}\\ \text{factor (E)}\end{array}\right] \times \left[\begin{array}{c}\text{surface}\\ \text{area}\end{array}\right] \times \left[T_1^4 - T_2^4\right] \quad \text{(BTU/HR)}$$

- For two parallel surfaces whose emissivities are 'e_1' and 'e_2', respectively, the emissivity factor is given by:

$$E = \frac{e_1 \times e_2}{e_1 + e_2 - 1}$$

- Radiant heat transfer is not impacted by air movement.

Energy Conservation

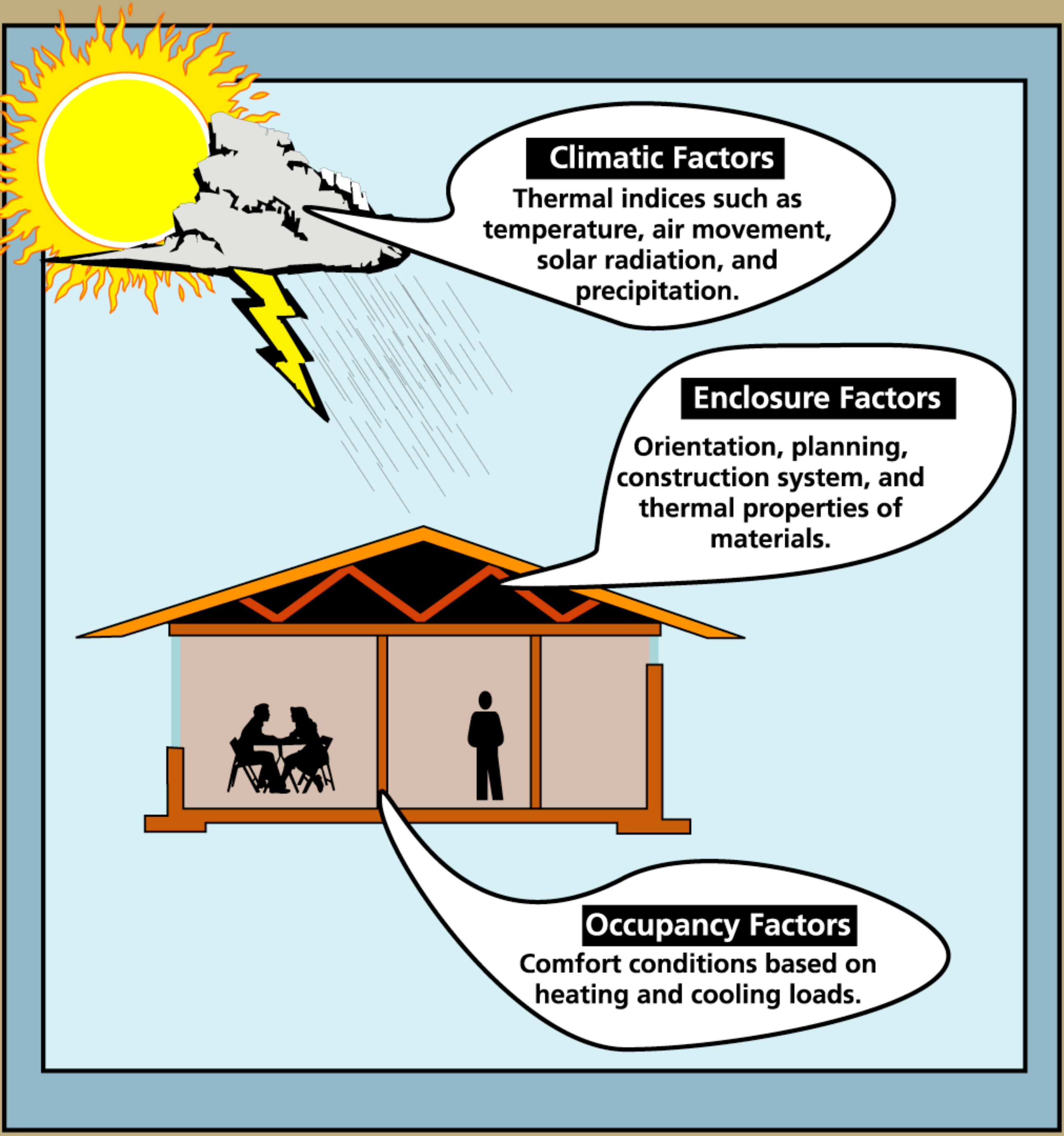
Heat Flow: Reflectivity

- Light surfaces are better reflectors of radiation than dark surfaces.
- Bright metallic surfaces are very efficient in reflecting solar radiation (i.e., more efficient than white paint).
- Reflectivity = (1 - emissivity).

Type of Surface Material	Reflectivity in Respect to Solar Radiation
aluminum	0.80
galvanized steel	0.45
white paint	0.70
black paint	0.10
cream bricks	0.40
red tiles	0.30

Energy Conservation

Thermal Building Design Factors



Climatic Factors

Thermal indices such as temperature, air movement, solar radiation, and precipitation.

Enclosure Factors

Orientation, planning, construction system, and thermal properties of materials.

Occupancy Factors

Comfort conditions based on heating and cooling loads.

SOLAR ENERGY

The 'Degree-Day' Concept

The Degree-Day (DD) concept provides a simplified procedure for calculating the size of a solar collector system. It assumes that there is no heating requirement if the external temperature is higher than a certain temperature (e.g., 65˚F).

- Each degree below the 'DD base temperature' (e.g., 65˚F) is considered to be one DD.
- If the mean monthly temperature for May in a particular locality is 60˚F, then each day of May has 5 DD (i.e., 5 DD/day or 155 DD/month).
- If the heat loss for a building (in the same locality) is 1,000 BTU/HR/˚F, then:

$$\text{heat loss} = 24 \times 1{,}000 \times [65 - 60] = 120{,}000 \text{ BTU/DD}$$

$$\text{heat loss} = 120{,}000 \times 155 = 18.6 \times 10^6 \text{ BTU/month}$$

Energy Conservation

Steady State Conditions: Assumptions

Reality

The Climatic Factors vary continuously over time, the Enclosure Factors cannot be modeled precisely, and the Occupancy Factors are subject to individual differences and preferences.

Simplifying Assumptions

A The temperature difference between the outdoor and indoor environments is large, and short-term outdoor temperature changes are small.

B The thermal capacity of the building shell is small in comparison to the total heat transfer.

Energy Conservation

Steady State Conditions: Equation

The rate of heat transfer through a construction component is determined by the thermal resistance of the material and the thermal resistance of the two surfaces of the material.

These are combined into a single thermal transmittance or U-Value.

The rate of heat transfer (Q) under Steady State Conditions is given by:

thermal transmittance of envelope

indoor air temperature

outdoor air temperature

$$Q = U \times A \times [T_1 - T_2] \text{ (BTU/HR)}$$

area of surface (portion of envelope under consideration)

temperature difference between indoors and outdoors

Energy Conservation

Steady State Conditions: U-Value

The U-Value of a composite building element is the inverse of the sum of the thermal resistances (R) of each material layer, cavity (if any), and the external and internal surfaces.

$$U = \frac{1}{\left[\begin{matrix}\text{total}\\ R_T\end{matrix}\right]} = \frac{1}{\left[\begin{matrix}\text{external}\\ \text{surface}\\ R_E\end{matrix}\right] + \left[\begin{matrix}\text{first}\\ \text{material}\\ R_{M1}\end{matrix}\right] + \left[\begin{matrix}\text{Air}\\ \text{Cavity}\\ R_C\end{matrix}\right] + \left[\begin{matrix}\text{second}\\ \text{material}\\ R_{M2}\end{matrix}\right] + \left[\begin{matrix}\text{internal}\\ \text{surface}\\ R_I\end{matrix}\right]} \quad \text{(BTU/SF-}^{\circ}\text{F)}$$

$$R = \frac{[\text{thickness of material (d)}]}{[\text{thermal conductivity of material (k)}]} \quad \text{(SF-}^{\circ}\text{F-HR/BTU)}$$

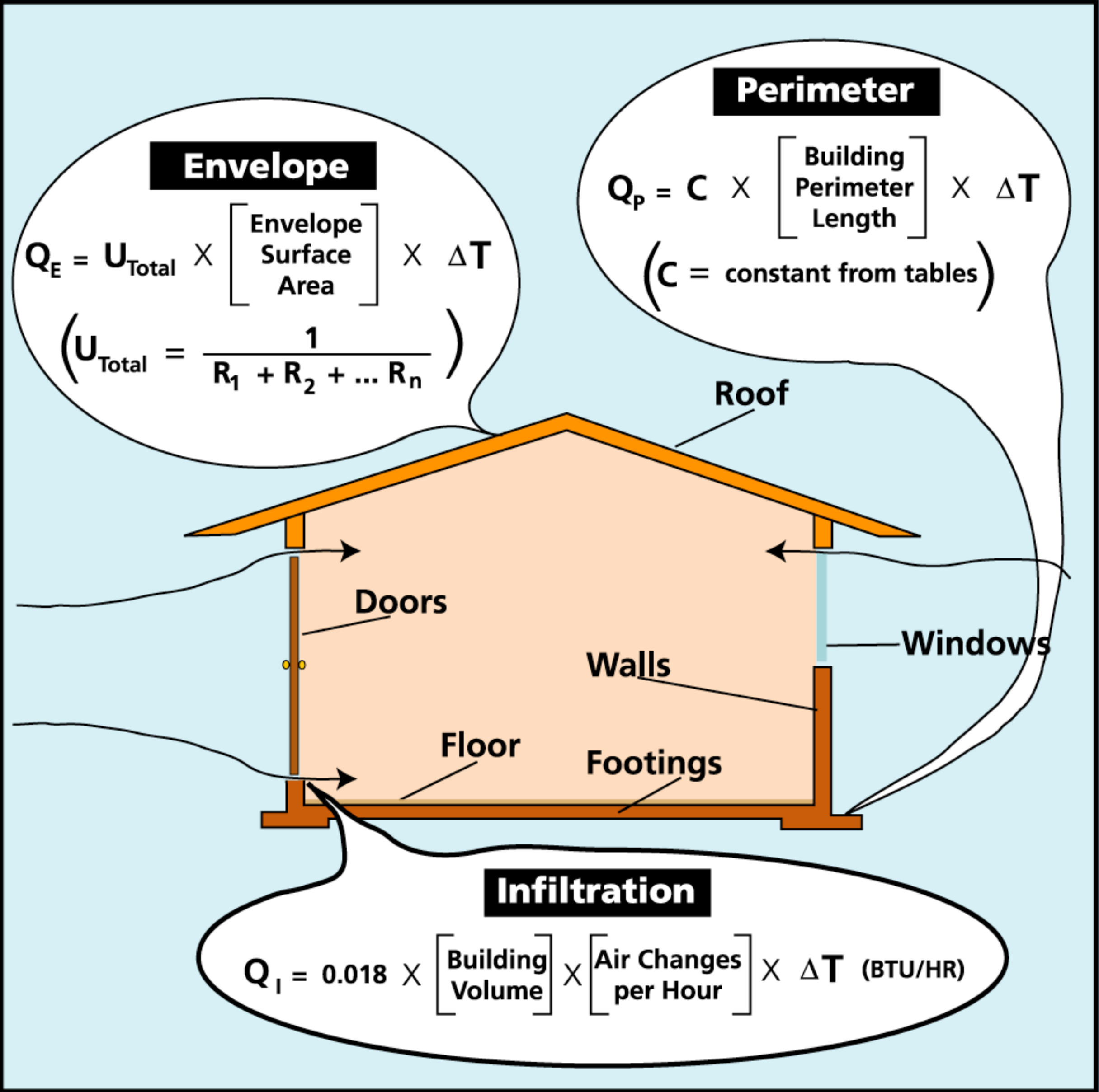
Energy Conservation

Materials: Thermal Resistance

Building Envelope Material/Component	Thermal Resistance (SF-°F-HR/BTU)
single brick (4-1/2" thick)	0.79
vert. boards (3/4" thick)	0.50
cement sheets (3/16" thick)	0.04
metal roofing (1/32" thick)	0.00
window glass (1/8" thick)	0.02
window glass (1/4" thick)	0.05
external surface	0.17
internal surface	0.61
air cavity	0.91
concrete (dense)	0.09 per inch
concrete (vermiculite)	1.25 per inch
timber	1.37 per inch
hardboard	0.71 per inch
fibreboard	2.50 per inch
polystyrene	3.57 per inch
polyurethane	6.25 per inch
mineral wool	3.86 per inch

Energy Conservation

Heat Loss/Gain Calculations



Envelope

$$Q_E = U_{Total} \times \begin{bmatrix}\text{Envelope}\\ \text{Surface}\\ \text{Area}\end{bmatrix} \times \Delta T$$

$$\left(U_{Total} = \frac{1}{R_1 + R_2 + \dots R_n}\right)$$

Perimeter

$$Q_P = C \times \begin{bmatrix}\text{Building}\\ \text{Perimeter}\\ \text{Length}\end{bmatrix} \times \Delta T$$

$$\left(C = \text{constant from tables}\right)$$

Infiltration

$$Q_I = 0.018 \times \begin{bmatrix}\text{Building}\\ \text{Volume}\end{bmatrix} \times \begin{bmatrix}\text{Air Changes}\\ \text{per Hour}\end{bmatrix} \times \Delta T \quad \text{(BTU/HR)}$$

Energy Conservation

Heat Loss/Gain: Envelope

The building Envelope is composed of elements such as roof, solid walls, doors, windows, and floor. Each has its own U-Value and area.

① Calculate area (A) of each envelope element:

area of roof = A_{Roof} (SF)
area of solid wall partition = A_{Wall} (SF)
area of windows = A_{Window} (SF)
area of doors = A_{Door} (SF)
area of above-grade floor = A_{Floor} (SF)

② Calculate thermal resistance (R) for each element.

③ Calculate U-Value for each element

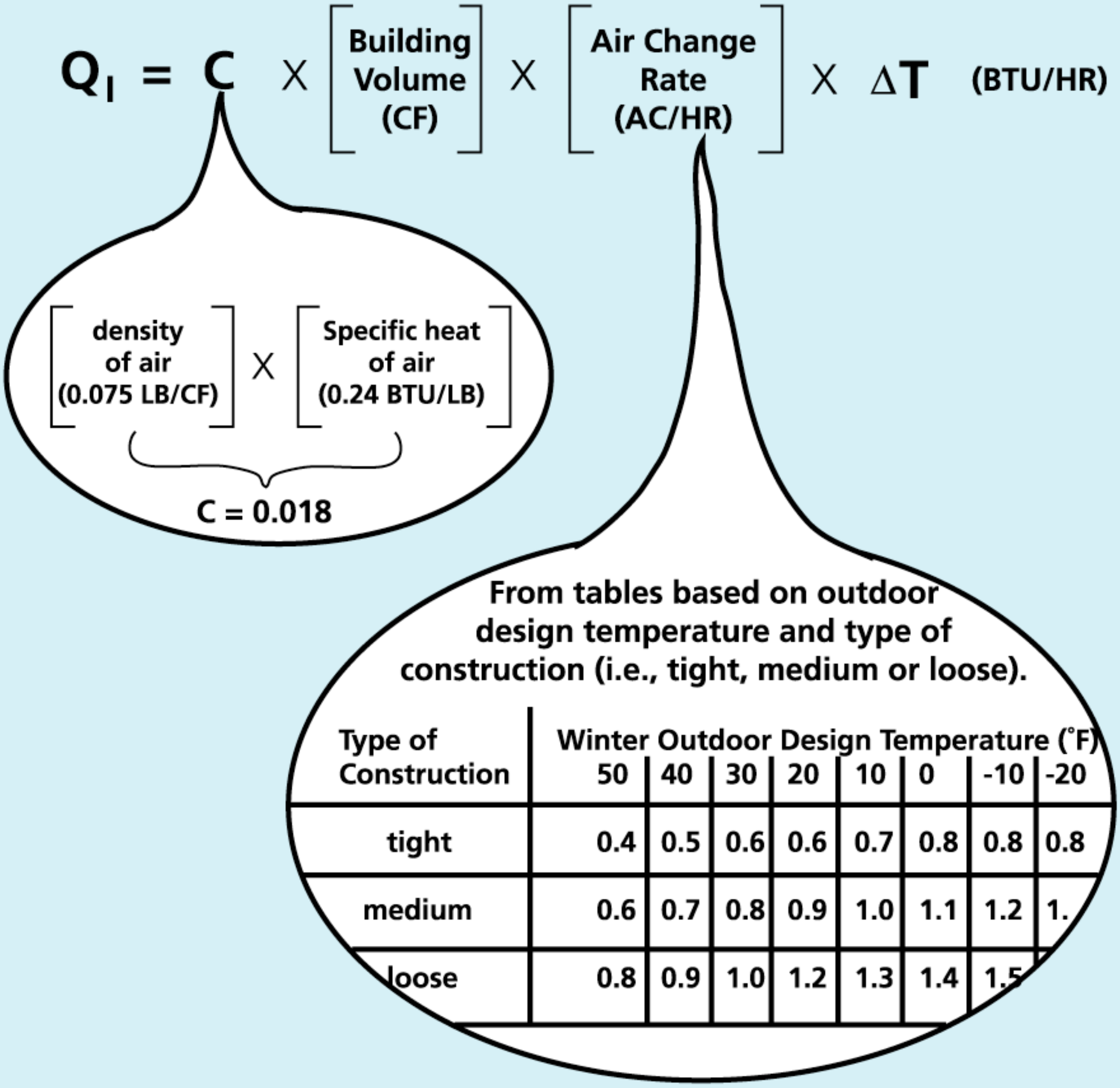
④ Calculate U x A for each element.

⑤ Calculate heat flow (Q_B) for entire building:

$$Q_B = [\Sigma UA] \times \Delta T \quad \text{(BTU/HR)}$$

Energy Conservation

Heat Loss/Gain: Infiltration



$$Q_I = C \times \left[\begin{array}{c}\text{Building}\\ \text{Volume}\\ \text{(CF)}\end{array}\right] \times \left[\begin{array}{c}\text{Air Change}\\ \text{Rate}\\ \text{(AC/HR)}\end{array}\right] \times \Delta T \quad \text{(BTU/HR)}$$

$$\underbrace{\left[\begin{array}{c}\text{density}\\ \text{of air}\\ \text{(0.075 LB/CF)}\end{array}\right] \times \left[\begin{array}{c}\text{Specific heat}\\ \text{of air}\\ \text{(0.24 BTU/LB)}\end{array}\right]}_{C = 0.018}$$

From tables based on outdoor design temperature and type of construction (i.e., tight, medium or loose).

Type of Construction	Winter Outdoor Design Temperature (˚F) 50	40	30	20	10	0	-10	-20
tight	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.8
medium	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.
loose	0.8	0.9	1.0	1.2	1.3	1.4	1.5	

Energy Conservation

Heat Loss/Gain: Perimeter/Floor

Slab On Grade

$$Q_P = G \times \left[\begin{array}{c}\text{Building}\\ \text{Perimeter}\\ \text{(FT)}\end{array}\right] \times \Delta T \quad \text{(BTU/HR)}$$

Wall Construction	Degree of Insulation	Degree Days (65˚F base) 7433	5350	2950
stud wall with external stucco	uninsulated	1.15	1.20	1.34
	R=5.4	0.51	0.53	0.58
block wall (8") with brick facing	uninsulated	0.62	0.68	0.72
	R=5.4	0.48	0.50	0.56

Floor Above Grade

$$Q_F = U_{\text{Floor}} \times A_{\text{Floor}} \times \Delta T \quad \text{(BTU/HR)}$$

$$\frac{1}{R_{\text{Floor}}} = \frac{1}{R_{\text{Ext.Surf.}} + R_1 + R_2 + \ldots R_{\text{Int.Surf.}}}$$

(for floor construction)

Energy Conservation

Materials: Thermal Conductivity

The thermal conductivity of a material is influenced by its structure (density and porosity), moisture content and temperature.

Structure: Good thermal insulation materials have closed cells with the internal and external surface resistance of each cell (i.e., cavity) contributing to the overall thermal resistance of the material.

Density: Heavy materials are better heat conductors than light materials (light materials tend to contain more air).

Moisture Content: The conductivity of water is about 25 times greater than air. Therefore, insulating materials must be kept dry at all times.

Temperature: Although the conductivity of materials tends to increase at higher temperatures, this is negligible over the range of temperatures normally encountered in buildings.

Energy Conservation

Air Cavities: Characteristics

About 65% of the heat transfer in an air cavity occurs by radiation. A layer of reflective foil can lower the conductivity of the air space in a brick cavity wall by some 50%.

- Ventilation of an air cavity will have little (if any) impact on the radiant heat transfer.
- Test results have shown that there is little difference in the thermal conductivity of air spaces varying in width from 0.75 to 6 inch.
- The thermal conductivity of air spaces less than 0.75 inch in width increases disproportionally with decreasing width.
- Care must be taken to keep wall cavities relatively clean during construction.

Energy Conservation

The Value of Thermal Insulation

The first 3" of thermal insulation provide the greatest return on investment.

Calculations based on the heat transfer through 1SF of the building envelope per hour, where the outdoor temperature is 40°F and the indoor temperature is 70°F (i.e., 30°F temperature difference).

Construction Component	Thermal Resistance (R)	Heat Flow Calculation	Heat Loss (Q) (BTU/SF-HR)
single glass (1/8")	0.80	Q = 1(1/0.80) (70-40)	37.50
double glass (1/8" + 1/8")	1.73	Q = 1(1/1.73) (70-40)	17.40
concrete wall (6")	1.32	Q = 1(1/1.32) (70-40)	22.73
(+) 1" polyurethane	(+) 6.25	Q = 1(1/7.57) (70-40)	3.90
(+) 3" polyurethane	(+) 18.75	Q = 1(1/20.07) (70-40)	1.50
(+) 10" polyurethane	(+) 62.50	Q = 1(1/63.82) (70-40)	0.66
For external stucco (3/4") and internal drywall on 2" x 4" stud frame:			
with no insulation	2.00	Q = 1(1/2.00) (70-40)	15.00
with 1" polyurethane	(+) 6.25	Q = 1(1/8.25) (70-40)	3.50

Energy Conservation

Insulation: Return on Investment

Assume a 1,600 SF home with an external surface area (envelope) of around 3,000 SF (including an allowance for the perimeter footings).

IF:

cost of polyurethane (in place) = $0.50/SF

cost of electricity ($1.80/therm) = $0.000018/BTU

30˚F temp. diff. for 15 HR on 200 days = 3,000 HR

home (uninsulated) =

15.00 x 3,000 x 3,000 x 0.000018 = $2,430/year

home (with 1" polyurethane) =

3.50 x 3,000 x 3,000 x 0.000018 = $566/year

cost of 1" polyurethane = 0.50 x 3,000 = $1,500

Even 1" of polyurethane insulation pays for itself in less than one year.

Energy Conservation
Condensation: Causes

The ability of air to hold moisture increases with higher temperatures. Condensation occurs whenever the air temperature falls below the Dew Point.

Surface condensation and interstitial condensation may occur due to:

- **The addition of moisture to the air due to the occupancy of the building (e.g., cooking, rigorous exercising, industrial processes, etc.)**
- **The intentional humidification of air for reasons of comfort or safety.**
- **Humid air coming in contact with much colder surfaces.**

Energy Conservation

Condensation: Principles and Prevention

Cold surfaces and steep temperature gradients are likely to produce condensation.

Surface Condensation: Occurs whenever the temperature of any exposed surface (e.g., window pane) within a building falls below the Dew Point of the indoor air.

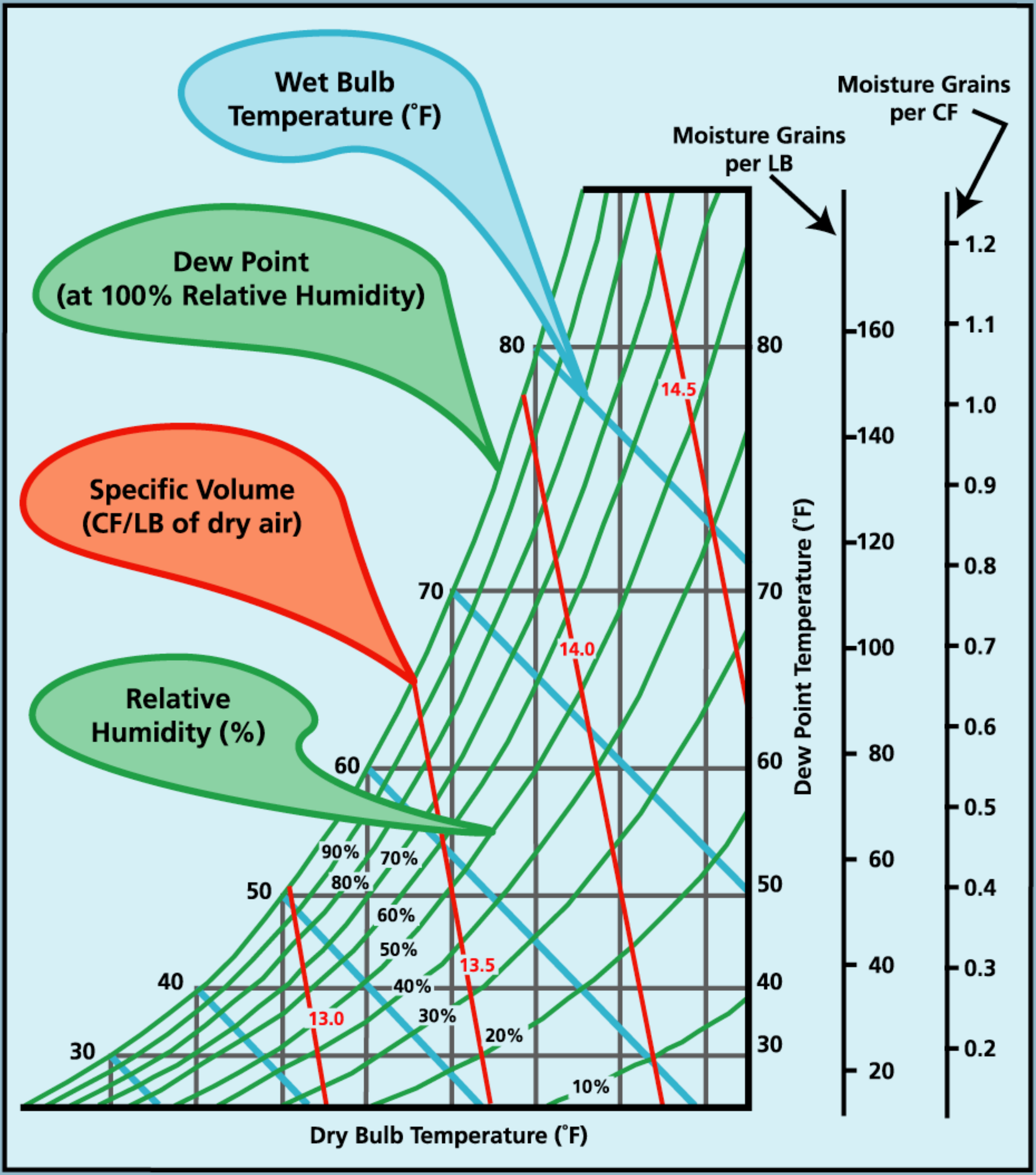
Remedies: (1) Adequate thermal insulation
(2) Absorbent surface finishes

Interstitial Condensation: May occur within the layers of the building envelope whenever the temperature difference between the indoor and outdoor air is very large, and the reduction in vapor pressure across the envelope is abrupt.

Remedies: (1) A vapor barrier (foil or plastic membrane on the warmer side of the envelope.
(2) Avoidance of materials that are impervious to moisture (causing an abrupt vapor pressure drop).

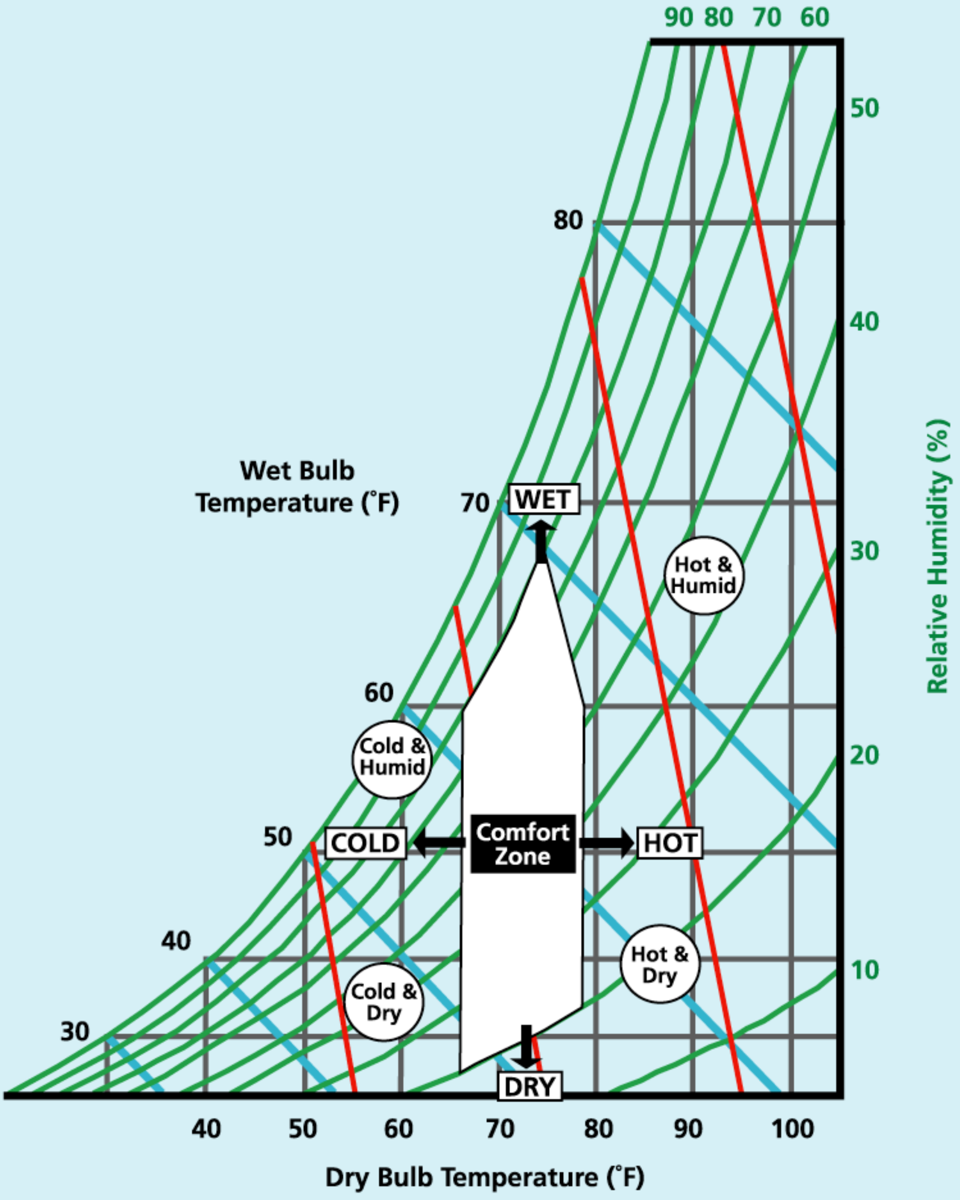
Energy Conservation

The Psychrometric Chart

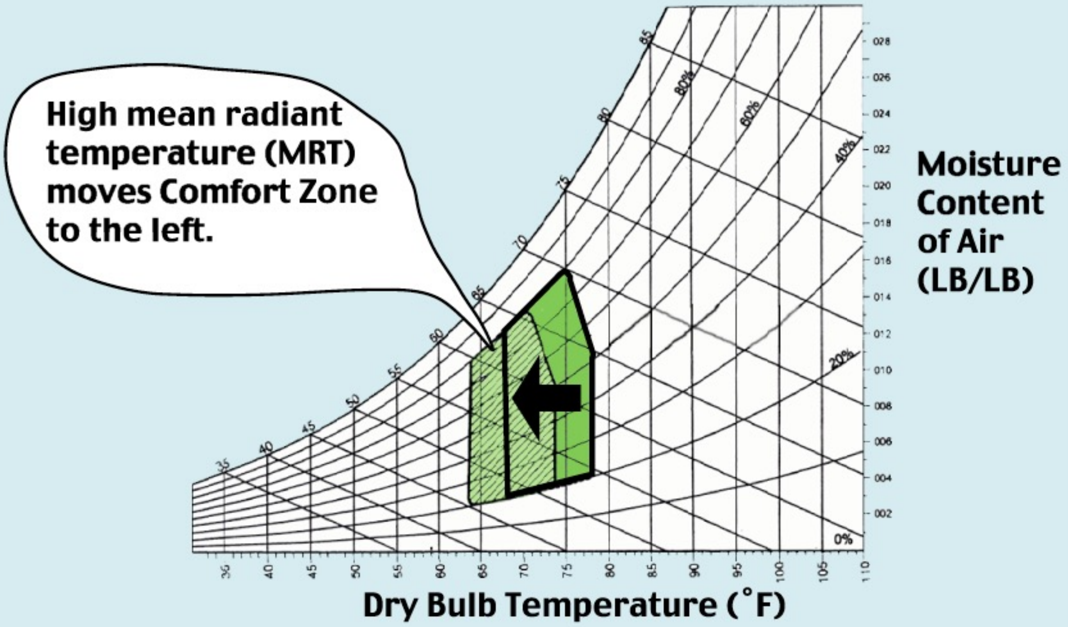


Energy Conservation

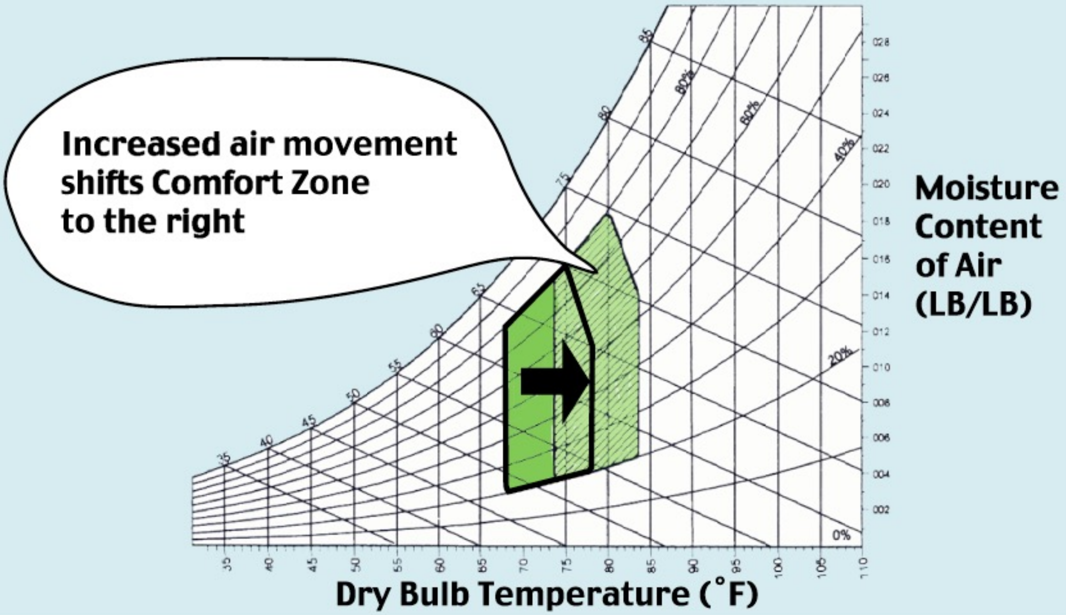
Comfort Zone Relationships



Energy Conservation
Impacts on Comfort Conditions



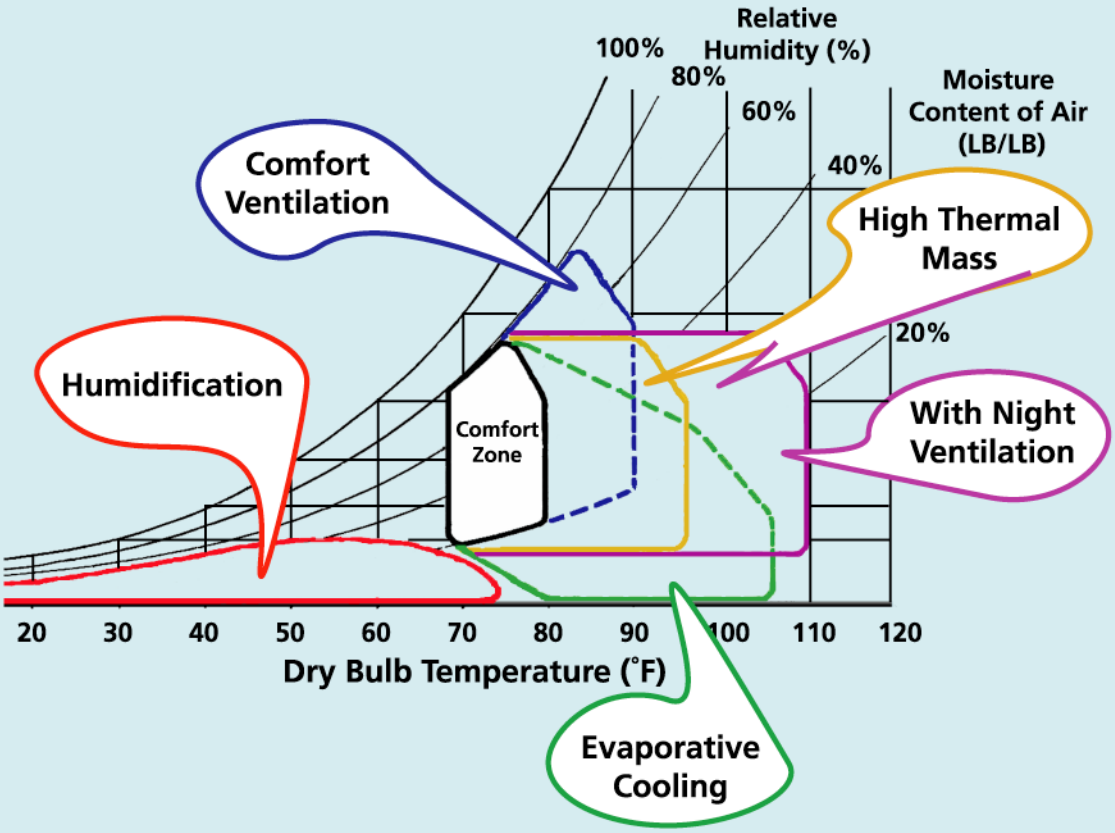
High mean radiant temperature (MRT) moves Comfort Zone to the left.



Increased air movement shifts Comfort Zone to the right

Energy Conservation

Thermal Design Strategies

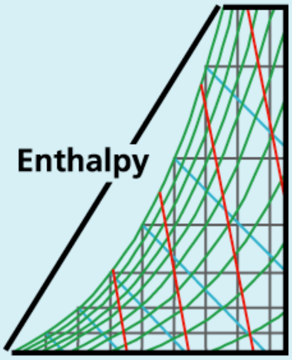


Energy Conservation

Further Definitions

Enthalpy

Enthalpy is the total sensible and latent heat content of an air-moisture mixture, relative to the enthalpy at 0°F and standard atmospheric pressure (14.7 LB/SI).



Specific Heat

Specific Heat of a substance is the amount of heat that can be absorbed by 1 LB of that substance. Specific Heat of water is 1 BTU/LB-°F.

Heat Capacity

Heat Capacity = [Specific Heat (BTU/LB-°F)] X [Density (LB/CF)] (BTU/CF-°F)

For the same Heat Capacity: