CAE 463/524
Building Enclosure Design
Fall 2012

Lecture 1: Introduction

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Built Environment Research Group
www.built-envi.com

Objectives for today's lecture

- Introduce myself
- Introduce course topics
- Introduce yourselves
- Discuss syllabus
  - Course information, outline, schedule, ground rules
  - Why are we all here?
- Introduce fundamentals of building enclosures
- Review heat, air, and moisture (HAM) fundamentals

About me

- B.S. Civil Engineering
  - Tennessee Technological University
- M.S. Environmental and Water Resources Engineering
  - The University of Texas at Austin
  - Thesis: "Energy implications of filtration in residential and light-commercial buildings"
- Ph.D. Civil Engineering
  - The University of Texas at Austin
  - Dissertation: "Characterizing the impacts of air-conditioning systems, filters, and building envelopes on exposures to indoor pollutants and energy consumption in residential and light-commercial buildings"
- First time teaching a full course
  - Learning experience for everyone (and I mean ***everyone***)

Course information

CAE 463/524: Building Enclosure Design

Course Unique Number(s)
- CAE 463 Section 1: 10411 (undergraduate)
- CAE 463 Section 2: 13228 (undergraduate online)
- CAE 524 Section 1: 10421 (graduate)
- CAE 524 Section 2: 13229 (graduate online)

Classroom and Meeting Time
- Stuart Building 204
- Mondays 6:25 PM – 9:05 PM

Prerequisites
- CAE 331 Building Science

Course information

Course Catalog Description

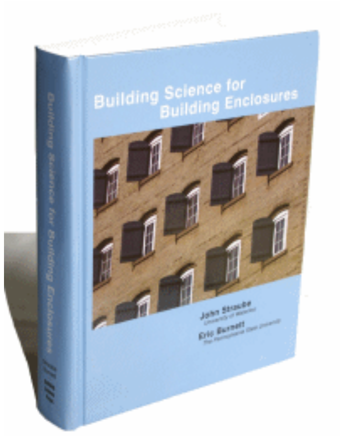
- Design of building exteriors, including the control of heat flow, air and moisture penetration, building movements, and deterioration. Study of the principle of rain screen walls and of energy conserving designs. Analytical techniques and building codes are discussed through case studies and design projects.

Course objectives

To introduce students to the design of building enclosures (i.e., "building envelopes"), elements of which include walls, floors, roofs, and intentional openings. By taking this course students will be able to:

1. Design and assess building enclosure elements for heat transfer, airflow, and moisture control.
2. Be proficient in current building codes as they pertain to building enclosure design.
3. Critically analyze designs for advanced building enclosures for their impacts on energy use, airflow, and potential moisture issues.

Textbook (highly recommended)



Building Science for Building Enclosures
Straube, J. and Burnett, E., 2005.
Building Science Press. Westford, MA.
ISBN: 0-9755127-4-9.
http://buildingenclosures.buildingsciencepress.com/

I just ordered some copies at the bookstore

I will also draw from several other references:

- ASHRAE 2009. *Handbook of Fundamentals.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.
- ASHRAE 90.1-2010. *Energy Standard for Buildings Except Low-Rise Residential Buildings.*
- Moss, K.J. 2007. *Heat and Mass Transfer in Buildings (Second Edition)*. Taylor & Francis, New York, NY. ISBN: 978-0-415-40908-7.
- Kuehn, T.H., Ramsey, J.W., and Threlkeld, J.L. *Thermal Environmental Engineering (Third Edition)*. Prentice Hall, Saddle River, NJ. ISBN: 0-13-917220-3

Course topics

- Purpose and importance of building enclosure design
- Heat transfer in building enclosures
- Airflow in building enclosures
- Moisture flows in building enclosures
- Moisture problems and prevention
- Dynamic heat, airflow, and moisture
- Analytical and software techniques
- Applications: Exterior walls and windows
- Applications: Roofs and floors
- Advanced/high performance building enclosure designs
- Impacts of building enclosures on indoor air quality

About you

- Who are you?
  - Name
  - Where you are from
- What is your primary degree emphasis?
  - Undergraduate or graduate
  - Engineering or other
  - If graduate, masters or PhD?
    - Doing research?
- Why are you taking this course?
- Relevant work experiences

Course expectations

- Grading
  - Course is mixed undergraduate/graduate
  - Graduate students will have higher expectations
- Homework
  - Several HW assignments throughout semester
- Exam(s)
  - One (*likely*) take-home exam will be given in mid/late October
  - No final exam scheduled as of now
- Project(s)
  - Two projects in this course
  - One will involve assessing the exterior of IIT buildings
  - The other, larger, project will involve a report and presentation on high performance building enclosures

Course grading

• HW	20%
• Project 1 (IIT buildings)	15%
• Project 2 (final)	35%
• Exam	30%
• Total	100%

Course website

- http://built-envi.com/courses/cae-463-bed-f12/
  - Course calendar

- Will also use Blackboard
  - Lecture notes
  - Reading materials
  - Assignments

Tentative schedule

Tentative Course Schedule

Date	**Topic**	**Suggested reading for this date:**	**Due date for:**
08/20/12	Purpose and importance of building enclosure design	Straube Ch. 2-3; Lstiburek 2004	
08/27/12	Heat transfer in building enclosures	Straube Ch. 4-5; Lstiburek 2012	HW1
09/03/12	Labor Day – No class		
09/10/12	Airflow in building enclosures	Straube Ch. 7; Younes et al. 2012	HW2
09/17/12	Moisture flows in building enclosures	Straube Ch. 6	HW3
09/24/12	Moisture problems and prevention	Straube Ch. 9-10	
10/01/12	Dynamic heat, airflow, and moisture		HW4
10/08/12	Fall Break Day – No class		
10/15/12	Analytical and software techniques	Kazmierczak 2010; Karagiozis et al. 2010	
10/22/12	Applications: Exterior walls and windows	Selkowitz 2011	Take-home exam (due 10/24)
10/29/12	Applications: Exterior walls and windows (*Likely to have a guest lecturer*)	OAA, *The Rain Screen Wall System*	
11/05/12	Applications: Roofs and floors		
11/12/12	Advanced/high performance building enclosures		IIT campus building project
11/19/12	Impacts of building enclosures on indoor air quality	Liu and Nazaroff 2001; Stephens and Siegel 2012	
11/26/12	Final project presentations		Final project

*Note that two class periods will be interrupted by IIT's official academic calendar: Labor Day (September 3, 2012) and Fall Break Day (October 8, 2012)

Questions thus far?

Today's topics

1. Introduction to building enclosures
   – Enclosure purposes, components, and materials

2. Review of environmental conditions
   – Purpose of enclosure analysis

3. Review of heat, air, and moisture fundamentals
   – Work some examples

1. INTRODUCTION TO BUILDING ENCLOSURES

Building enclosure design: why bother?

- Building science is important
  - Buildings use ~40% of energy in US
  - People spend 90% of their time indoors

- Building enclosures (or “envelopes”) serve to separate indoor and outdoor environments
  - Major impacts on energy and indoor environment
  - Deterioration and failures of building envelopes account for the majority of building defect claims in North America

- Building enclosures are crucial to building science

Important organizations to know

- American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE)
  - Handbook of Fundamentals
  - Standards and design guidelines
- National Institute of Building Sciences
  - Whole Building Design Guide
- National Resources Canada
  - RETScreen Software Suite
- Lawrence Berkeley National Laboratory
  - THERM
  - WINDOW
- Oak Ridge National Laboratory
  - WUFI
- Building Science Corporation
  - Building Science - Information

Important publications to know

- Publications*
  - *ASHRAE Journal*
  - *HVAC&R Research*
  - *ASHRAE Transactions*
  - *Building and Environment*
  - *Energy and Buildings*
  - *ASCE Journal of Architectural Engineering*
  - *Journal of Building Enclosure Design* (free online)

*I believe these are all available through the Galvin Library

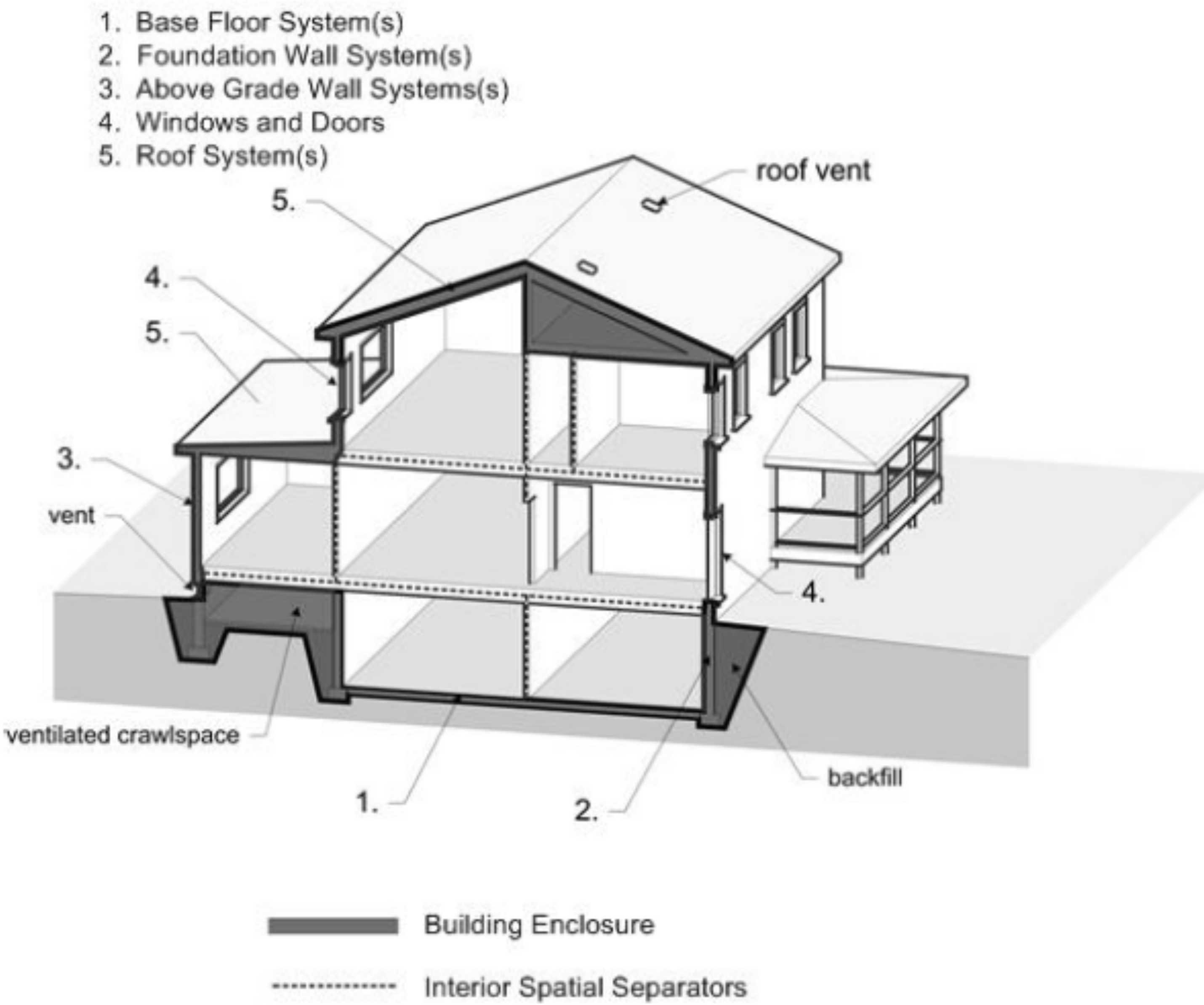
Building enclosures

- Definition of building enclosure (or “envelope”):
  - The part of any building, above or below grade, that physically separates the outside or exterior environment from the interior environment

*“**Envelopes** are for FedEx. **Enclosures** are for builders and architects.”*

- Joe Lstiburek
Building Science Corporation

Building enclosure components



Building enclosure components

- Roof system(s)
- Above-grade wall system(s) including windows (fenestration) and doors
- Below-grade wall system(s)
- Base floor system(s)

- Each enclosure component is a 3-D, multi-layer, multi-material assembly that extends from the inside face of the innermost layer (e.g., interior painted surface) to the outside face of the outermost layer (e.g., painted siding or roof shingles)

Basic functions of building enclosures

- **Support**
- Control
- Finish
- Distribution

Lateral

Wind and Earthquake

Gravity

Dead load, snow

Rheological

Temp, Moisture

Impact

Wear/Abrasion

Support – Resist and transfer physical forces from inside and out

Basic functions of building enclosures

- Support
- **Control**
- Finish
- Distribution

Heat
Air
Moisture
Rain
Sound
Fire
Insects
Access

Control – Manage mass and energy flows

Basic functions of building enclosures

- Support
- Control
- **Finish**
- Distribution

Color
Texture
Reflectance
Pattern

Finish – interior and exterior surfaces for people

Basic functions of building enclosures

- Support
- Control
- Finish
- **Distribution**

Electricity
Communications
Plumbing
Air Ducts
Gas Lines
Roof Drains

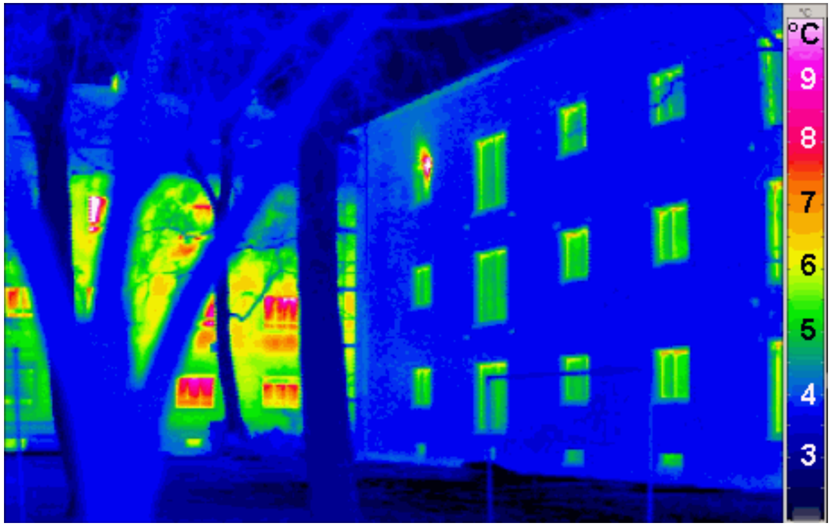
Distribute – protect and house building services

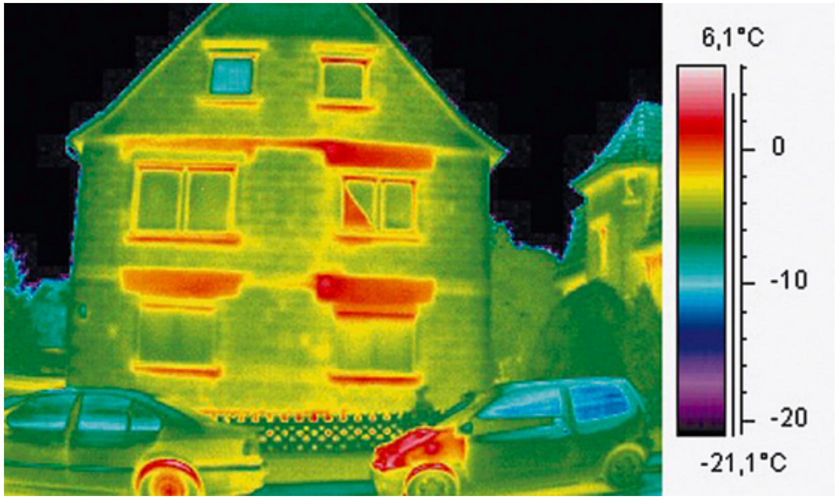
Major functions: thermal and moisture control

- A large number of the enclosure functions are related to heat and moisture control

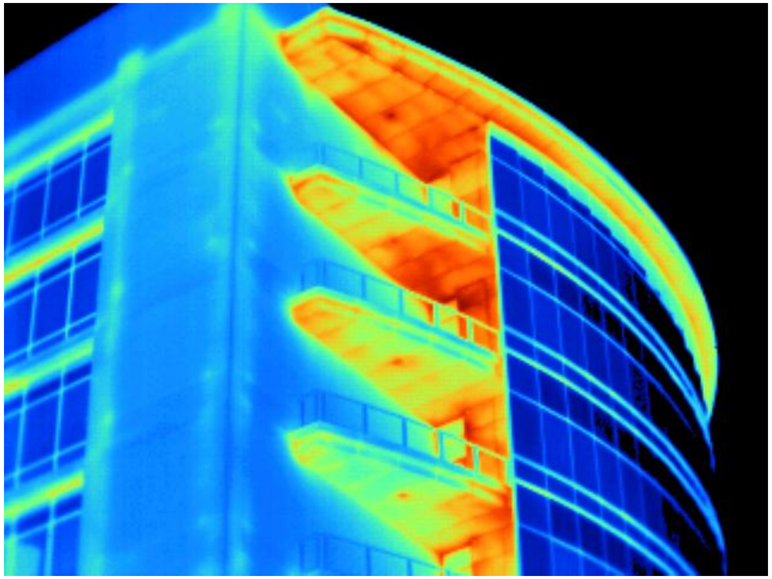
- In this class we will spend much of our time on the thermal and moisture aspects of building enclosures
  - Other topics that will receive some, albeit less attention
    - Air infiltration/ventilation
    - Impacts on indoor environment
    - Exterior degradation

Visual evidence for why building enclosures are important





Thermal

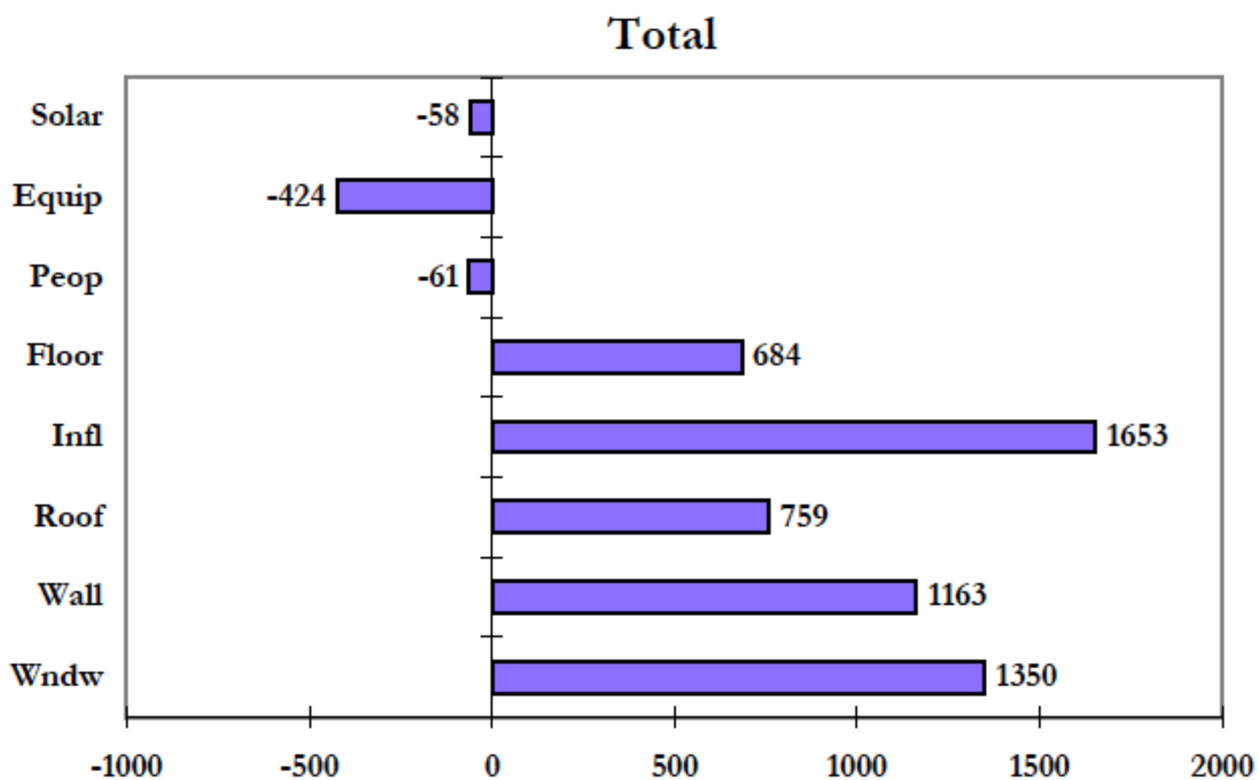


Visual evidence for why building enclosures are important

Moisture

Just how important are building envelopes for energy use?

- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
    - Report #LBNL-44636



Aggregate component loads for all residential buildings (trillion BTUs)

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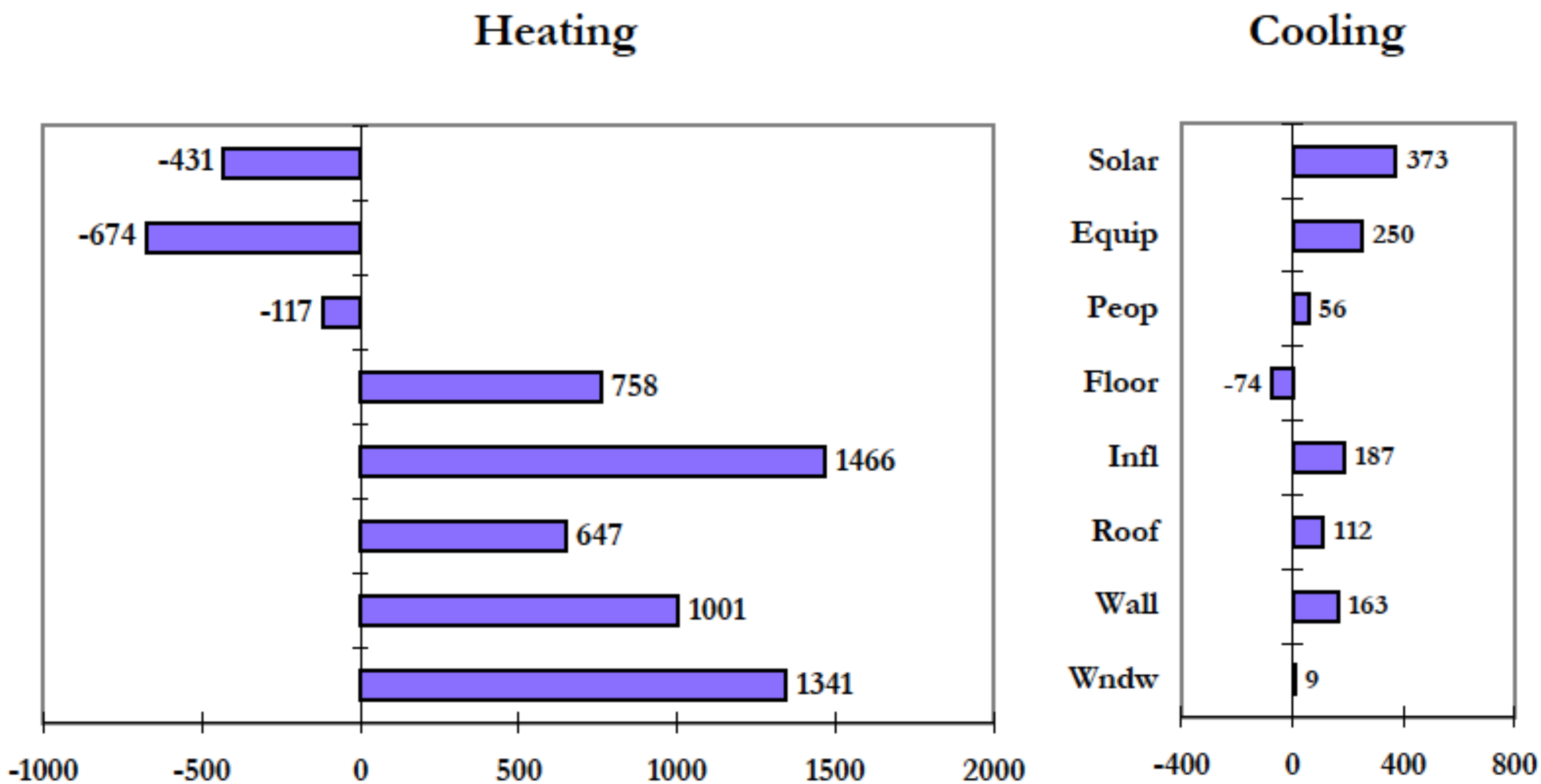


Aggregate component loads for all residential buildings (trillion BTUs)

Just how important are building envelopes for energy use?

- (Another) 1999 study by Lawrence Berkeley National Lab
  - *Commercial Heating and Cooling Loads Component Analysis*
    - Report #LBNL-37208
  - Largest contributors to heating loads in US commercial bldgs
    - Windows
    - Walls
    - Infiltration
  - Largest contributors to cooling loads in US commercial bldgs
    - Lighting
    - Solar gain
    - Equipment

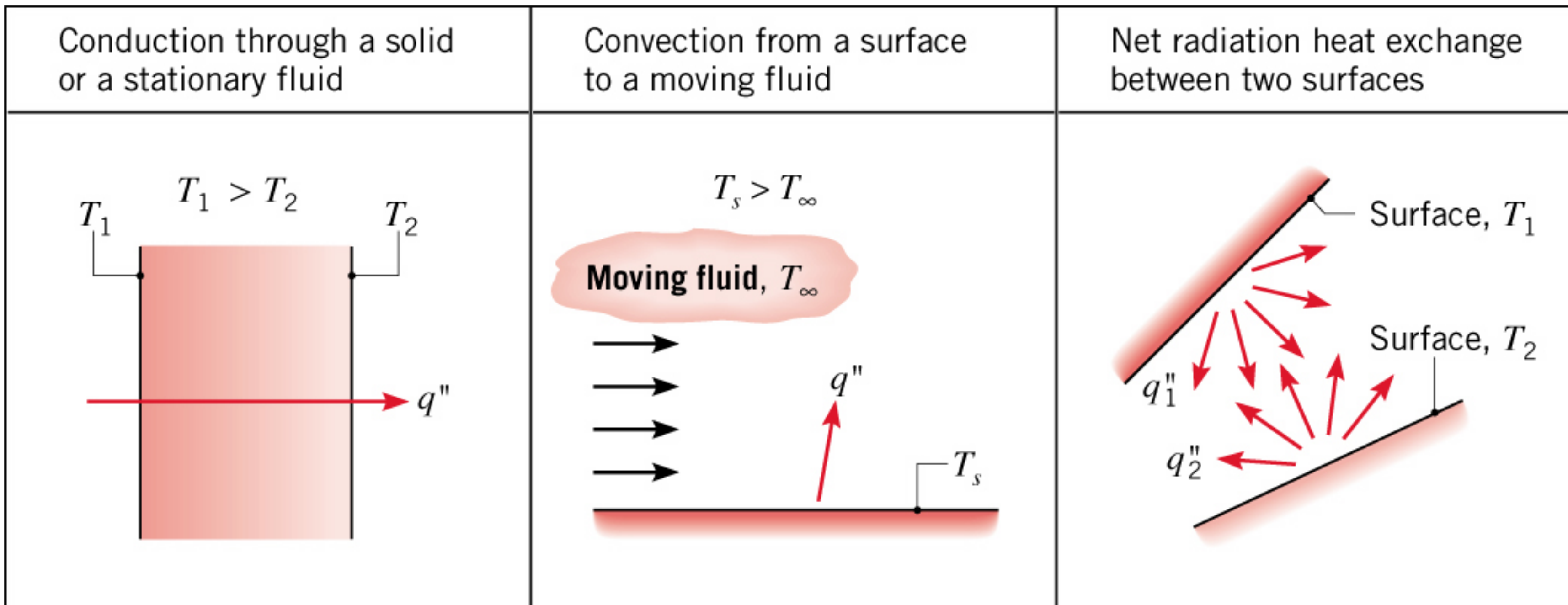
How important are building envelopes?

- Without walls, roofs, and floors, there is no building!
  - Let's think about how much surface area building envelopes take up in the U.S….
- Residential http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.2.1
  - 256 billion ft^2 of floor space in 2005
- Commercial http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.2.1
  - 81 billion ft^2 of floor space in 2010
- Federal http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=4.2.1
  - 3 billion ft^2 of federal buildings in 2007
- Total floor area of U.S. buildings
  - 340 billion ft^2 of floor space in buildings in the U.S.
  - 12,200 square miles
  - About 20% of the state of Illinois
  - Approximately equal to the size of Taiwan

\+ walls + roofs…

Building enclosure: some primary functions

- Controlling heat transfer
  - Three modes: Conduction, Convection, Radiation
  - Heat moves from hot to cold



Controlling conduction

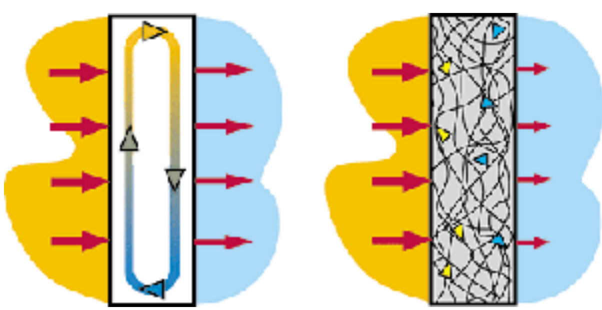
- You can reduce conductive heat transfer through enclosures by increasing the thermal resistance (R-value)
  - i.e., dropping the U-value

  What are some strategies?
  - Use low-conductivity materials
  - Proper use/installation of insulation
  - Avoiding constructions with thermal bridges

Controlling convection

- Convection is one of two mechanisms for heat transfer to/from the enclosure. Reduce convective heat transfer by reducing air flow and limiting air motion

  What are some strategies?
  - Reduction of air gap size between elements
  - Add inserts to block convection
  - Reducing surface roughness of materials
  - Installation of air barrier materials



Controlling radiation

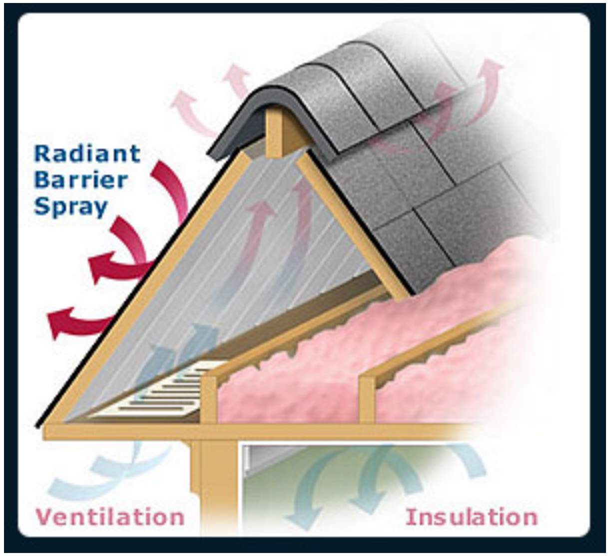
- Radiation is the other heat transfer mechanism to/from the enclosure
  – Reduce radiative heat transfer by reducing building exposure to radiation

  What are some strategies?

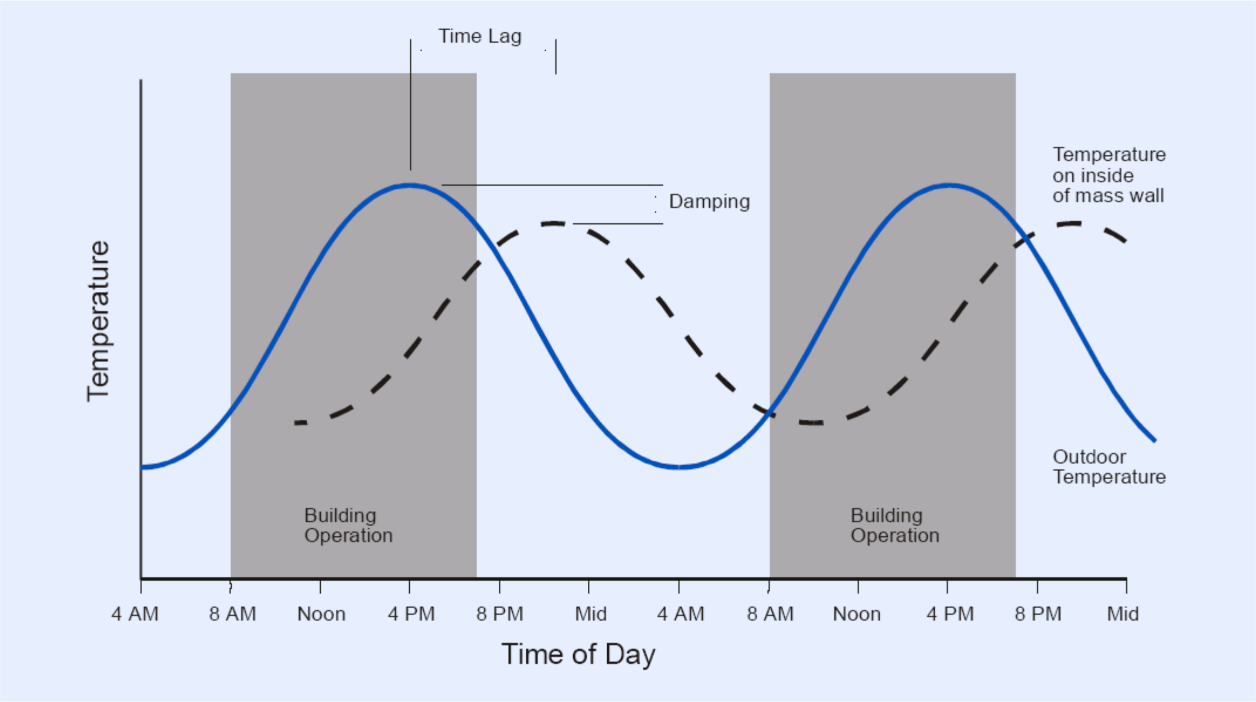
  – Careful selection of building location and layout

  – Careful selection of glazing system and glazing controls

  – Use radiant heat barriers



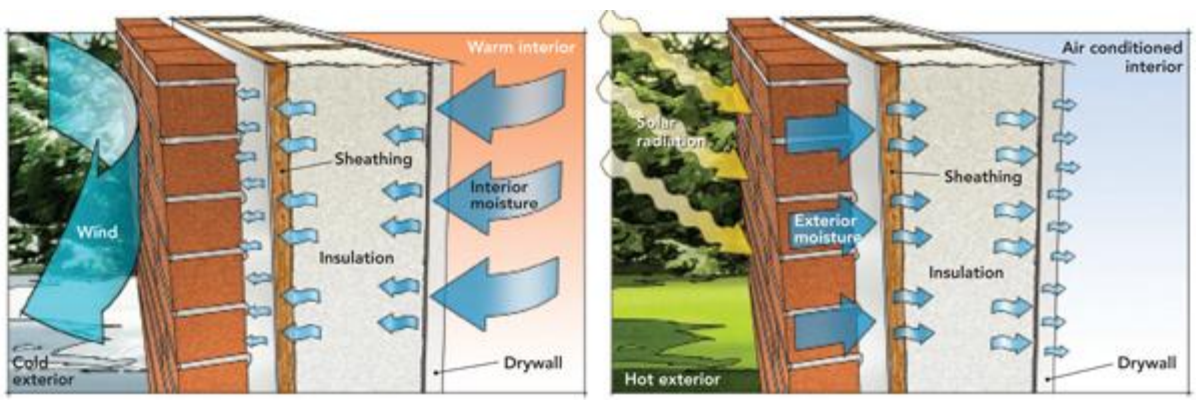
Thermal mass



- A massive wall takes time to heat up and cool off. This time lag can be used to absorb heat during the occupied day and release heat during the unoccupied evening

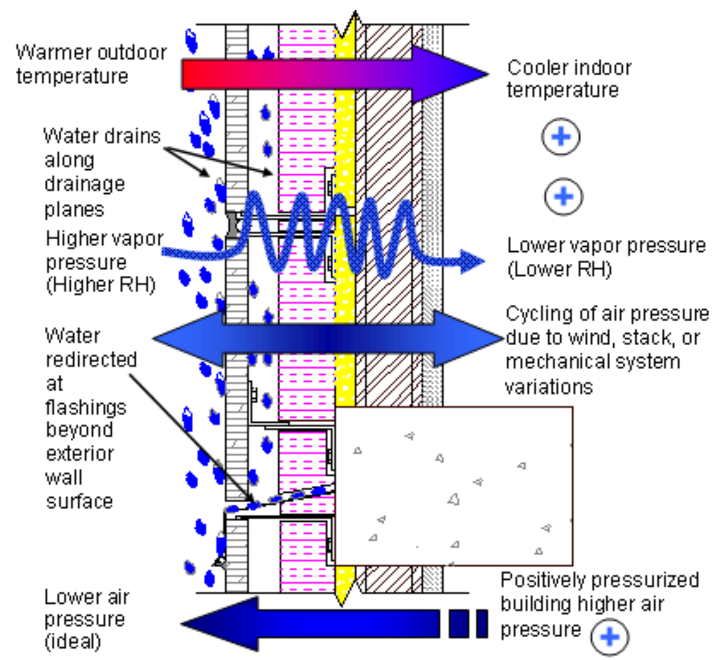
Moisture transfer

- Moisture transfer is the transfer of water vapor into and through the enclosure
- We want to understand and control moisture transfer because unwanted moisture can:
  - Increase latent heating/cooling load
  - Cause deterioration of the building enclosure
  - Create conditions amenable to mold growth



Moisture transfer

- From high temperature to low temperature
  - Driven by thermal gradient
- From high humidity to low humidity
  - Driven by concentration gradient
- Carried with air
  - Driven by air leakage into/through enclosure
- Need to ensure that moist air does not contact and condense on cold elements within the enclosure
  - Chemical deterioration and corrosion
  - Freeze-thaw deterioration
  - Mold and mildew
  - Staining/damage to interior finishes



Some information on our course projects

- Two course projects

  1. Intermediate Project:

  – Assessment of the enclosure of a building on IIT's main campus (15% of grade)

  2. Final Project:

  – Research high performance enclosures (35% of grade)

Project 1: Assessment of IIT building enclosures

- Objective
  - Take what you learn about heat, air, and moisture transport (and failures) in building enclosures and apply those fundamentals to critically assess the enclosure of a building on IIT's campus
    - Will also recommend retrofits to increase performance
    - In previous versions, all students used Crown Hall
      - We'll expand on that
    - Use of thermal imaging
    - "Real" field experience
- Deliverable
  - Short report of findings (I will give you an example)

Project 1: Assessment of IIT building enclosures

- Many famous (and not-so-famous) buildings on campus
  - But how do they perform?

Project 2: High performance enclosure research

- Objective
  - Extend what you've learned about HAM transport and failures, as well as practical considerations for building enclosures, and research a "high performance" enclosure construction
    - Literature review, product review, and examples
    - Advantages and disadvantages
    - HAM analysis
    - Cost considerations
    - Practical design considerations
    - Environmental and sustainability impacts
- Deliverables (replaces final exam)
  - Final report of findings (approx. 6-10 pages)
  - Final presentation of findings (like a conference presentation)
  - Will have some intermediate deliverables to keep you on track

Project 2: High performance enclosure research

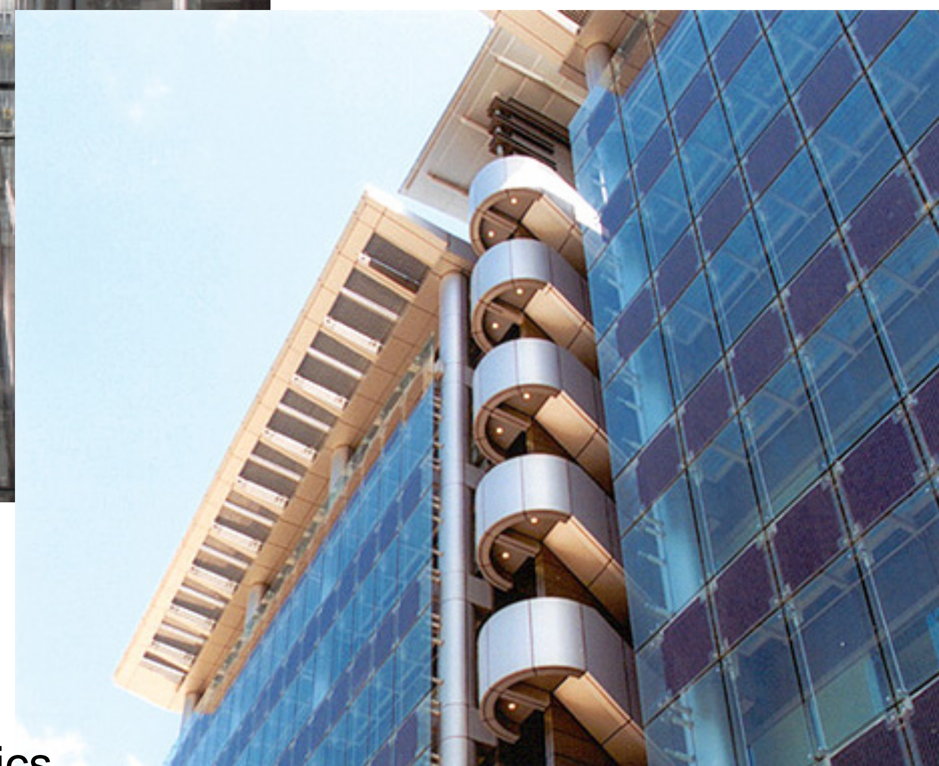
- Many new enclosure products/technologies/designs exist
  - How do they perform and what are their advantages/disadvantages?

Green roofs

Green walls

Project 2: High performance enclosure research

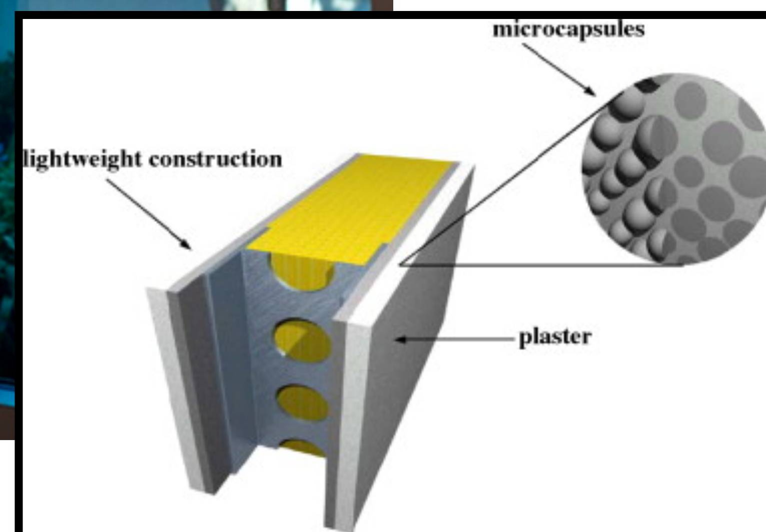
Double skin facades



Building integrated photovoltaics

Project 2: High performance enclosure research

Electrochromic windows (“smart glass”)



Phase change insulation materials

Project 2: High performance enclosure research

Bio-based insulation materials (mushroom

Structural insulated panels (SIPS)

Project 2: High performance enclosure research

“Cool” roofs (e.g., white roofs)

Straw bale construction

Project 2: High performance enclosure research

List of example technologies

- Green roofs
- Green walls
- Double skin facades
- Building integrated photovoltaics
- Electro chromic windows
- Phase change materials
- Bio-based insulation materials (mushrooms, straw)
- Structural insulated panels
- Cool roofs
- Whatever you come up with!

2. ENVIRONMENTAL CONDITIONS

Environmental conditions

- Loads on the enclosure result from I/O differences
  - Temperature, humidity, solar insolation, wind, precipitation

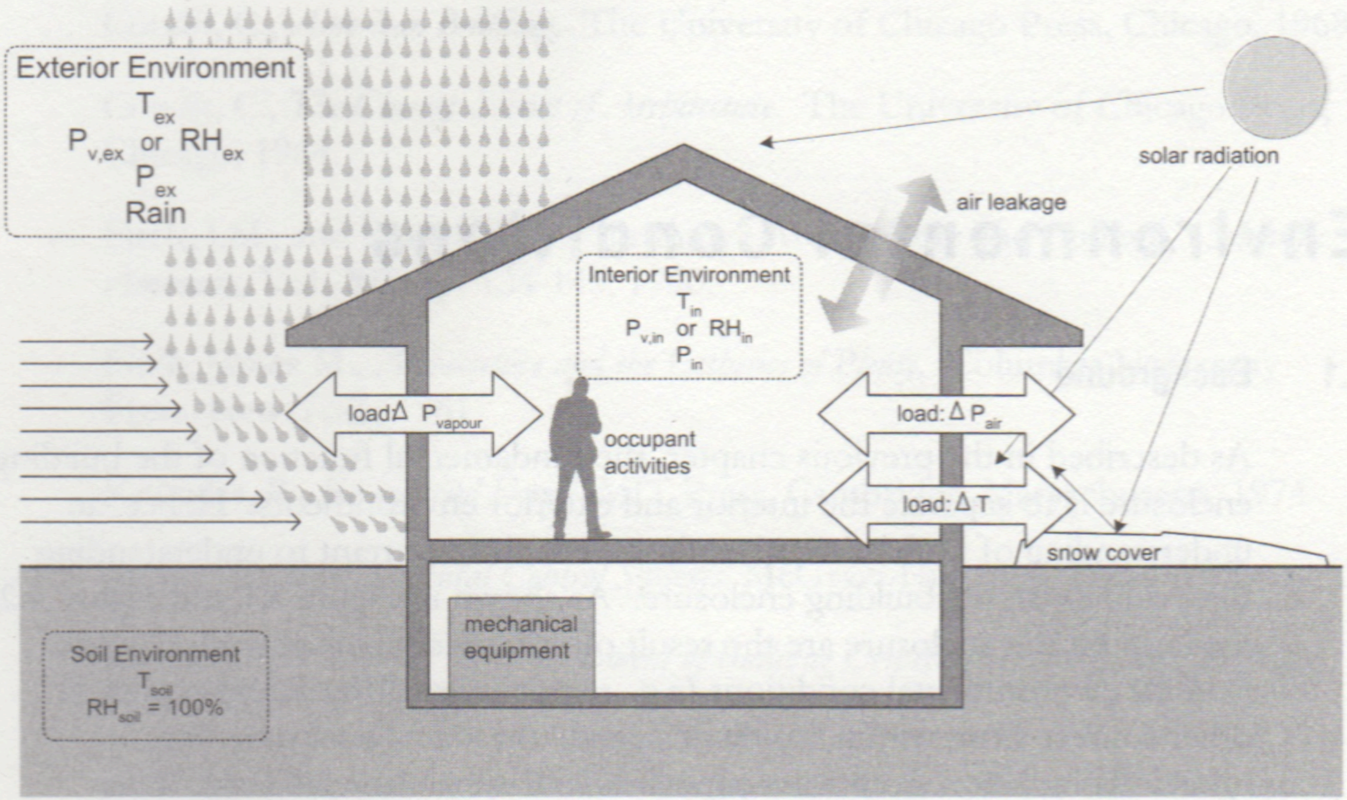


Figure 3.1: Important environmental factors influencing enclosure performance

Important environmental parameters

Temperature
- Absolute
- Relative

Humidity
- Absolute
- Relative

Precipitation
- Rain
- Snow
- Hail, sleet, etc.

Solar insolation
- Infrared
- Visible light
- Ultraviolet radiation

Wind
- Speed
- Direction
- Resulting ΔP

Hygrothermal analysis:
Use basic building physics equations to model energy and moisture transport

Time scales of environmental conditions

- Annual average
- Annual average extreme
- Extreme values
- Seasonal means
- Mean daily maximum
- Mean daily minimum
- Daily mean
- Hourly average
- 15-minute average
- Peak values

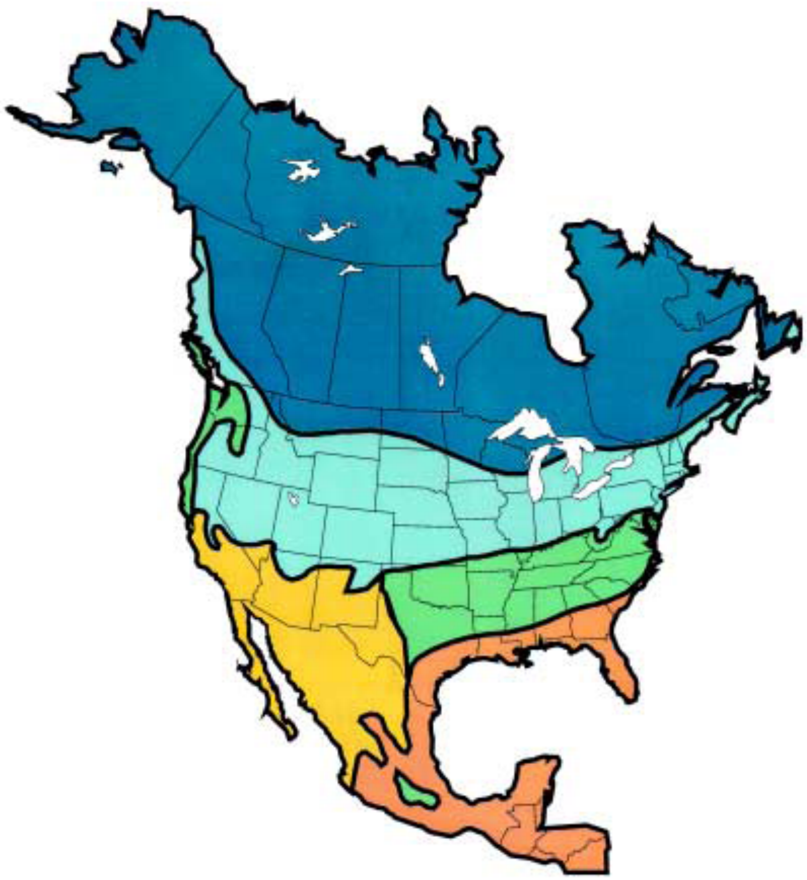
All time scales can be important

Enclosure design and analysis may use more than one time scale

For example:
Peak values are important for HVAC

Annual averages are fine for slow-response situations

Temperature and humidity: climate zones



- Severe Cold
- Cold
- Mixed-Humid
- Hot-Humid
- Hot-Dry/Mixed-Dry

Temperature: Heating- and Cooling-Degree Days

- Annual Degree-Day Method

Heating Degree Days (HDD)

$$HDD = (1\ day) \times \sum_{days} \left(T_{balance} - T_{outdoor} \right) \qquad \text{[K-days]}$$

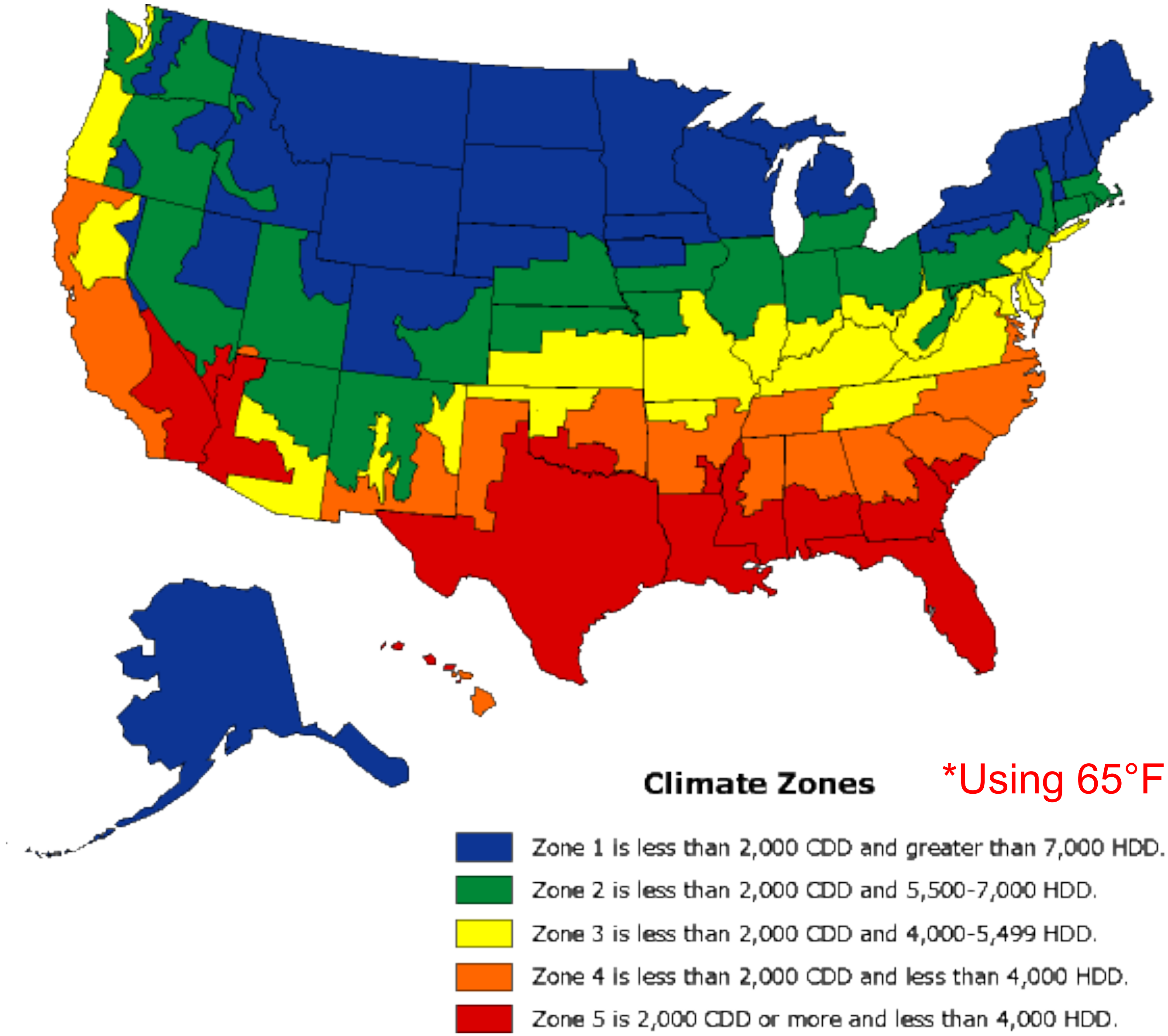
Notes:

- Summed over entire year or entire heating season
- $T_{outdoor}$ = daily average outdoor temperature
- $T_{balance}$ = balance point temperature, or the outdoor temperature at which heating is required (function of specified interior temperature, internal heat gains, and heat loss properties of building)
- Typical $T_{balance}$ = 18.3°C (65°F)

Cooling Degree Days (CDD)

$$CDD = (1\ day) \times \sum_{days} \left(T_{outdoor} - T_{balance} \right) \qquad \text{[K-days]}$$

Department of Energy U.S. temperature zones



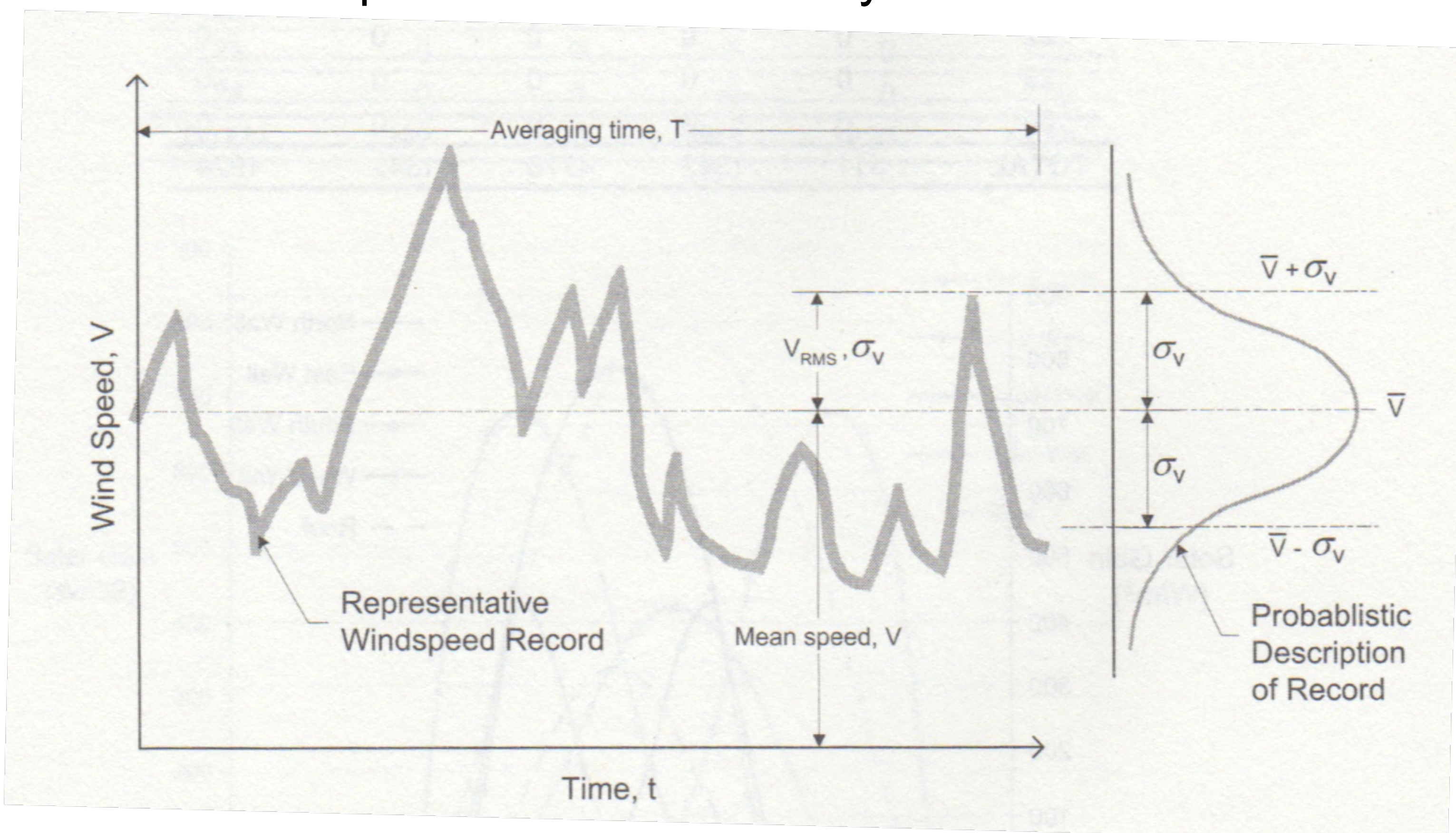
*Using 65°F base

Solar radiation

- The sun is the source of most energy on the earth
- Need to have a working knowledge of earth's relationship to the sun
- Should be able to estimate solar radiation intensity
  - Understand thermal effects of solar radiation and how to control or utilize them
  - Need to estimate solar gains on a building
  - Need to predict intensity of solar radiation and the direction at which it strikes building surfaces
    - Start with relationships between the sun and surfaces on the earth
    - Will cover this next lecture

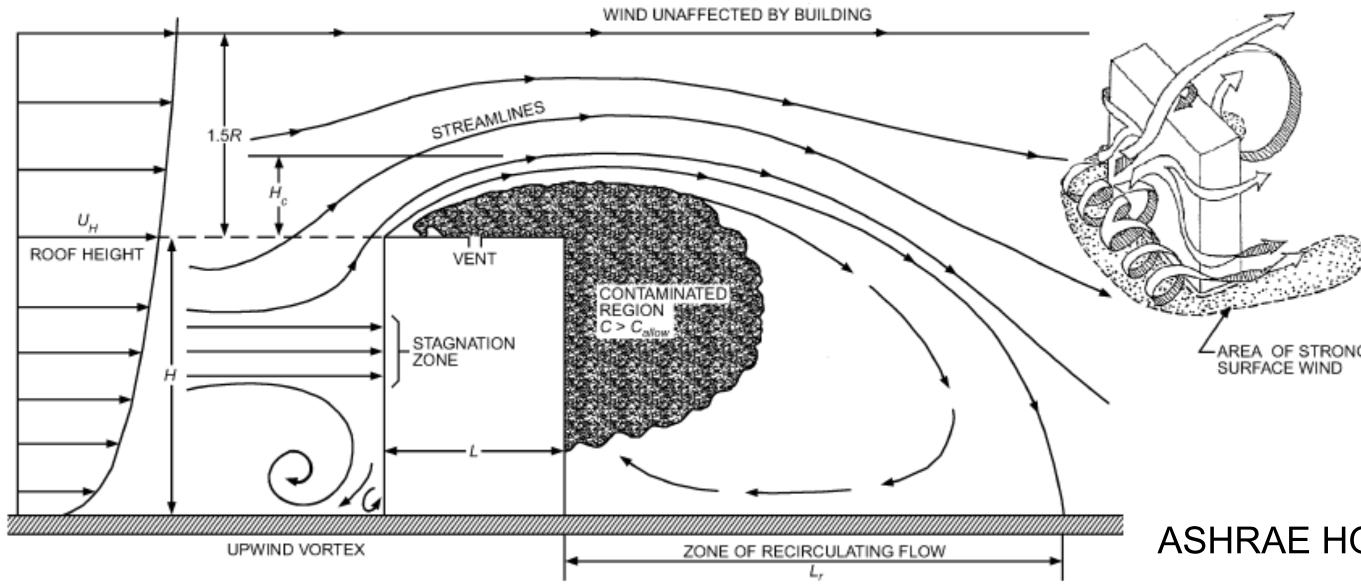
Wind

- Wind speed usually described by an average and probability distribution
  - But speed changes often and quickly enough that sub-one-second velocities are required for detailed analysis



Wind

- Flow patterns are important



ASHRAE HOF

- Wind also induces a pressure on building surfaces
  - Remember Bernoulli?

$$P_{velocity} = \frac{1}{2}\rho_{air}U_h^2$$

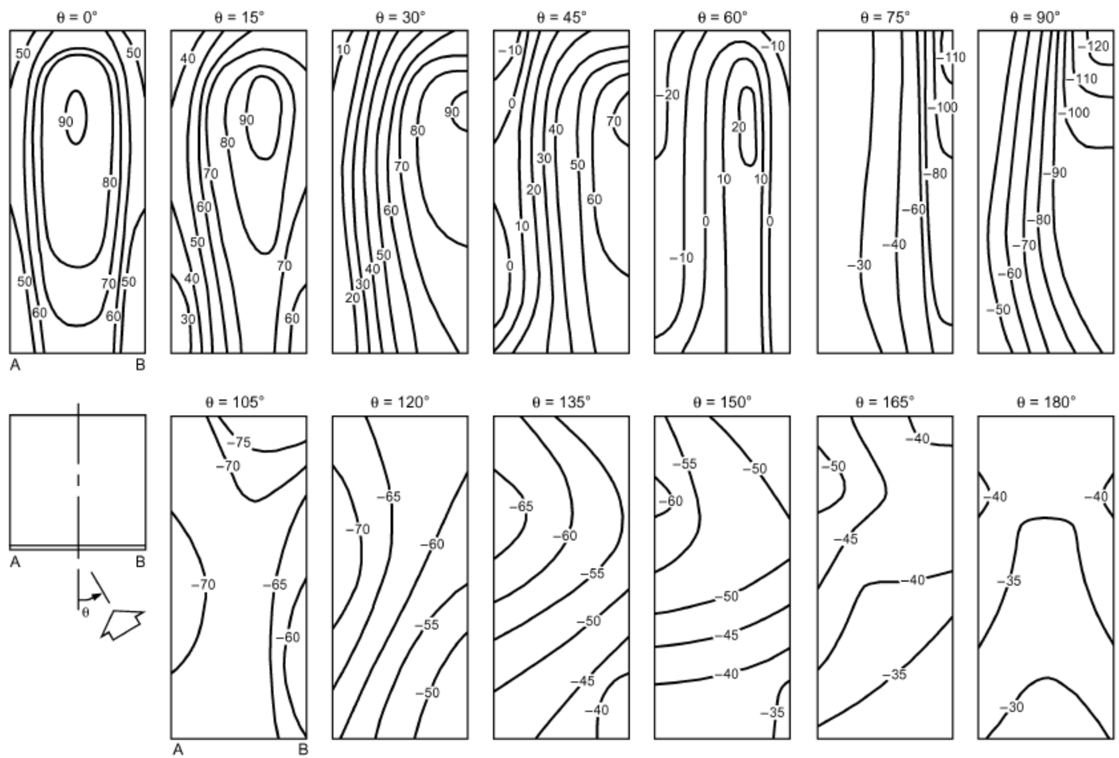
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

Wind pressure coefficients

- Difference between pressure on a building surface and the local outdoor atmospheric pressure at the same height, P_s:

$$P_s = C_p P_{velocity}$$

C_p = local wind pressure coefficient for building surface



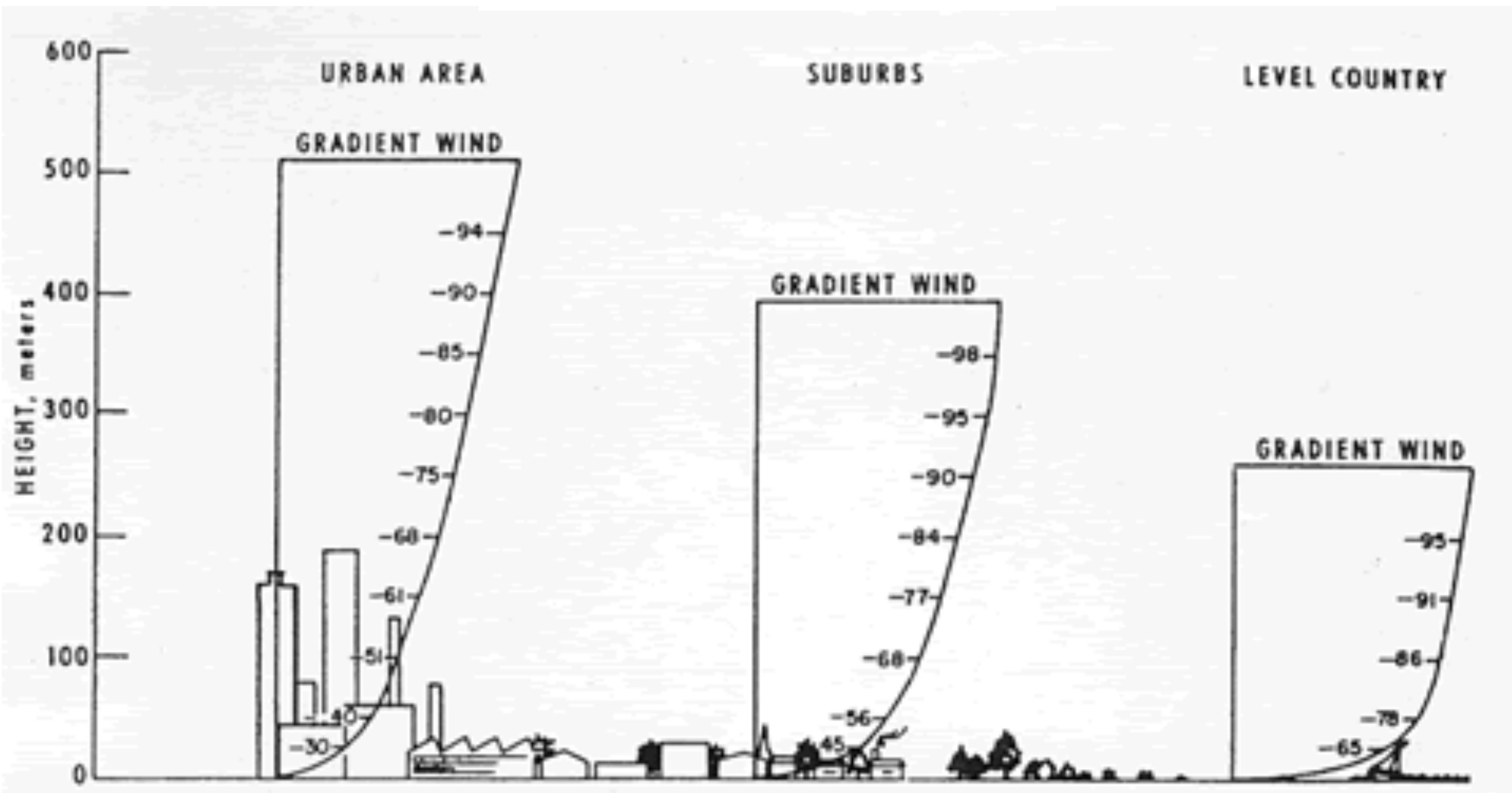
ASHRAE HOF

Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

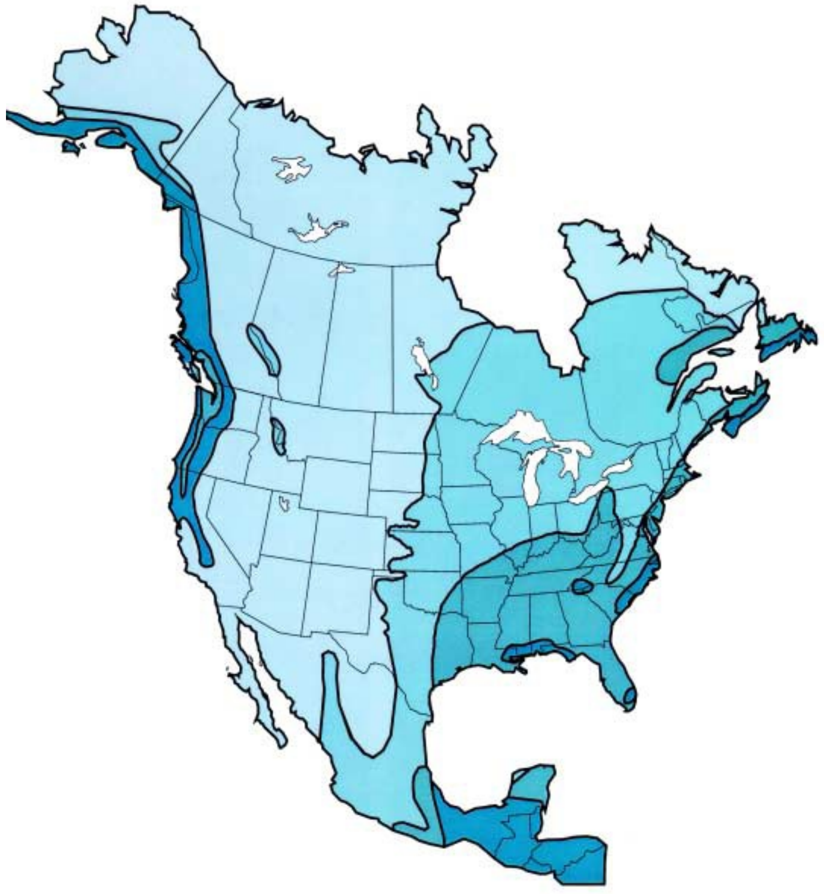
Wind speed gradients

- Local wind speed at height H can be estimated by applying height and terrain corrections (ASHRAE HOF)

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{a}$$



Precipitation: Rain zones



- > 60 in/yr
  Pressure Equalized or Moderated Rain Screens
- 40 – 60 in/yr
  Rain Screen, Vented Cladding or Drainage
- 20-40 in/yr
  Drainage Space
- <20 in/yr
  Face Seal

Review: Important environmental parameters

Temperature
- Absolute
- Relative

Humidity
- Absolute
- Relative

Solar insolation
- Infrared
- Visible light
- Ultraviolet radiation

Wind
- Speed
- Direction
- Resulting ΔP

Precipitation
- Rain
- Snow
- Hail, sleet, etc.

You should become familiar with these parameters

3. HEAT, AIR, AND MOISTURE (HAM) FUNDAMENTALS

Nature of heat, air, and moisture

- States of matter
  - Gas
    - Molecules with high level of kinetic energy
    - Velocity $\propto$ temperature and partial pressure
    - Essentially no resistance to changing shape or volume
  - Liquid
    - Remove sufficient energy from a gas (or compress it sufficiently) and the strength of attraction between molecules will become stronger than kinetic energy of the moving molecules → liquid
    - Little resistance to changing shape; does resist changing volume
  - Solid
    - Removing even more energy slows movement of molecules until intra-molecular forces begin to dominate → solid
    - Resistance to changing shape and volume
  - Plasma
    - Compound stripped of electrons
  - Adsorbed compounds
    - Loosely attached to molecules of liquids or solids

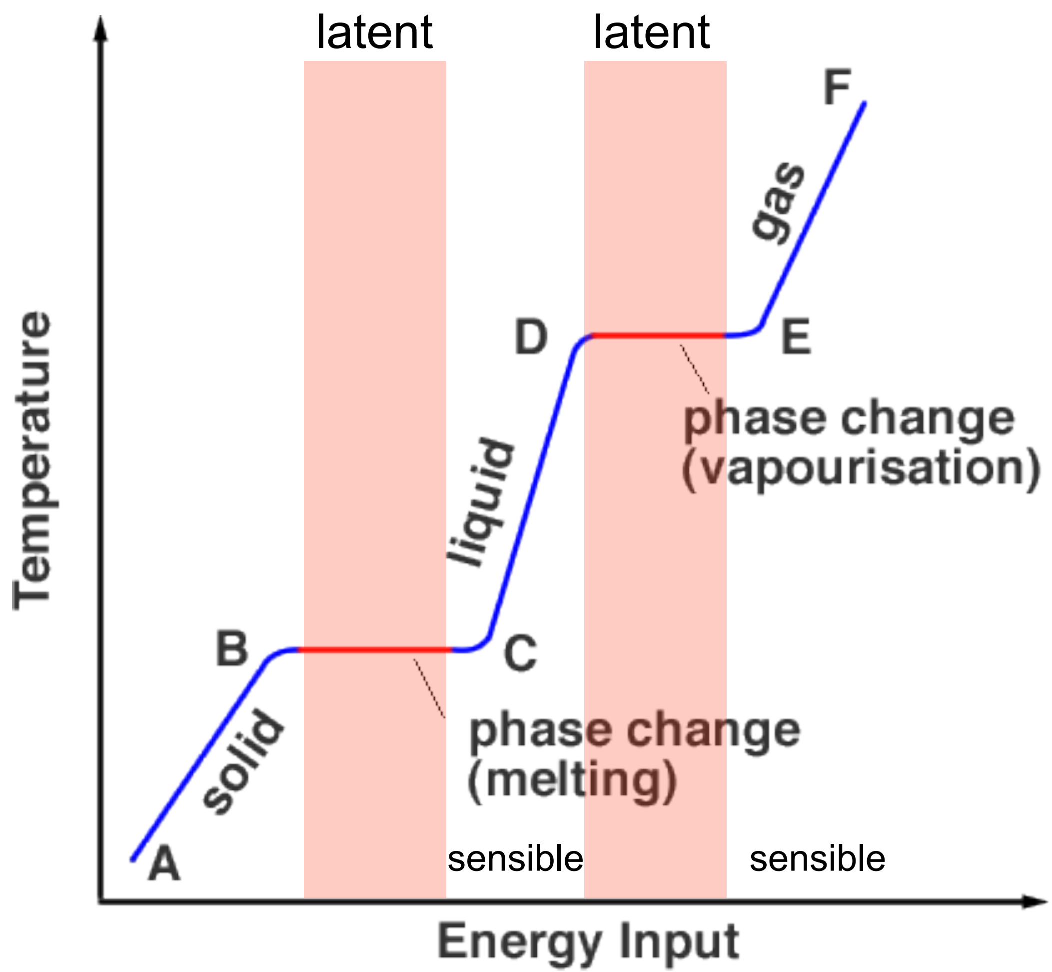
Nature of heat, air, and moisture

Heat and energy basics

- Sensible energy
  - Energy used to increase the velocity or vibrations of molecules
  - i.e., temperature
- Specific heat capacity
  - Sensible energy required to raise a unit mass of material one unit of temperature
- Latent energy
  - The material-specific amount of energy given off (or taken up) during a state change
  - Solid to liquid: heat of fusion
  - Liquid to gas: heat of vaporization

Nature of heat, air, and moisture

Heat and energy basics



Air

- What chemical species are in “clean” dry air?

Species	MW (g/mol)	%
Nitrogen	28	78.09
Oxygen	32	20.95
Argon	40	0.93
Carbon Dioxide	44	0.03

- What about water? Where does it fit in?

Air

- Chemical species in “clean” air:

Species	**MW (g/mol)**	**%**
Nitrogen	28	78.09
Oxygen	32	20.95
Water	18	up to ~4%
Argon	40	0.93
Carbon Dioxide	44	0.03

Does water vapor increase or decrease air density?

Useful air properties

- Density at standard conditions, $\rho = 1.205\ kg/m^3$
- Dynamic (absolute) viscosity, $\mu = 1.81 \times 10^{-4}$ g/cm/s
- Kinematic viscosity, $v = 0.15\ cm^2/s$

Ideal Gas Law

- $pV = nRT$
- R = 8.314 pa m^3 /mol /K
  = 82.05×10^{-6} atm m^3 /mol /K

- Dalton's law of partial pressures

$$\frac{n_i}{n} = \frac{p_i}{p} = Y_i$$

p = pressure
V = volume
n = number of moles
R = gas constant
T = Absolute Temperature
Y = mole fraction

Common mole fraction and mass concentration units

- %, ppm, ppb, ppt
  - Often called concentrations, not strictly correct
- µg/m^3, ng/m^3

$$\rho_{\mathrm{i}} = MW_i \frac{n_i}{V} = MW_i \frac{P}{RT} Y_i$$

$$N_i = \frac{n_i}{V} = \frac{P}{RT} Y_i$$

$$P = \rho R_{\mathrm{specific}} T$$

p = pressure
V = volume
n = number of moles
R = gas constant
R_{specific} = specific gas constant
T = Absolute temperature
MW = molecular weight
Y = mole fraction
N = molar concentration
ρ = mass concentration

Role of water in air

- Relative humidity (RH) = $P_w/P_{w,s}(T)$
- Where can you get $P_{w,s}$?

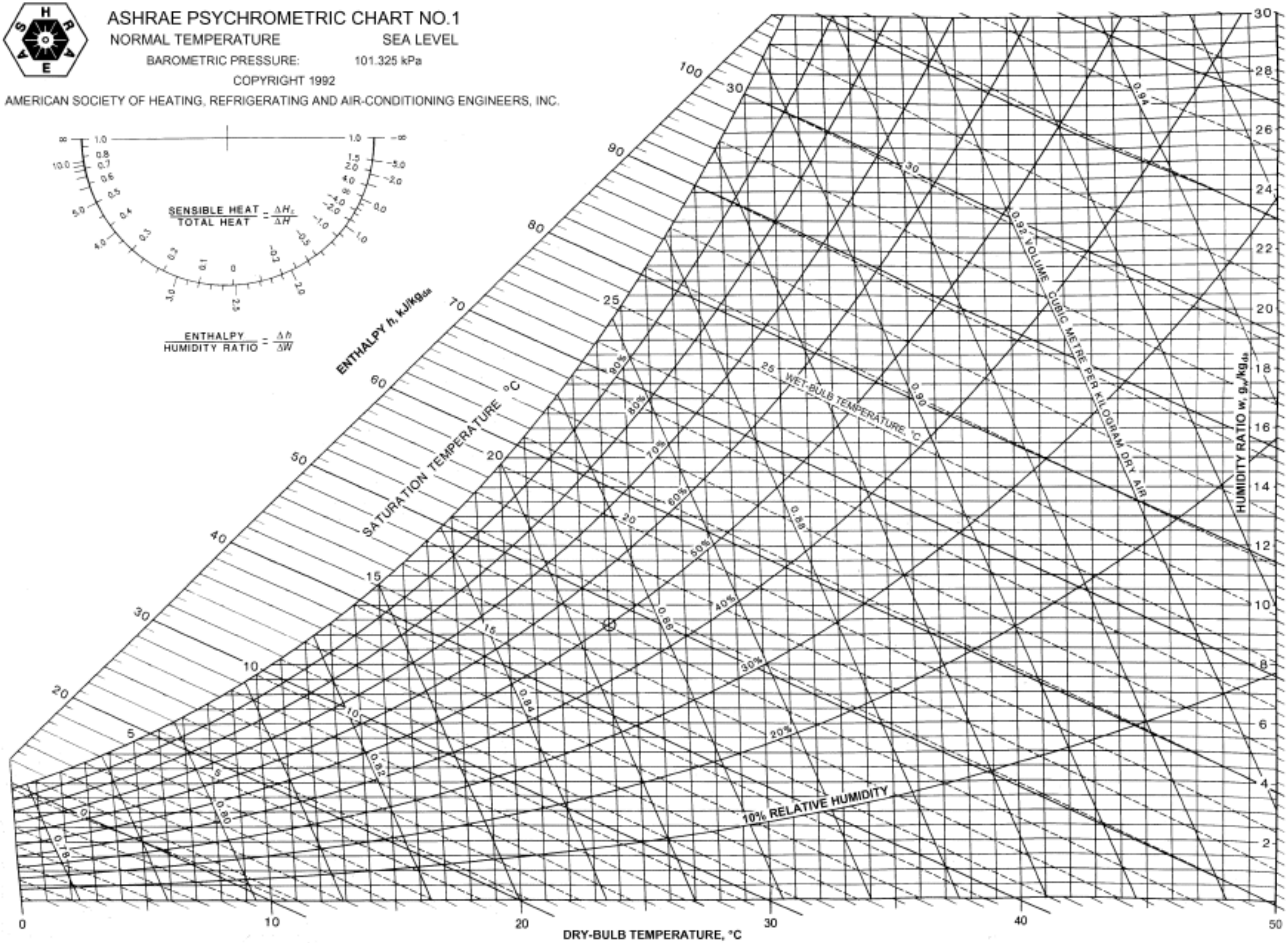
$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where

C_8 = –5.800 220 6 E+03
C_9 = 1.391 499 3 E+00
C_{10} = –4.864 023 9 E–02
C_{11} = 4.176 476 8 E–05
C_{12} = –1.445 209 3 E–08
C_{13} = 6.545 967 3 E+00

p_{ws} = saturation pressure, Pa
T = absolute temperature, K = °C + 273.15

ASHRAE HoF: equation or chart


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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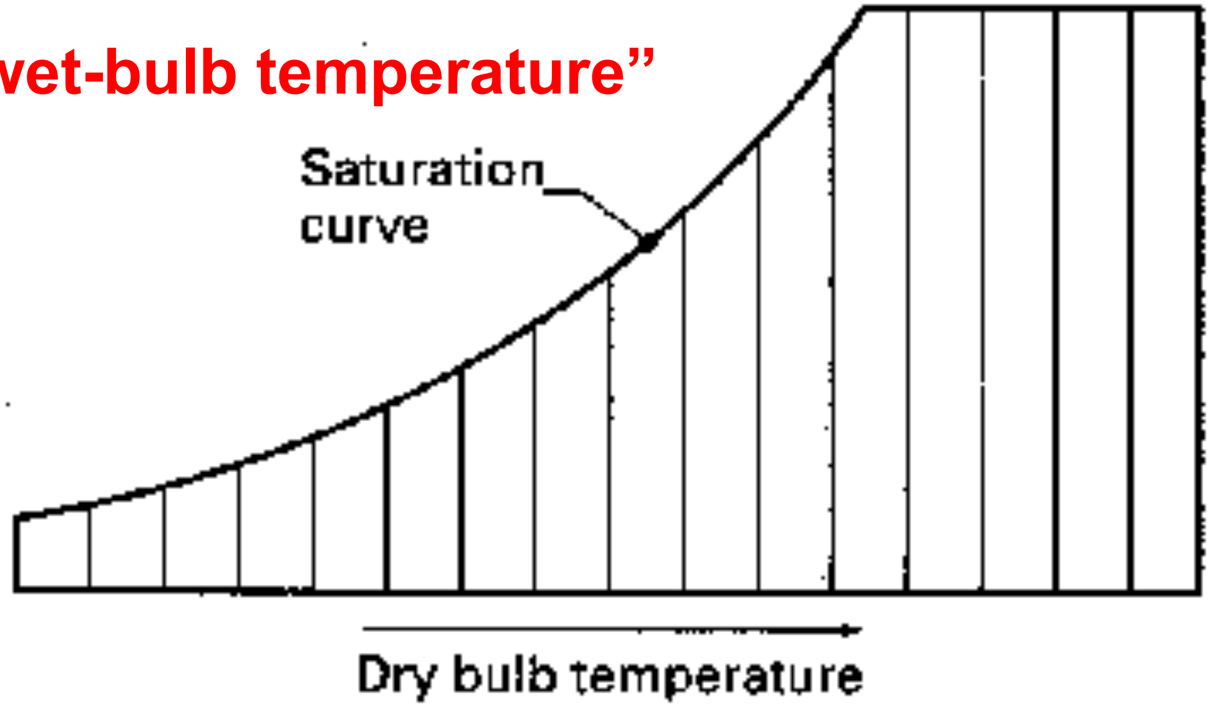
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
20%
30%
40%
50%
60%
70%
80%
90%
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
DRY-BULB TEMPERATURE, °C
0
10
20
30
40
50

Psychrometric chart

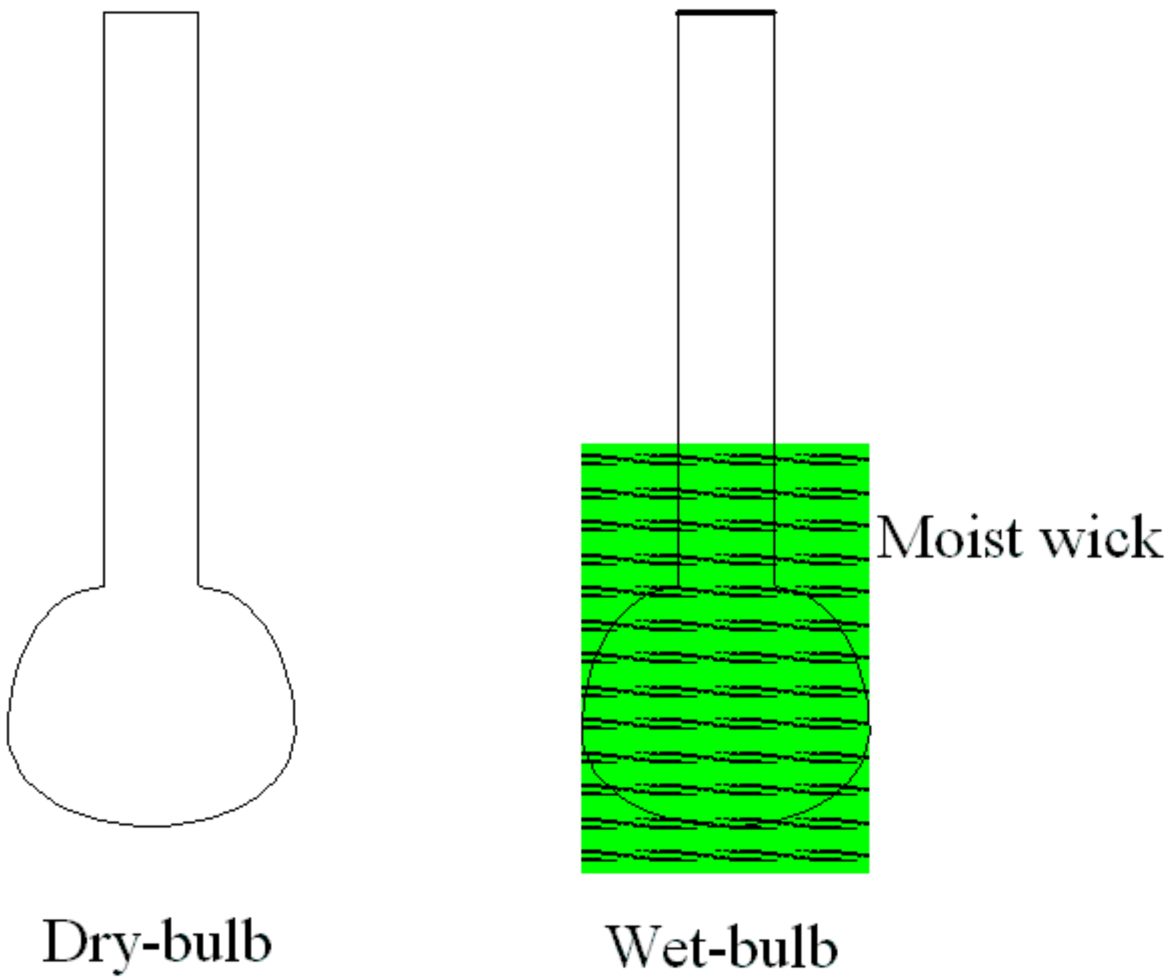
- Need two quantities for a state point
  - Can get all other quantities from a state point
- Can do all calculations without a chart
  - Often require iteration
  - Many "digital" psychrometric charts available
    - Can make your own
  - Best source is *ASHRAE Fundamentals* (Chapter 6)
    - SI version is on Blackboard

i.e., “wet-bulb temperature”



Which temperature do you expect to be higher?

A. Wet-bulb
B. Dry-bulb

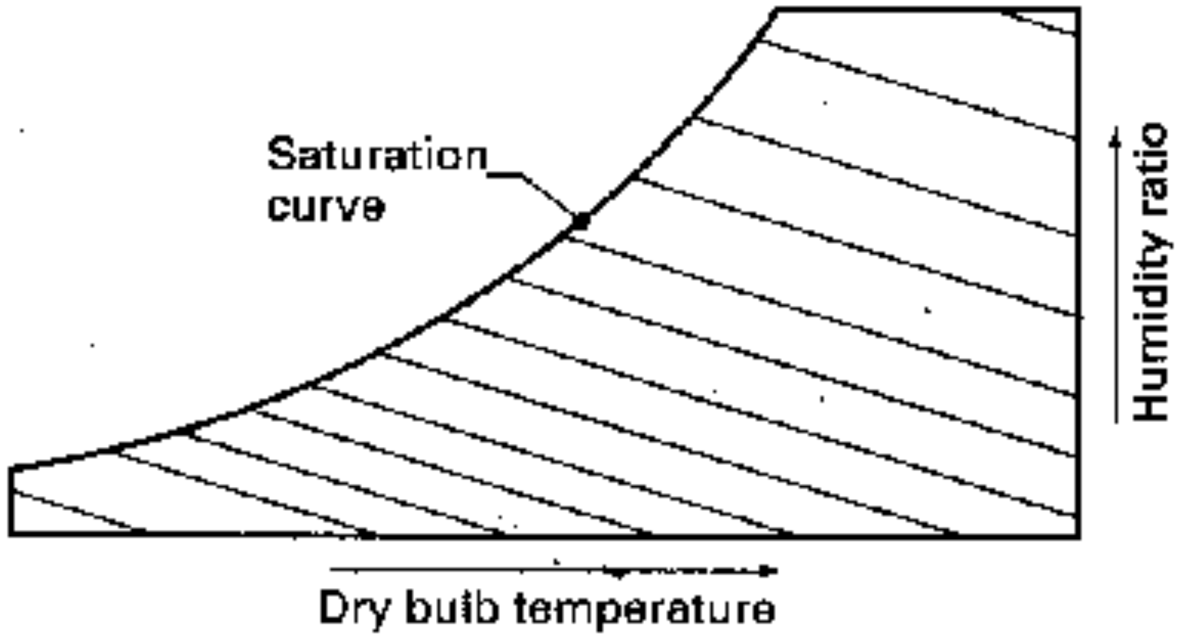


Wet-bulb temperature (t^*)

- Temperature measured by a psychrometer
- Lower than dry-bulb temperature
  - Evaporating moisture removes heat from thermometer bulb
  - Wet-bulb temperature is the minimum temperature which may be achieved by purely evaporative cooling of a wetted surface
  - The higher the humidity
    - Smaller difference between wet-bulb and dry-bulb temperature
  - Requires iterative solution to actually calculate
    - Find the t^* that satisfies this equation:

$$\boxed{W = \frac{(2501 - 2.326t^*)W_s^* - 1.006(t - t^*)}{2501 + 1.86t - 4.186t^*}}$$

    - Can also use psych chart



Lines of constant wet bulb

Dew-Point Temperature, t_d

- Given a sample of air with a **known absolute humidity**
  - t_d is defined as temperature of that air at saturation
    - i.e. RH = 100%
  - AKA saturation temperature
- Surfaces below the dew point temperature will have condensation

Between dew points of 0 and 93°C,

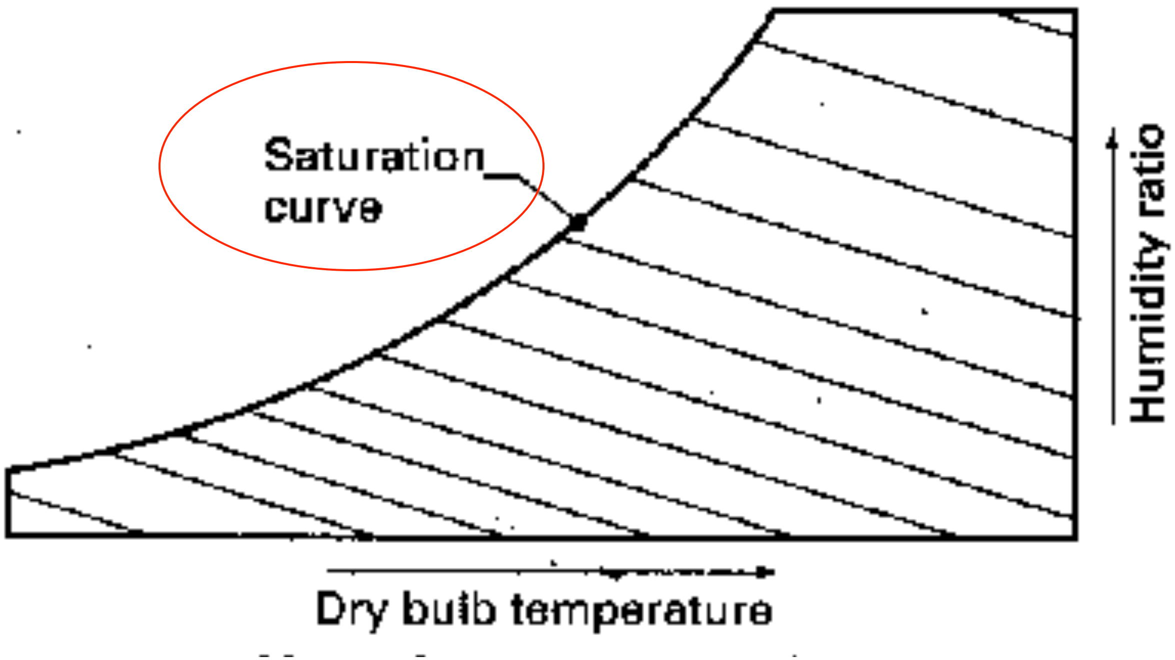
$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984}$$

Below 0°C,

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2$$

where

t_d = dew-point temperature, °C
$\alpha = \ln p_w$
p_w = water vapor partial pressure, kPa
$C_{14} = 6.54$
$C_{15} = 14.526$
$C_{16} = 0.7389$
$C_{17} = 0.09486$
$C_{18} = 0.4569$



Saturation curve
Humidity ratio
Dry bulb temperature

Moisture question

If you have a sample of air at its dew-point (AKA saturation) temperature?

A. The water will condense out.
B. It will be pure water vapor.
C. Putting the sample in a sealed container and heating it will cause condensation.
D. Putting the sample in sealed container and cooling it will cause condensation.

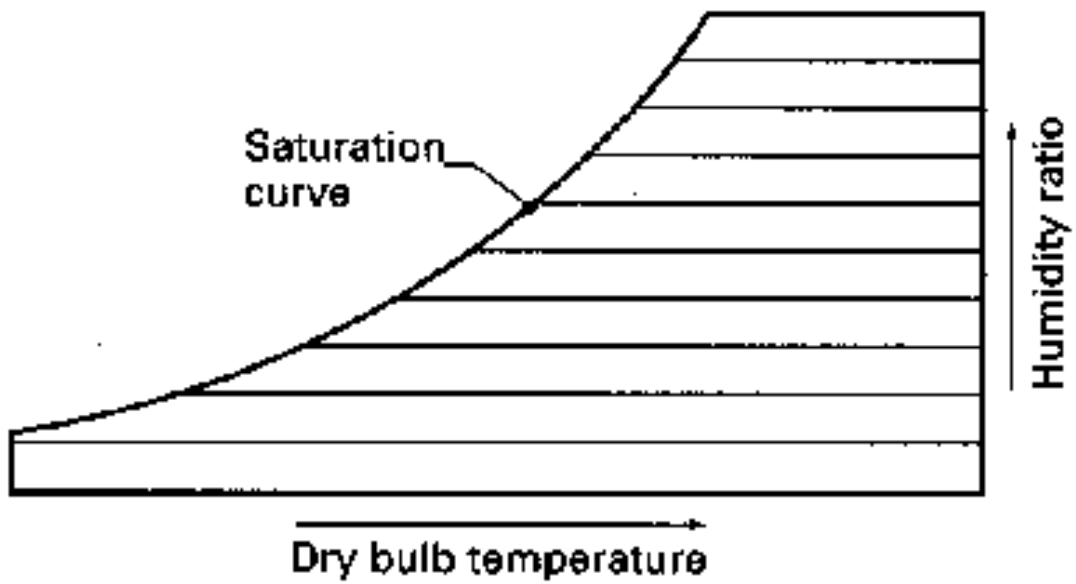
Humidity

- Humidity ratio (*W*) [lb/lb, g/kg, grains]
- Relative humidity (*RH*, ϕ) [%]
  - Fraction of saturation

Humidity Ratio, *W*

- Mass of water vapor/divided by mass of dry air
- Orthogonal to temperature
  - Not a function of temperature
- Most convenient form for calculations involving airflow
- Very hard to measure directly

$$\boxed{W = 0.62198 \frac{p_w}{p - p_w}}$$

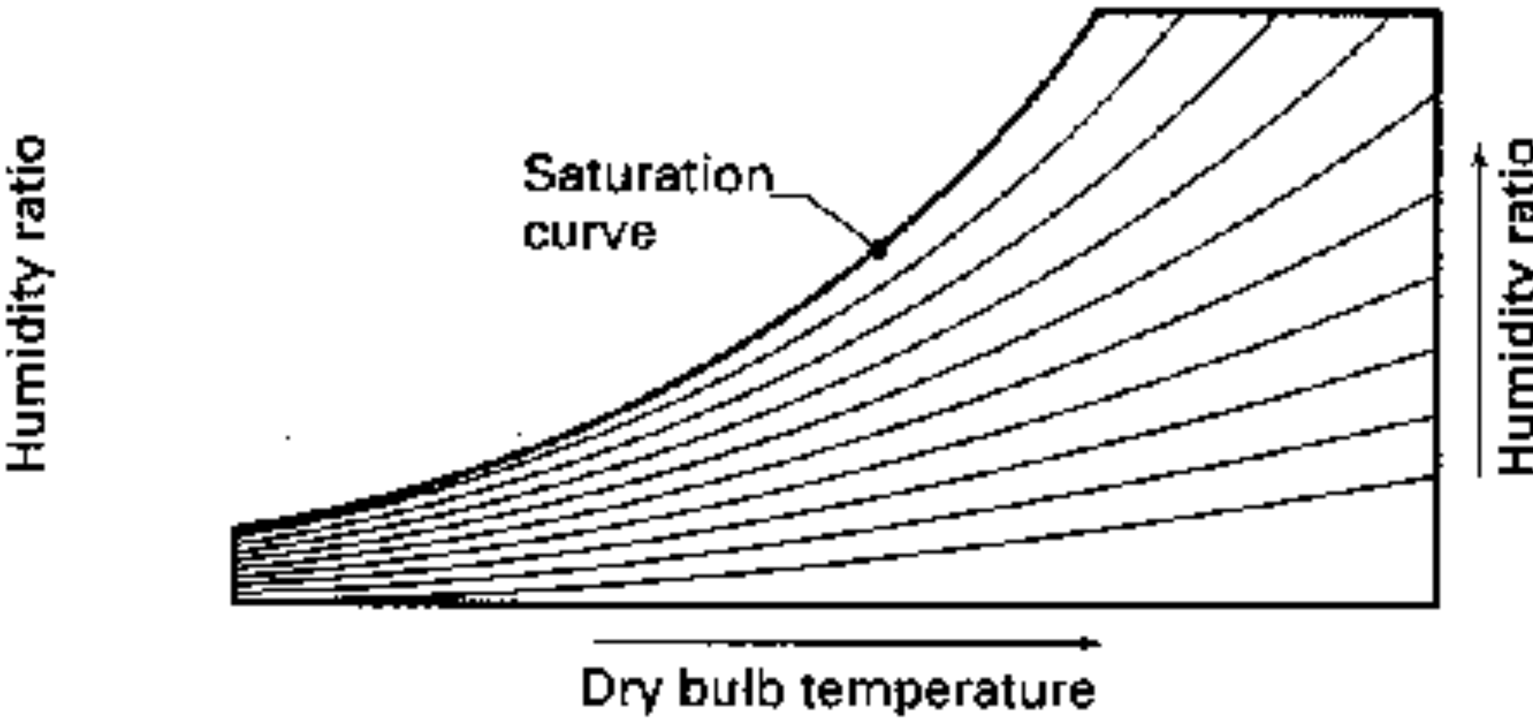


Lines of constant absolute humidity

Relative Humidity, *RH* or ϕ

- Ratio of partial pressure of water vapor to partial pressure of water vapor at same T and P at saturation
- Strong function of temperature
  - For constant humidity ratio
    - Higher temperature, lower relative humidity

$$\boxed{\phi = \left.\frac{p_w}{p_{ws}}\right|_{t,\,p}}$$



Lines of constant relative humidity

Relative Humidity

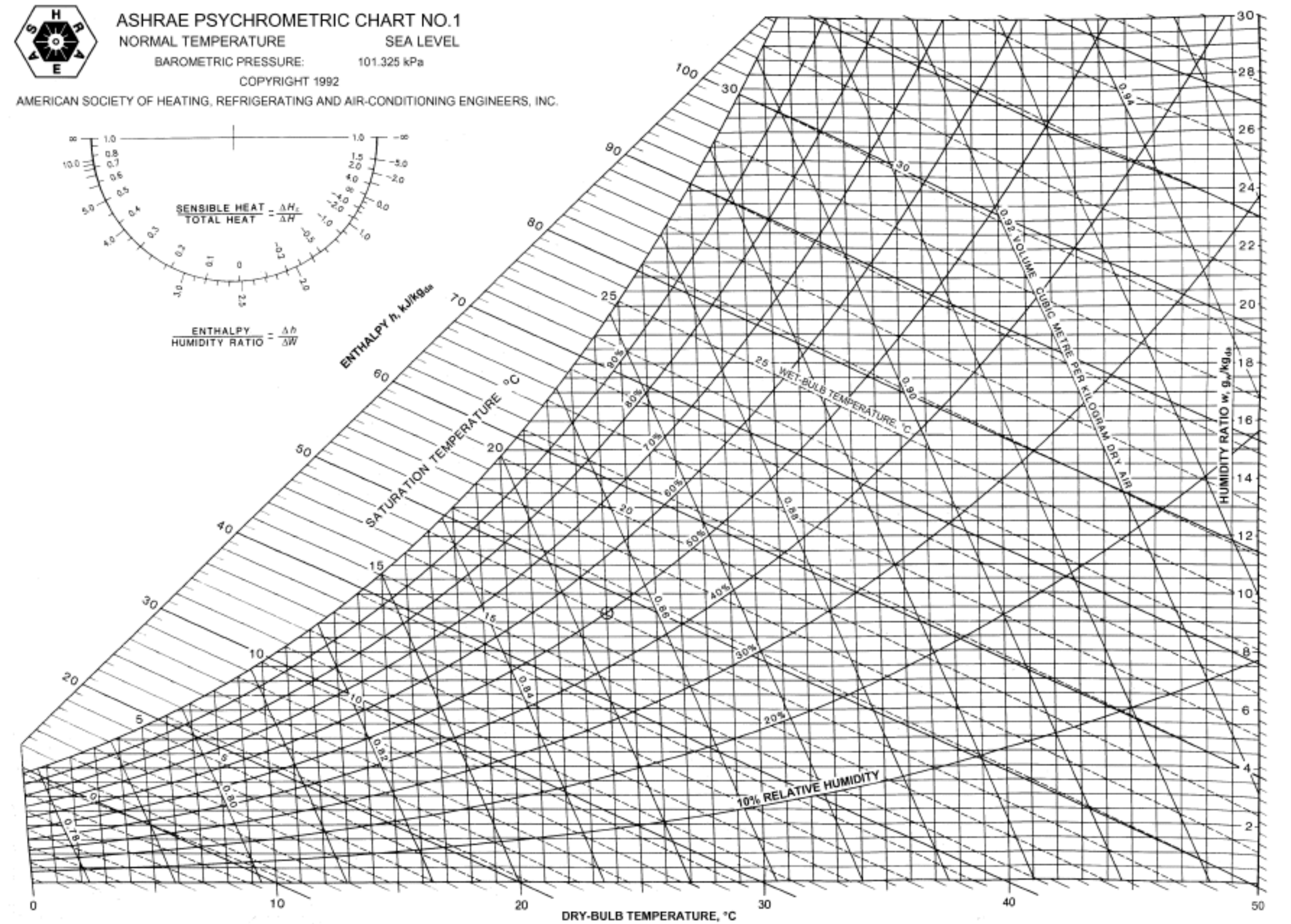
- Driving force for moisture transport
  - Human comfort
  - Moisture absorption/desorption
- Can be measured with
  - Resistive sensors
  - Capacitive sensors
  - Horse hair

Enthalpy, *h or H*

- Enthalpy (from Psychrometric chart) =
  - Total energy in air [J/kg, BTU/lb]
  - Sensible + latent
  - Very valuable for calculations

$$\boxed{h = 1.006t + W(2501 + 1.86t)}$$

- Sensible
  - Energy associated with temperature change
- Latent
  - Energy associated with moisture change
  - Often more important than sensible


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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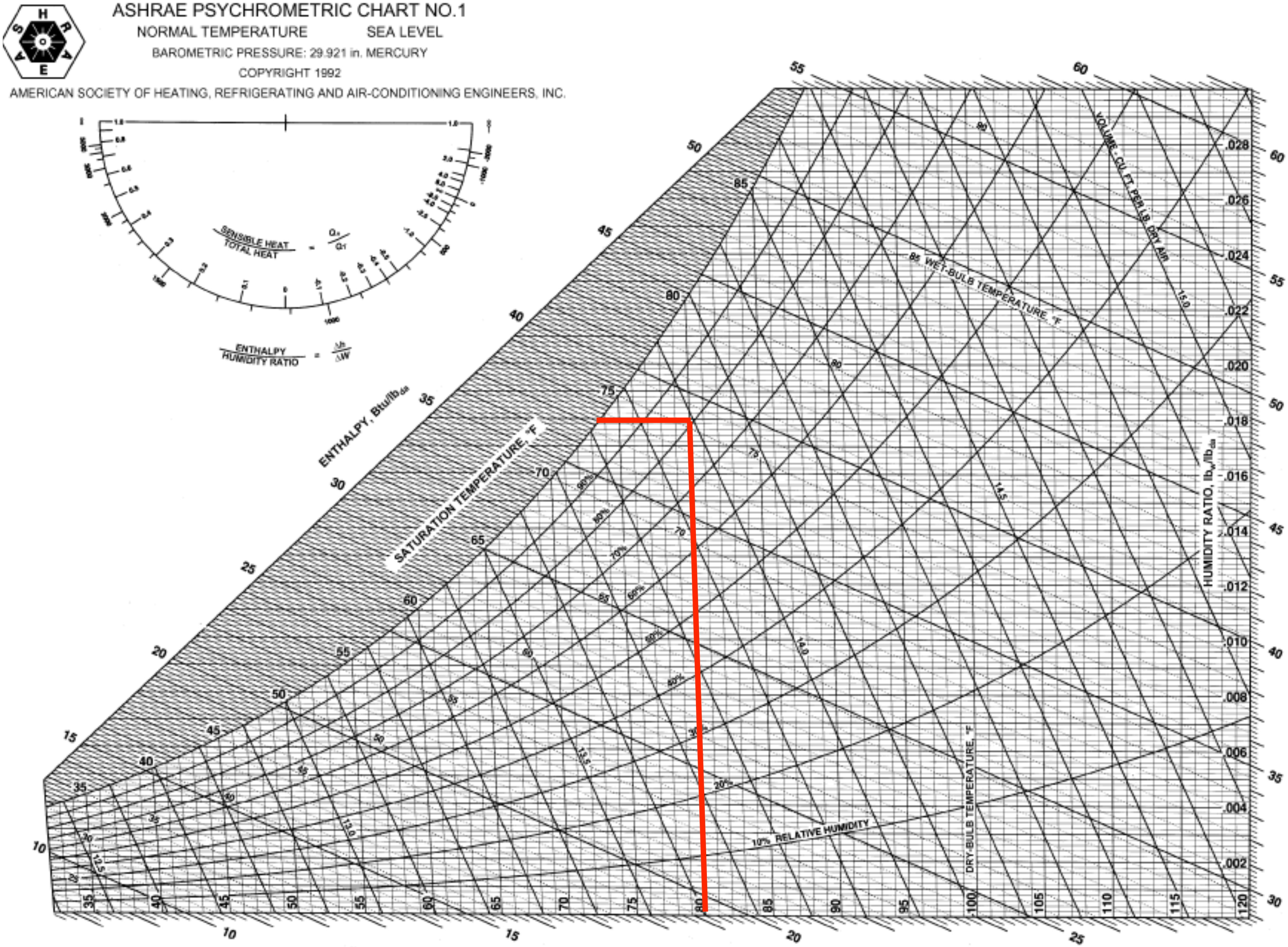
SENSIBLE HEAT / TOTAL HEAT = $\Delta H_s / \Delta H$
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
ENTHALPY h, kJ/kg$_{da}$
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO W, g$_w$/kg$_{da}$
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C

Psychrometric Charts

1. Make sure chart is appropriate for your environment
2. Figure out what two quantities you know
3. Understand their slopes on the chart
4. Find the intersection
   - Watch for saturation

Example

- Condensation on windows when taking a shower
  - How cold does it have to be outside for condensation to form on windows?
    - Assumption: windows are the same temperature as outside air
    - Indoor conditions: 80°F, RH = 80%


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 29.921 in. MERCURY
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SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb w/lb da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F

Helpful equations

ASHRAE HOF has more equations and explanations

*Some of the HOF equations are different (use ASHRAE when in doubt)

Table 4.2: Summary of approximate psychrometric equations

Property	Equation	Eqn #
Partial water vapor pressure	$P_w = \frac{w \cdot R_{wv} \cdot T}{V}$ [consistent units]	4.20
Density of dry air	$\rho = \frac{351.99}{T} + \frac{344.84}{T^2}$ [kg/m³ ,K]	4.23
Dewpoint temperature	$t_d = \frac{4030}{18.689 - \ln(\frac{Pw}{133})} - 235$ [°C, Pa]	4.19
Saturation vapor pressure	$P_{ws} = 1000 \cdot e^{\left(52.58 - \frac{6790.5}{T} - 5.028 \cdot \ln T\right)}$ [K, Pa]	4.16
Saturation vapor pressure	$P_{ws} = 611.2 \cdot e^{\left(\frac{17.67 \cdot t}{t + 243.5}\right)}$ [°C, Pa]	4.24
Relative humidity	$\phi = RH = \frac{W_w}{W_{ws}} = \frac{P_w}{P_{ws}}$ [consistent units]	4.17
Humidity ratio	$W_w = \frac{0.622 \cdot P_w}{P_t - P_w}$ [kg/kg, Pa]	4.21
Heat capacity of dry air	$c_p = 1030 - 0.2 \cdot T + 0.0004 \cdot T^2$ [J/kg·K, K]	4.25
Enthalpy	$h = 1.006\, t + W \cdot (2501 + 1.805\, t)$ [J/g]	4.26

Helpful relationships

Table 4.3: Saturated (100%RH) air properties from -40 °C to 60 °C[1]

Temperature [°C]	Dry Density [kg/m^3]	Saturation Vapor Pressure [Pa]	Saturation Humidity Ratio [g/kg]	Saturation Humidity Ratio [g/m^3]
-40	1.52	13	0.08	0.12
-35	1.48	22	0.14	0.20
-30	1.45	38	0.23	0.34
-25	1.42	63	0.39	0.55
-20	1.40	103	0.63	0.88
-15	1.37	193	1.18	1.62
-10	1.34	288	1.78	2.37
-5	1.32	424	2.62	3.43
0	1.29	615	3.80	4.88
5	1.27	877	5.43	6.83
10	1.25	1235	7.67	9.45
15	1.23	1714	10.70	12.89
20	1.20	2350	14.77	17.37
25	1.18	3182	20.17	23.13
30	1.16	4262	27.31	30.46
35	1.15	5645	36.70	39.70
40	1.13	7402	49.02	51.21
45	1.11	9610	65.18	65.45
50	1.09	12362	86.43	82.89
55	1.08	15760	114.6	104.1
60	1.06	19930	152.3	129.6

[1] Source: ASHRAE *Handbook of Fundamentals*, 2001

Helpful constants (specific)

Gas constant for dry air

$$R_{da} = 8314.41/28.9645 = 287.055\ \mathrm{J/(kg_{da} \cdot K)}$$

$MW_{dry\ air}$

Gas constant for water vapor

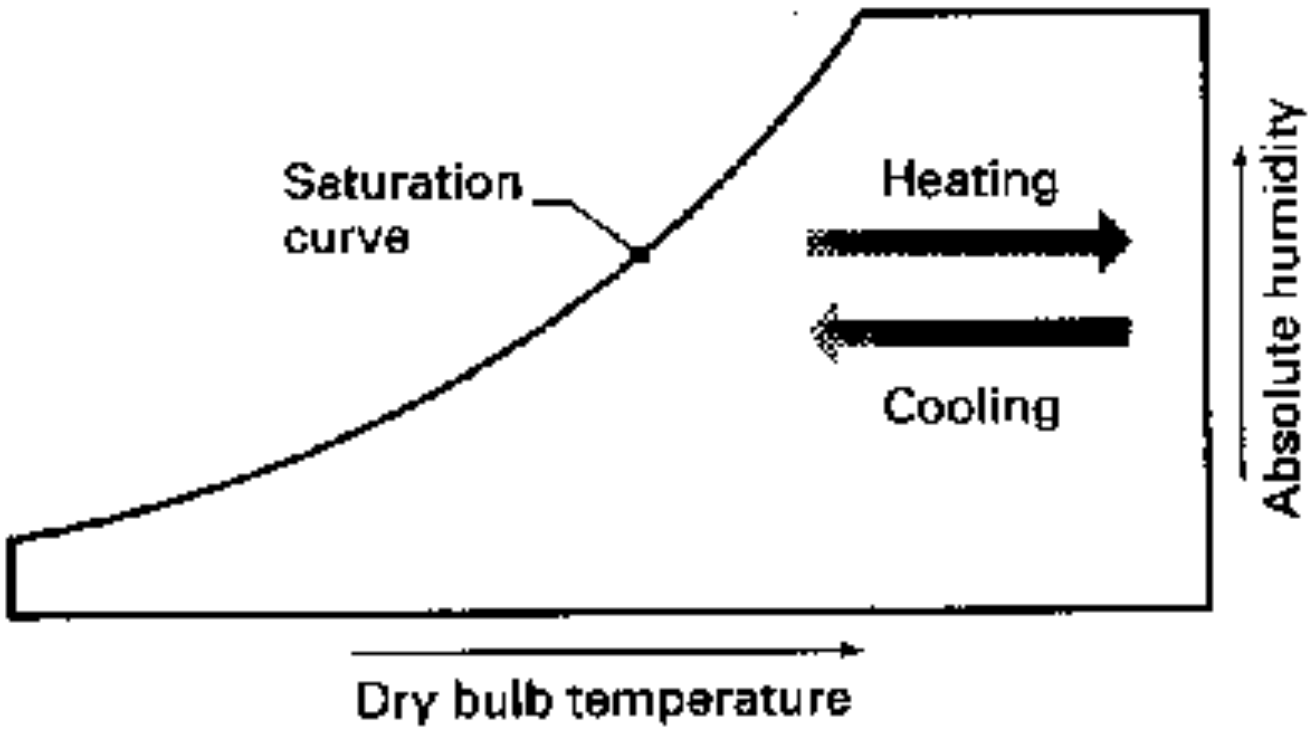
$$R_w = 8314.41/18.015\ 28 = 461.520\ \mathrm{J/(kg_w \cdot K)}$$

$MW_{water\ vapor}$

More examples

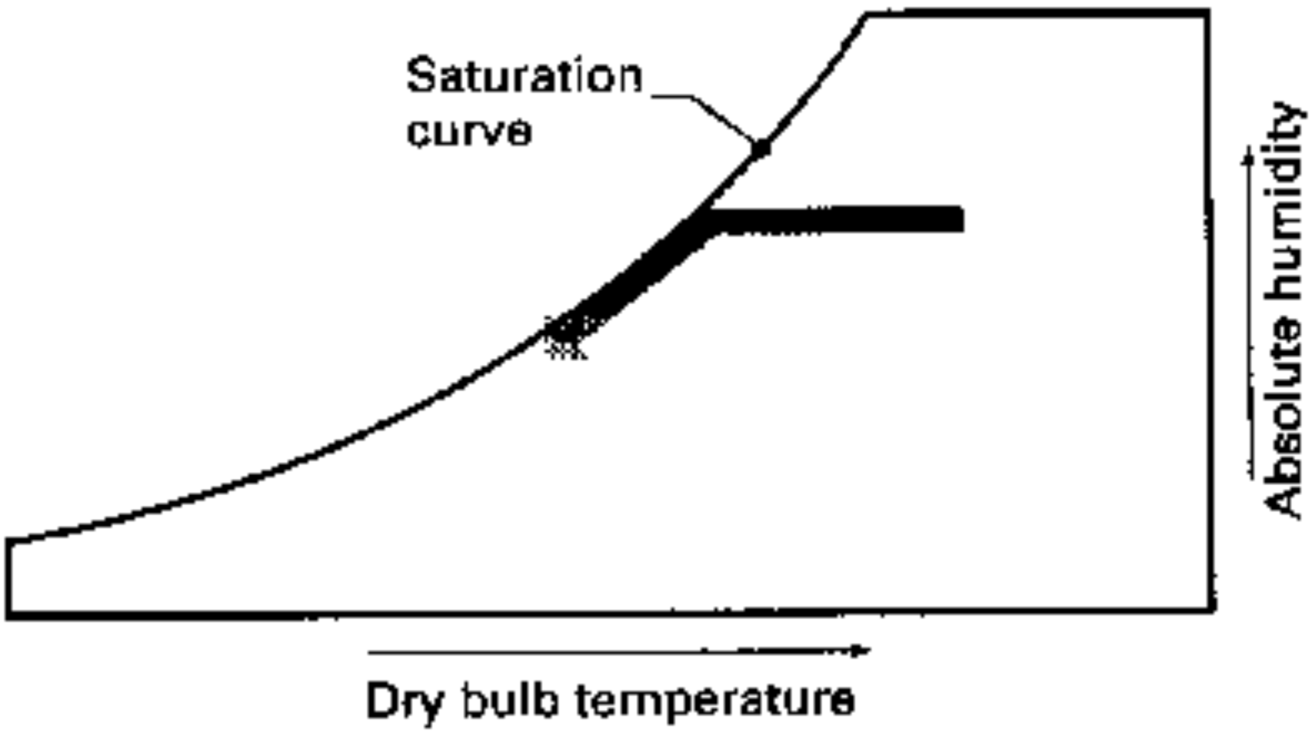
- Identifying points on psychrometric chart
  - Moist air at 25 °C dry-bulb temperature and 60% relative humidity at atmospheric pressure. Determine:
    - humidity ratio
    - dew-point temperature
    - wet-bulb temperature
    - enthalpy
- Calculating density of moist air
  - Calculate density of air at 20°C and 75% RH
    - Density of moist air = density of dry air + density of water vapor

Some useful processes



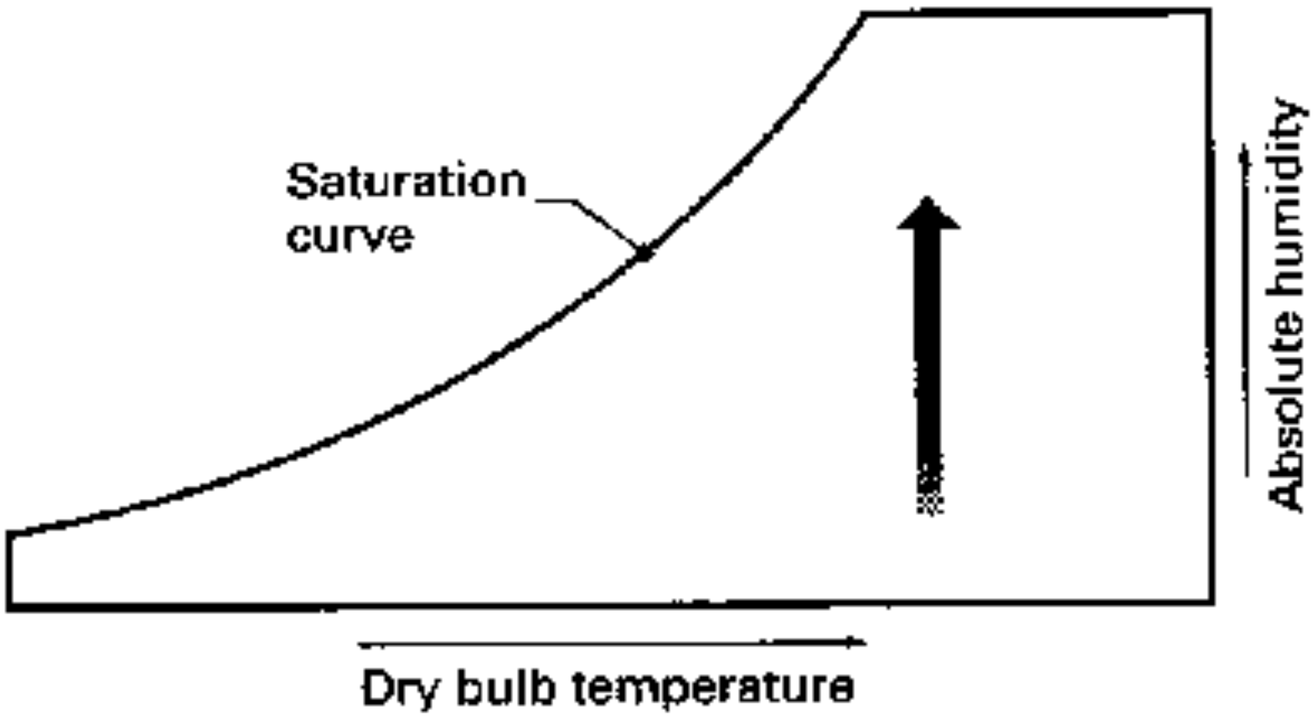
Sensible heating and cooling

Other useful processes



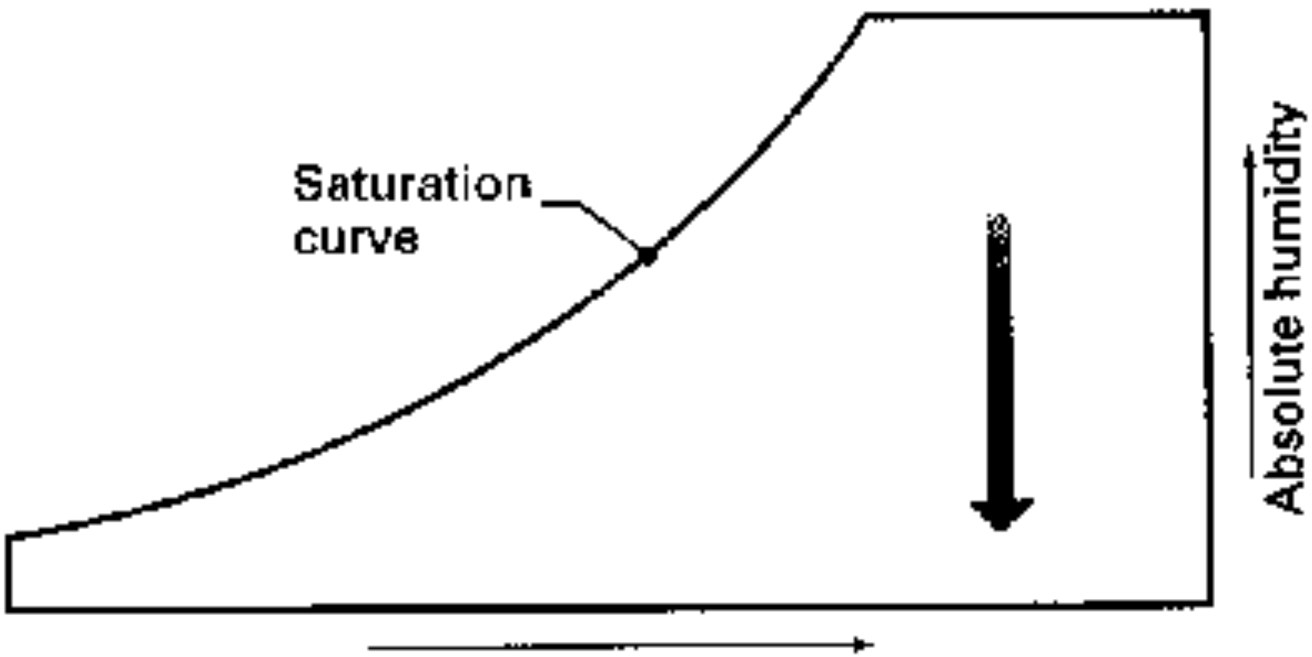
Dehumidification by cooling

Other useful processes



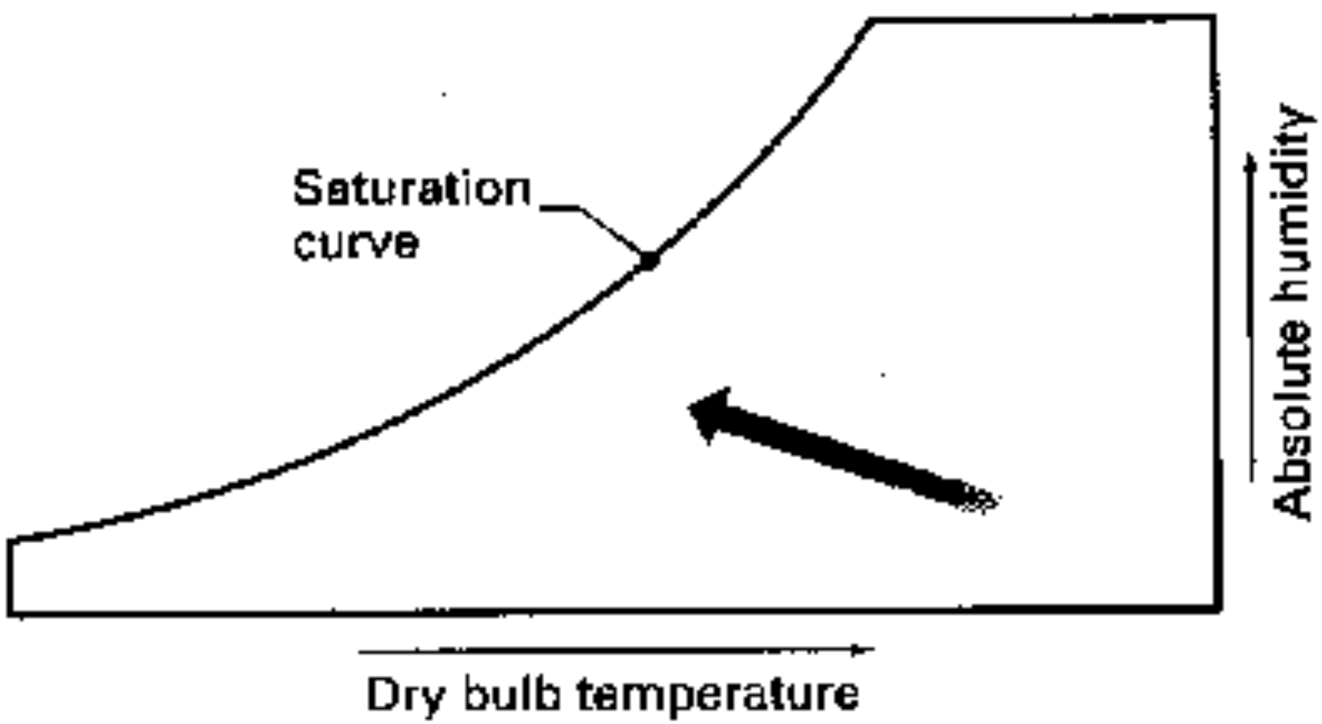
Humidification with steam

Other useful processes



Dehumidification by absorption

Other useful processes



Humidification by evaporative cooling

HW for next time

- Upload to Blackboard tonight
  – Some basic concepts and psychrometric calculations
- Due beginning of next class
  – August 27, 2012 6:25 PM
  – Bring it to class or just email me a PDF
    - Scanned or typed are both fine

Next lecture

- Heat transfer in building enclosures
  - Start with solar orientation
  - Then conduction, convection, radiation
- Suggested reading
  - Straube Ch. 4 and Ch. 5
  - Lstiburek 2012 *ASHRAE Journal* article
- Note that I had also suggested reading Lstiburek's 2004 article "Built wrong from the start" for today's lecture, as well as some chapters from Straube
  - Won't be tested on it; just useful information