CAE 463/524
Building Enclosure Design
Spring 2016

Week 1: January 12, 2016
Introduction to building enclosure design

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Advancing energy, environmental, and sustainability research within the built environment

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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
- Begin review of heat, air, and moisture (HAM) fundamentals

About me

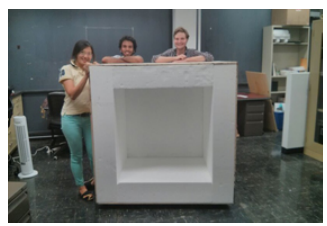
- B.S.E., Civil Engineering
  - Tennessee Tech University, 2007
- M.S.E., Environmental Engineering
  - The University of Texas at Austin, 2009
    - Thesis: “Energy implications of filtration in residential and light-commercial buildings”
- Ph.D., Civil Engineering
  - The University of Texas at Austin, 2012
    - 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”
- Work experience relevant to this course
  - NSF IGERT Fellow in Indoor Environmental Science in Engineering
  - Energy intern at Southface Energy Institute in Atlanta, GA

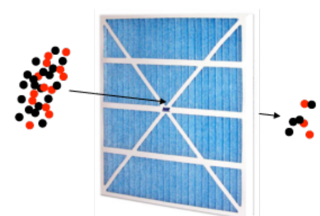
BERG: Built Environment Research Group

The **Built Environment Research Group** at IIT is dedicated to investigating problems and solutions related to energy and air quality within the built environment

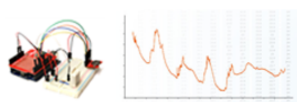
Read more online: http://built-envi.com

Built Environment Research @ IIT





OSBSS



Advancing energy, environmental, and sustainability research within the built environment

IIT Armour College of Engineering
ILLINOIS INSTITUTE OF TECHNOLOGY

Course information

CAE 463/524: Building Enclosure Design

Course Unique Number(s)
- CAE 463 Section 1: 26562 (undergraduate)
- CAE 463 Section 2: 26563 (undergraduate online)
- CAE 524 Section 1: 26766 (graduate)
- CAE 524 Section 2: 26767 (graduate online)

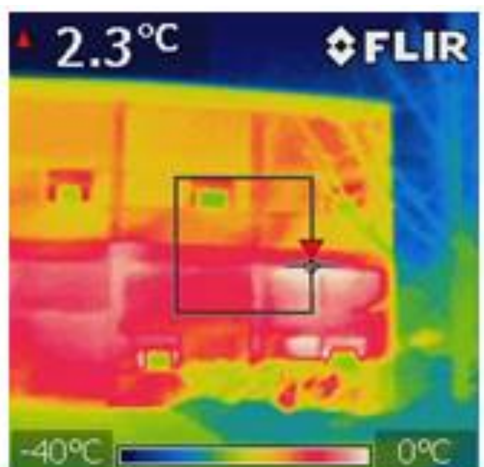
Classroom and Meeting Time
- Wishnick Hall, Room 115
- Tuesdays 5:00 PM –7:40 PM

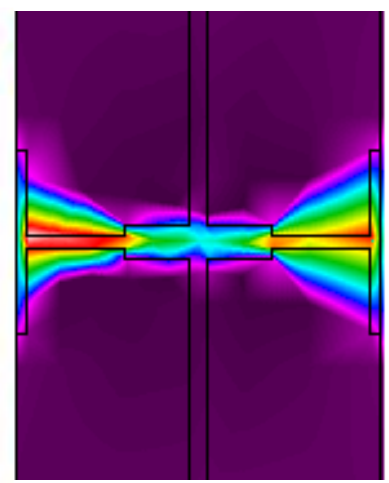
Prerequisites
- CAE 331/513 Building Science (some flexibility on this for 524)

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.





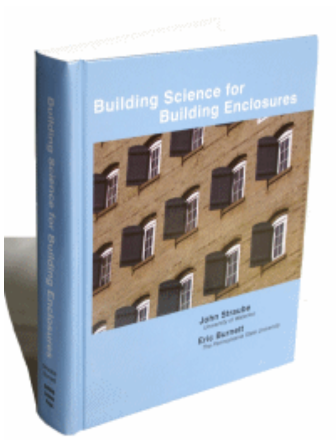
Course objectives

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
4. Be proficient with several software tools used in building enclosure design

Textbook is not required

My main resource:



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/

BUT, this book is now out of print

I will also draw on lots of other references in this course:

- You do not need to purchase them
- I do highly recommend purchasing the ASHRAE Handbook of Fundamentals (cheap for students)

Other references (*not required*)

- Aksamija, A. 2013. *Sustainable facades: design methods for high-performance building envelopes*. John Wiley & Sons. ISBN: 978-1-118-45860-0.
- ASHRAE 2009. *Handbook of Fundamentals.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers.
- ASHRAE 90.1-2010. *Energy Standard for Buildings Except Low-Rise Residential Buildings.*
- Janis, R.R. and Tao, W.K.Y. 2009. *Mechanical and Electrical Systems in Buildings*. Pearson Prentice Hall. ISBN: 978-0-13-513013-1.
- Kuehn, T.H., Ramsey, J.W., and Threlkeld, J.L. *Thermal Environmental Engineering*. Prentice Hall. ISBN: 0-13-917220-3.
- Kreider, J.F., Curtiss, P.S., and Rabl, A. *Heating and Cooling of Buildings: Design for Efficiency* (Second Edition), CRC Press, Taylor & Francis Group. ISBN: 978-1-4398-1151-1.
- McQuiston, F.C., Parker, J.D., and Spitler, J.D. 2005. *Heating, ventilating, and air conditioning: analysis and design*. John Wiley & Sons, Inc. ISBN: 0-471-47015-5.
- Moss, K.J. 2007. *Heat and Mass Transfer in Buildings* (Second Edition). Taylor & Francis. ISBN: 978-0-415-40908-7.
- Straube, J. 2012. *High Performance Enclosures*. Building Science Press. ISBN: 978-0-9837953-9-1

Course topics to be covered

- Purpose and importance of building enclosure design
- Heat transfer in building enclosures
- Moisture flows in building enclosures
- Moisture/water problems and prevention
- Airflow and building enclosures
- Fenestration and daylighting
- Roofing materials
- Energy simulation and building enclosure design
- Applications in enclosure design (codes, standards, requirements, materials, and field diagnostics)
- Advanced/high performance building enclosure designs

About you

- Who are you?
  - First and last name
  - Where are you from?
- What is your primary degree emphasis?
  - Undergraduate or graduate?
  - Engineering or other?
  - If graduate, masters or PhD?
    - Doing research (MS/PhD or MAS)?
- Why are you taking this course?
- Any relevant work experiences?

Course expectations

- Grading
  - Course is mixed undergraduate/graduate
- Homework
  - 5 HW assignments throughout semester
- Exam(s)
  - One take-home exam will be given in late March (released March 29)
  - No final exam scheduled
- Projects
  - 2 projects in this course
  1. Assessing the exterior of IIT campus buildings
  2. Report and presentation on advanced enclosure designs and energy performance

Course grading

For both CAE 463 and CAE 524:

• HW	250 (25%)
• Project 1 (IIT buildings)	250 (25%)
• Project 2 (final)	250 (25%)
• Exam	250 (25%)
• Total	1000 (100%)

Grading scale for both 463 and 524:

A	B	C	D	F
90% and up	80.0-89.9%	70.0-79.9%	60.0-69.9%	<60.0%

Course website

- I will post lectures and updated syllabus on my website:
  - http://built-envi.com/courses/cae-463524-building-enclosure-design-spring-2016/

- I will also post HWs, exams, lecture notes, syllabus, and other materials to Blackboard

Course schedule (continuously updated – check often)

Week	Date	Lecture Topics	Reading	Assignment Due
1	Jan 12	Introduction to building enclosure design	Straube Ch. 2-3	
2	Jan 19	Building science review	Straube Ch. 4-5	
3	Jan 26	*No class – ASHRAE conference*		
4	Feb 2	Introduction to energy balances Solar radiation and enclosures	Lstiburek 2012	
5	Feb 9	Conduction in building enclosures (*half lecture*)		HW1
6	Feb 16	Complex conduction in building enclosures • Thermal bridges, 2-D, and 3-D conduction		
7	Feb 23	Moisture flows in building enclosures	Straube Ch. 6; Kazmierczak 2010; Karagiozis et al. 2010; Straube Ch. 9-10	HW2 (THERM)
8	Mar 1	Moisture management and control	Lstiburek 2004	
9	Mar 8	Air movements in enclosures • Blower door tests	Straube Ch. 7; Younes et al. 2012	HW3 (WUFI)
10	Mar 15	*No class – Spring Break*		
11	Mar 22	Fenestration and roofing	Selkowitz 2011; Straube 2008	
12	Mar 29	Campus project presentations		Campus projects due
13	Apr 5	Energy simulation and enclosure design • Introduction to energy modeling software • Use of eQUEST (commercial bldg.)	Asadi et al., 2012; Asan 2006; Medina 2000; TenWolde 1997	Take-home exam due
14	Apr 12	Finish energy simulation and enclosure design • Thermal mass • BEopt and EnergyPlus (residential bldg.)		HW4 (Energy modeling)
15	Apr 19	*Guest lecture, Bruce Kaskel, WJE*		HW5 (Energy modeling)
16	Apr 26	Codes and standards		
Final	May 3	No final scheduled		Final project report due

Questions thus far?

Today's topics

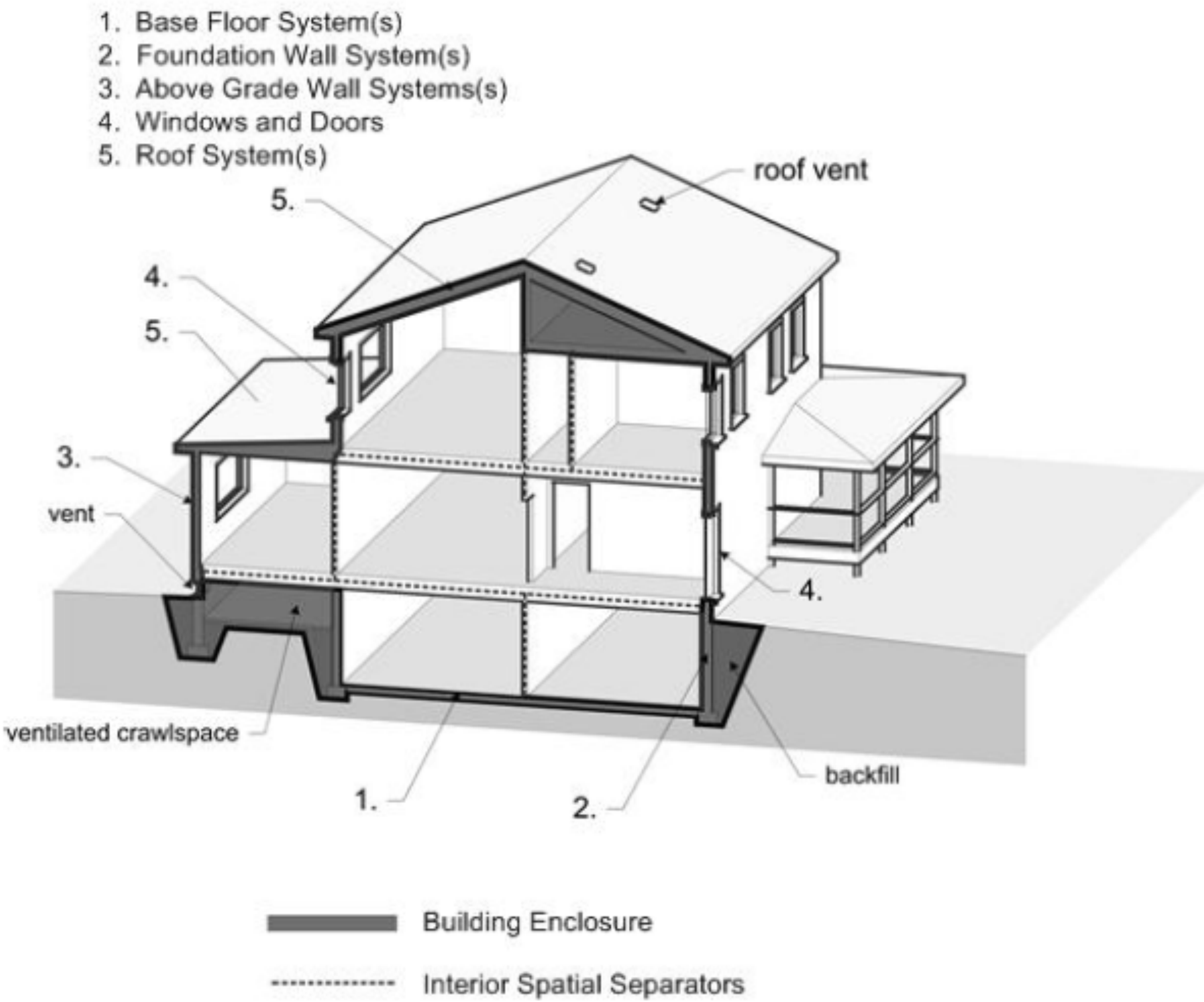
1. Introduction to building enclosures
   - Enclosure purposes, components, and materials

2. Review of environmental conditions that affect enclosures
   - Purpose of enclosure analysis

3. Begin reviewing heat, air, and moisture fundamentals from CAE 331/513 Building Science
   - Continue in the next lecture

INTRODUCTION TO BUILDING ENCLOSURES

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)

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 design: why bother?

- Building science is important
  - Buildings have major impacts on the economy, the environment, and human health, comfort and productivity

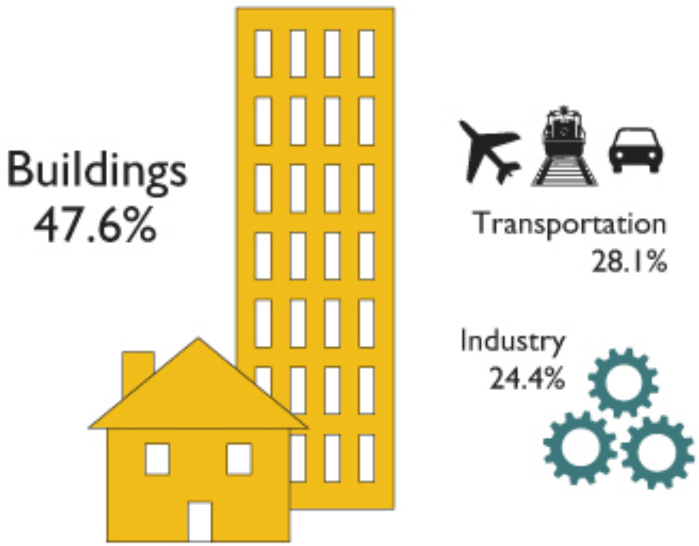
- Building enclosures (or “envelopes”) serve to separate indoor and outdoor environments
  - Major impacts on energy and indoor environment
  - Deterioration and failures of building envelopes account for the majority of building defect claims in North America

- Building enclosures are crucial to building science

Why study building enclosures?

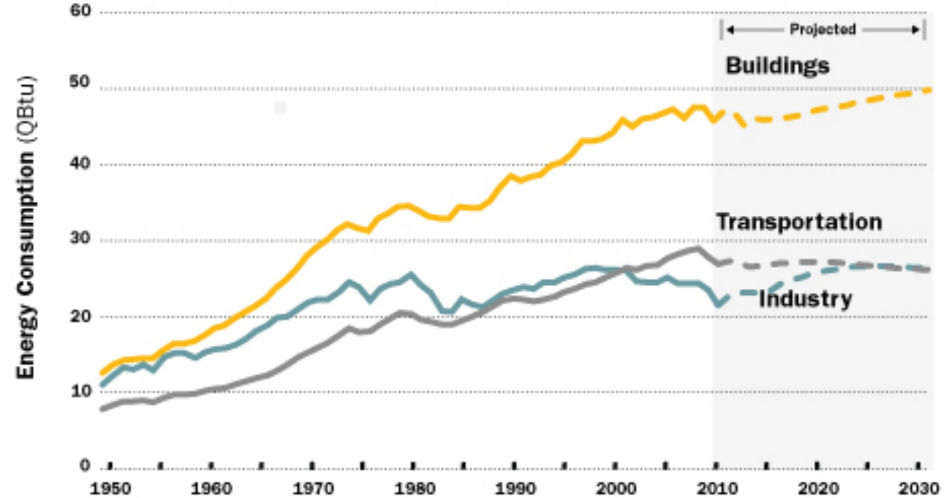
- How many of you are in a building right now?
  - Birds build nests
  - Rabbits dig holes
  - People build buildings
- How much time do you think people spend indoors, on average?
- How much energy do buildings use in the U.S.?
- How much money do we spend on energy use in buildings in the U.S.?
- How do building enclosures impact these measures?

Buildings use *a lot* of energy



U.S. Energy Consumption by Sector

Source: ©2013 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: U.S. Energy Information Administration (2012).



U.S. Energy Consumption by Sector (Historic / Projected)

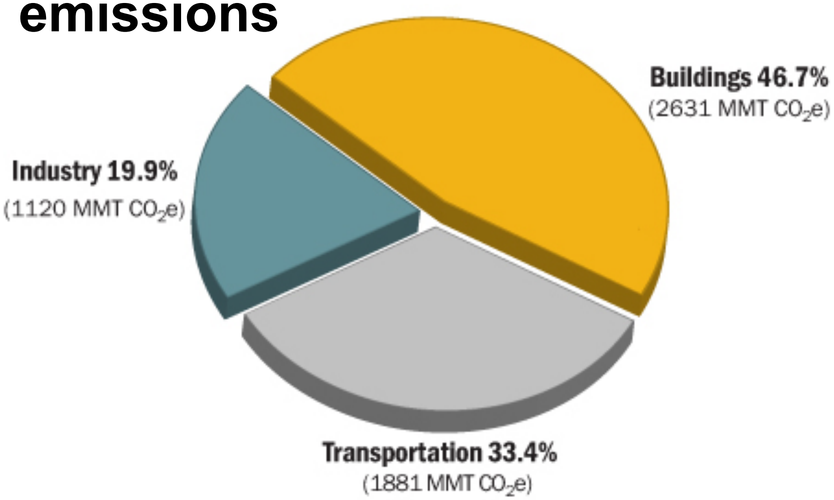
Source: ©2013 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: U.S. Energy Information Administration (2012).

Buildings account for ~47% of energy in the U.S.
(Operations: ~41% | Construction and materials: ~6%)

Buildings in the U.S. account for ~7% of the total amount of energy used in the world

Buildings account for *a lot* of GHG and pollutant emissions

Contribution to greenhouse gas (GHG) emissions



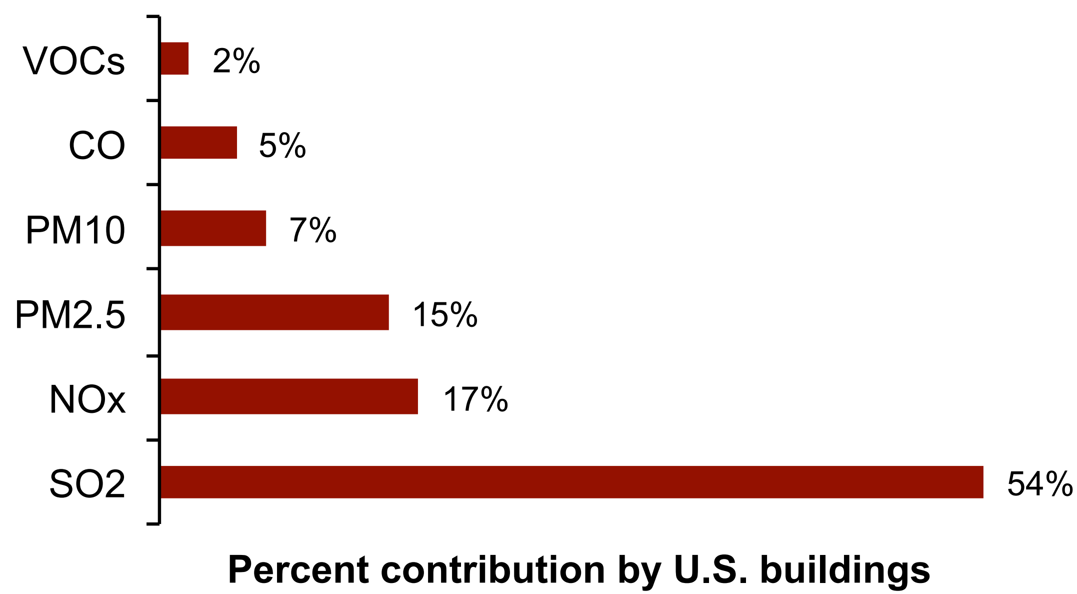
U.S. CO_2 Emissions by Sector

Data Source: U.S. Energy Information Administration (2011).

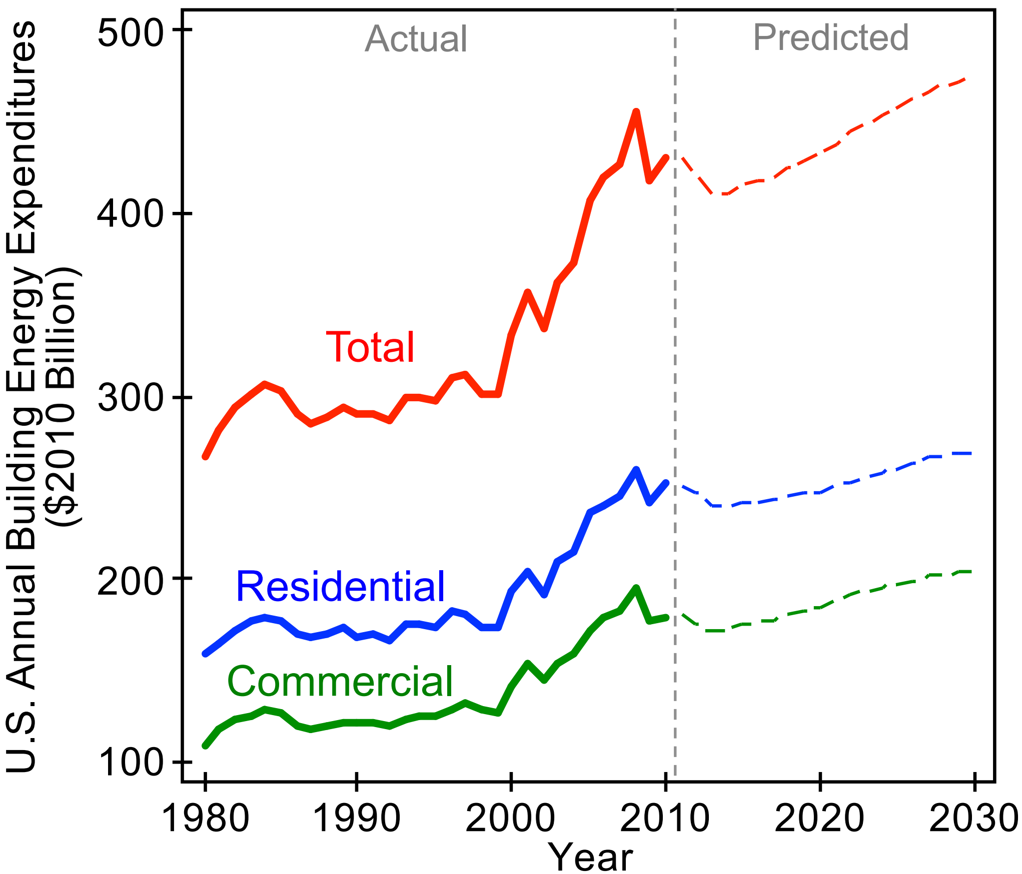
Major uses

1. Heating
2. Cooling
3. Lighting
4. Water heating

Contribution to outdoor air pollution

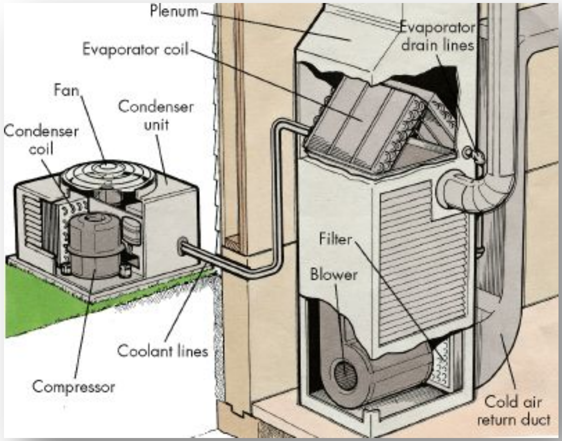


Building energy use costs *a lot* of money



U.S. building energy expenditures totaled ~$430 billion in 2010

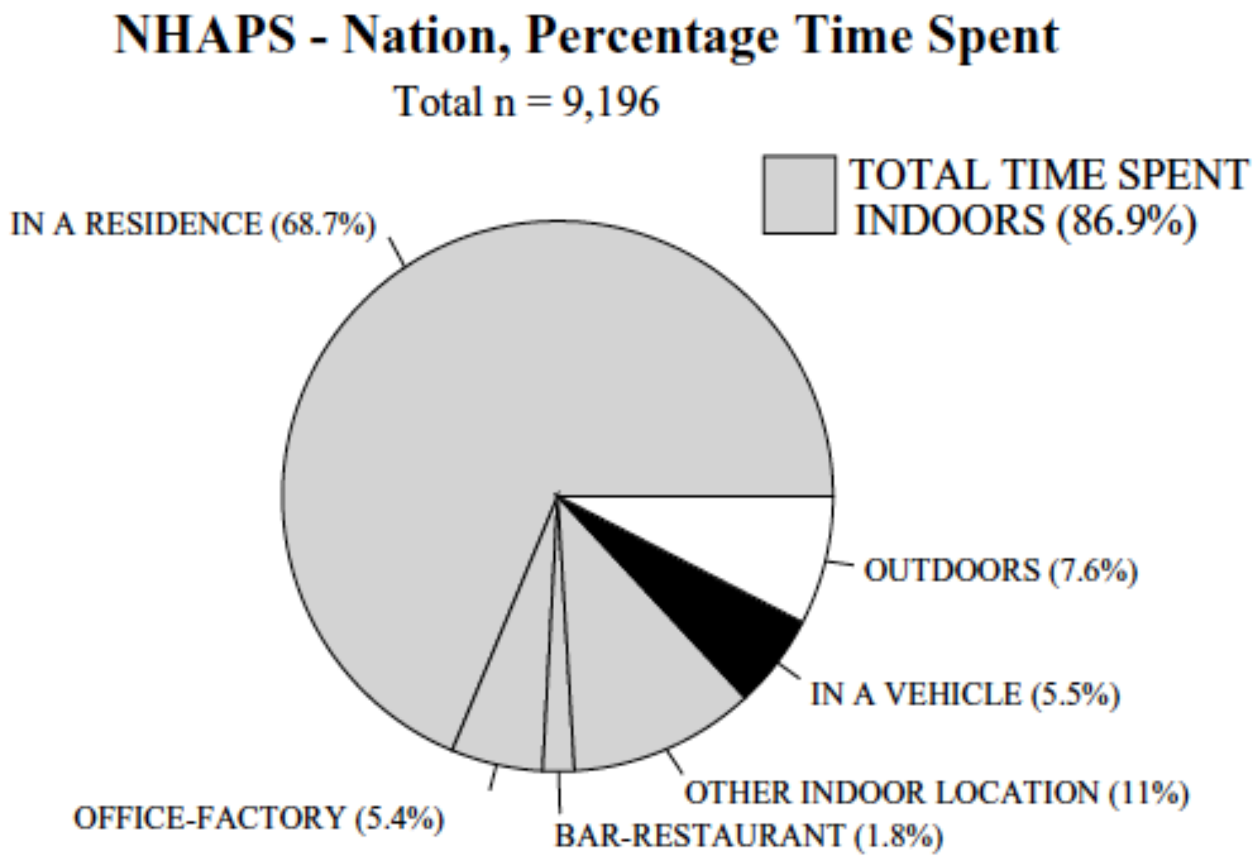
Approximately 3% of our GDP



Approximately 1/3 of building energy use is for space conditioning

~1% of our GDP is spent on heating and cooling buildings

We spend *a lot* of time in buildings



- Americans spend almost 90% of their time indoors
  - 75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* **2001**, 11, 231-252

Importance of 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…

Buildings impact people, energy, and the environment

The design, construction, and operation of buildings, including their heating, ventilation, and air-conditioning (HVAC) systems and their **building enclosures**, greatly affect their contribution to energy use, greenhouse gas emissions, financial expenditures, and human exposures to airborne pollutants in the indoor environment

Basic functions of building enclosures

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

Lateral
- Wind, earthquake, etc.

Gravity
- Dead load, snow load, etc.

Rheological
- Temperature, 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

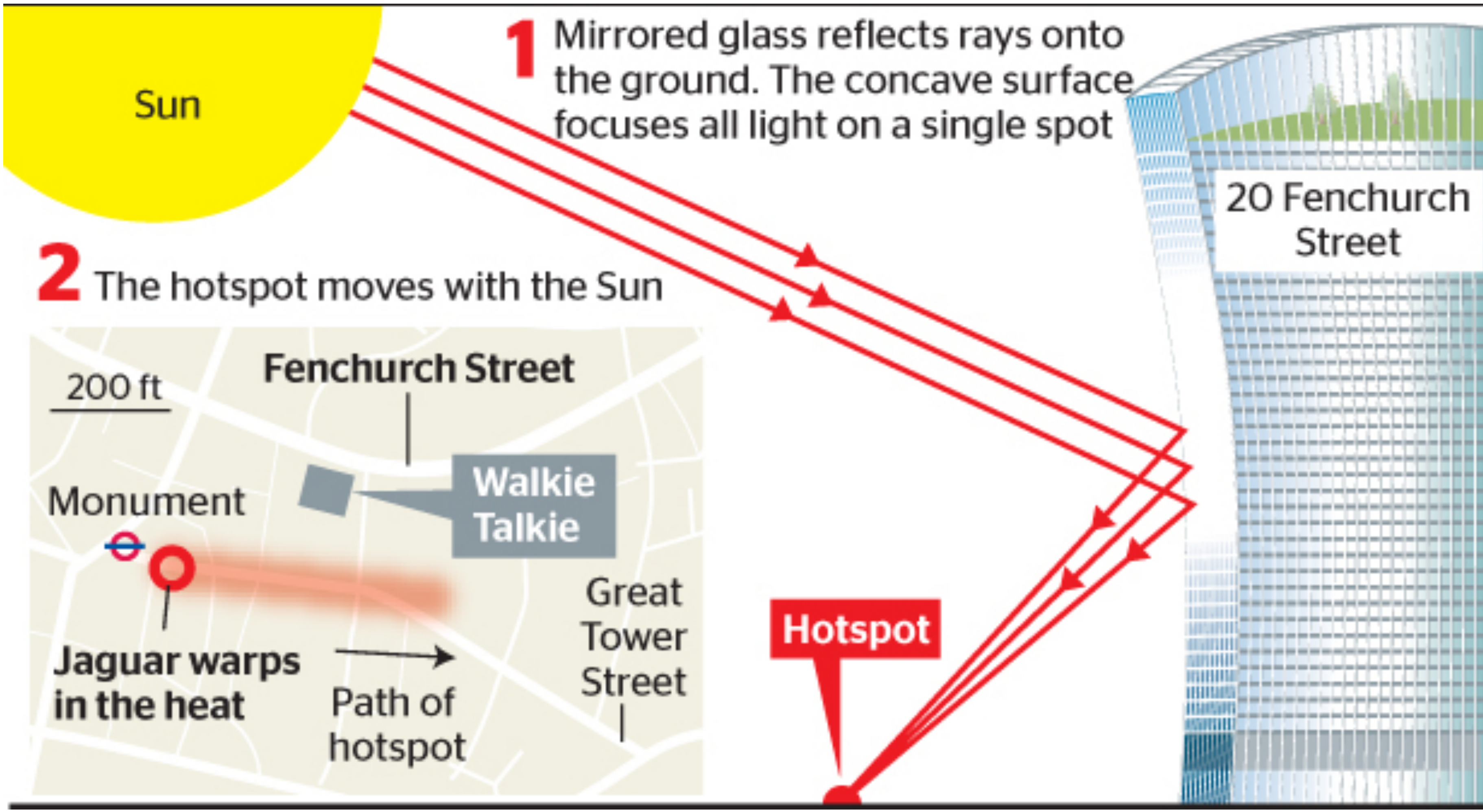
Basic functions of building enclosures

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

Color
Texture
Reflectance
Pattern

Finish – interior and exterior surfaces for people

Reflectance?



melt cars and set buildings on fire

Basic functions of building enclosures

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

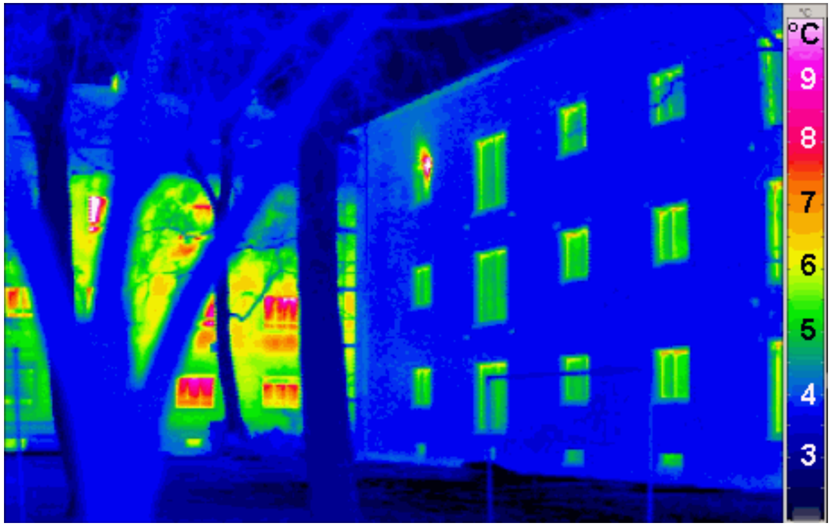
Electricity
Communications
Plumbing
Air ducts
Gas lines
Roof drains

Distribute – protect and house building services

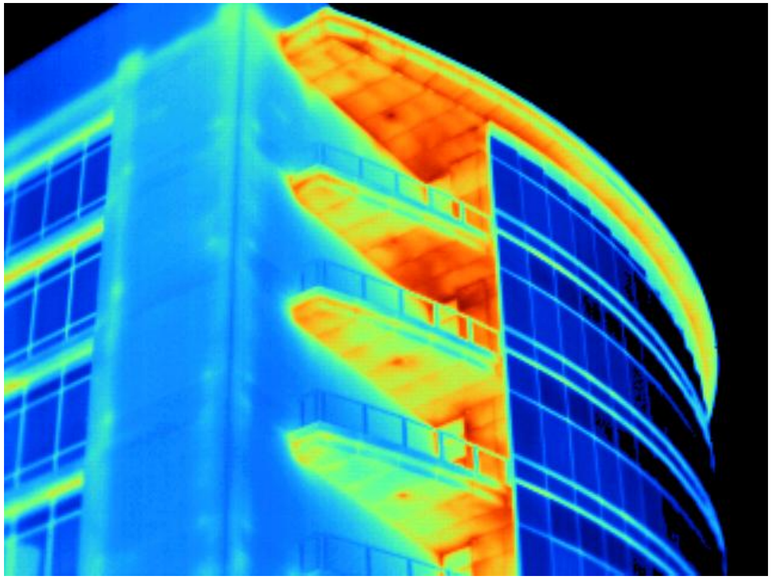
Major functions: heat and moisture control

- 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 the indoor environment
  - Physical degradation

Visual evidence for why building enclosures are important



Thermal performance



Visual evidence for why building enclosures are important

Moisture performance

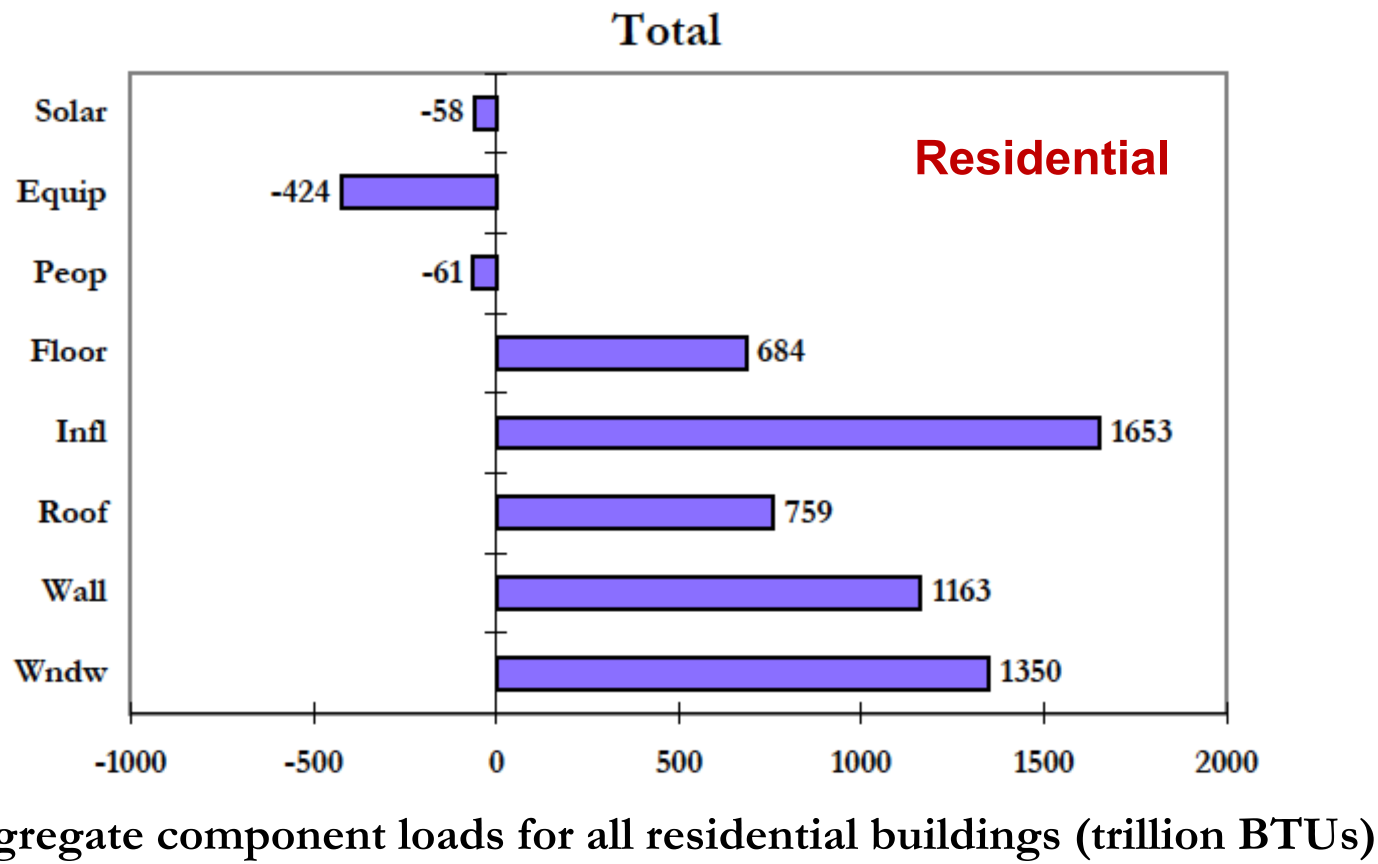
Questions for you…

- How important are building enclosures for building energy use?

- Are building enclosures more important for energy use in residential buildings or commercial buildings?
  – Large or small buildings?

Importance of building envelopes for energy use

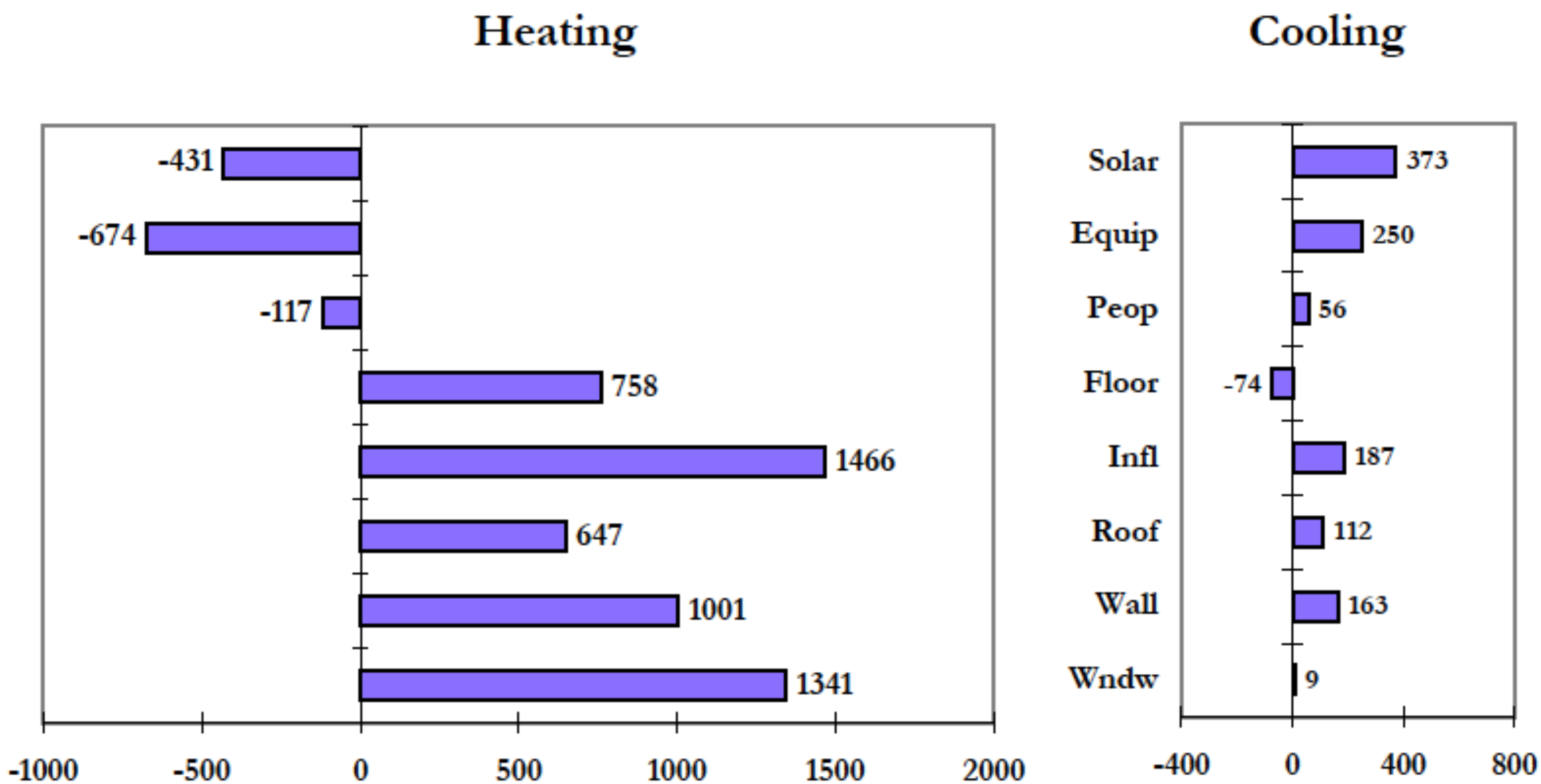
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
    - Report #LBNL-44636 (Huang et al. 1999)



Importance of building envelopes for energy use

- Heating vs. cooling in US homes

Residential



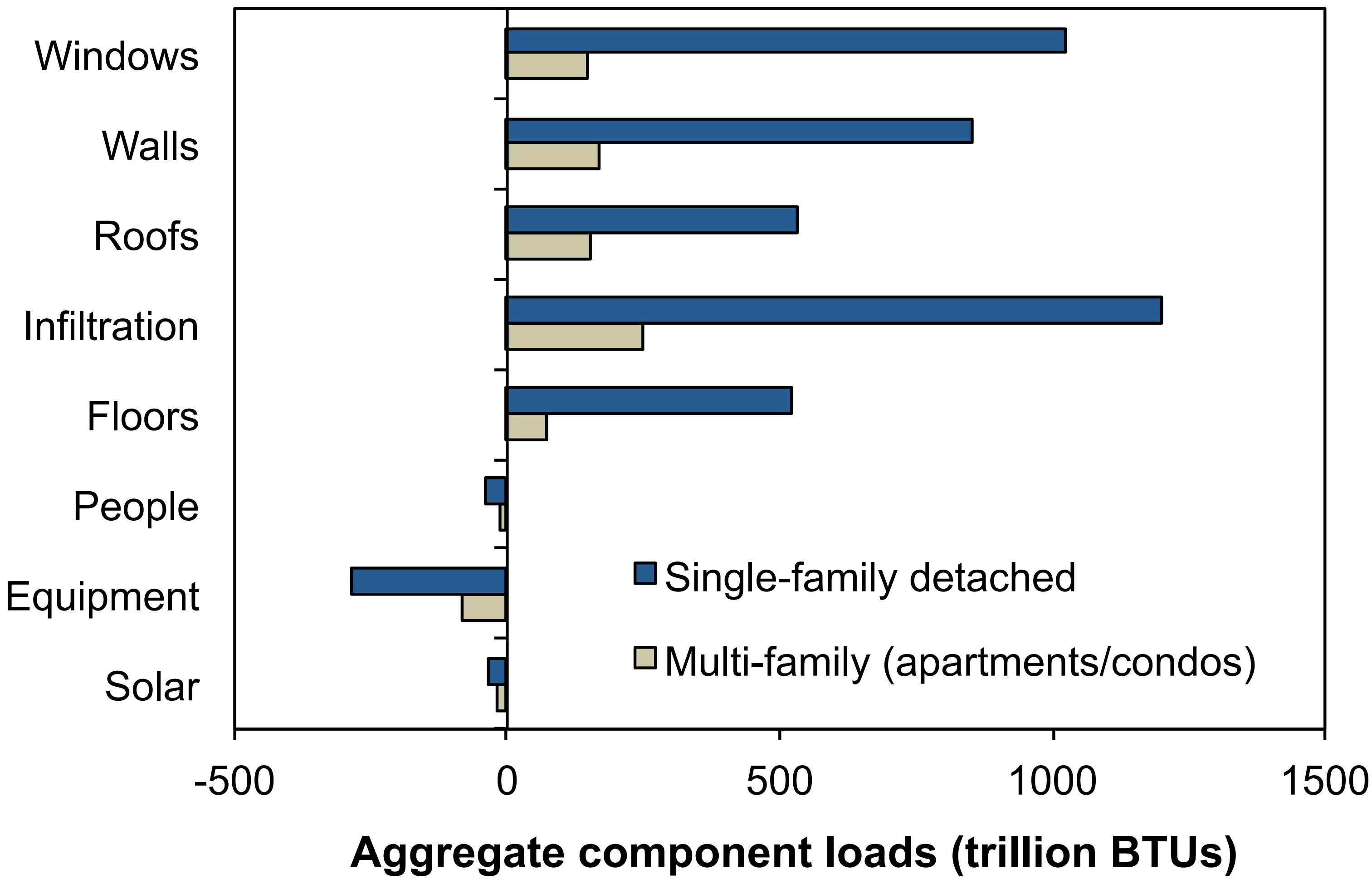
Aggregate component loads for all residential buildings (trillion BTUs)

Huang et al. 1999

Importance of building envelopes for energy use

- Single-family vs. multi-family homes

Residential



Huang et al. 1999

Importance of building envelopes for energy use

- Single-family vs. multi-family homes

- Why such a big difference?
  - We have more single-family homes in the US than apartments
  - Surface area to volume ratios
    - Single-family detached homes have more exposed surface area associated with their building envelopes

Importance of building envelopes for energy use

- Cold climate vs. warm climate residential

Residential

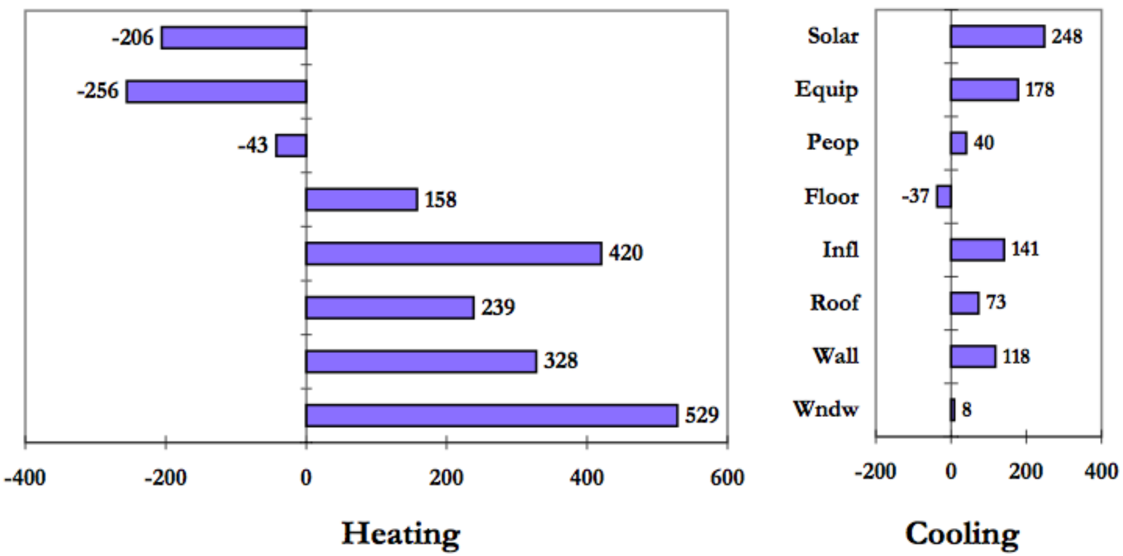


Figure B-14. Aggregate Component Loads for All South Buildings (Trillion Btu's)

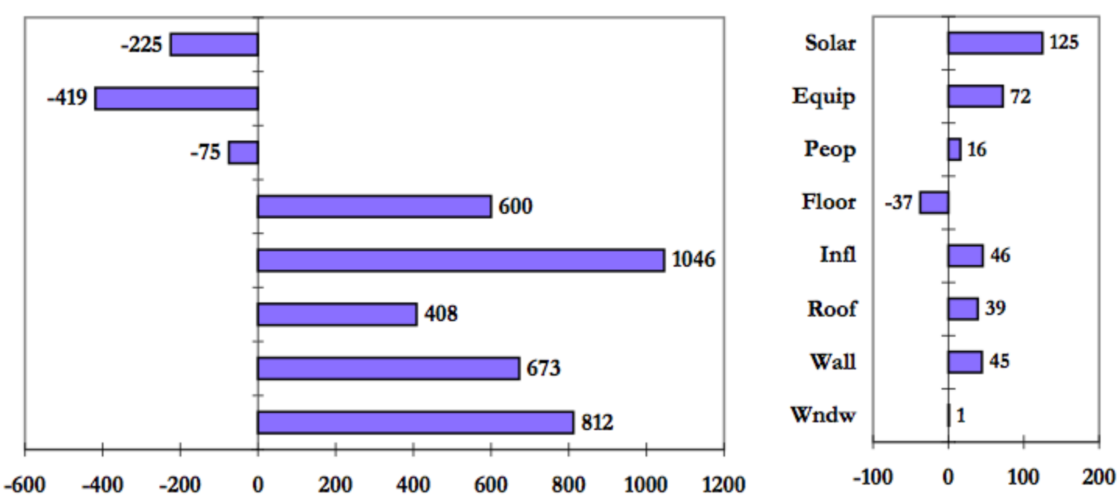


Figure B-13. Aggregate Component Loads for All North Buildings (Trillion Btu's)

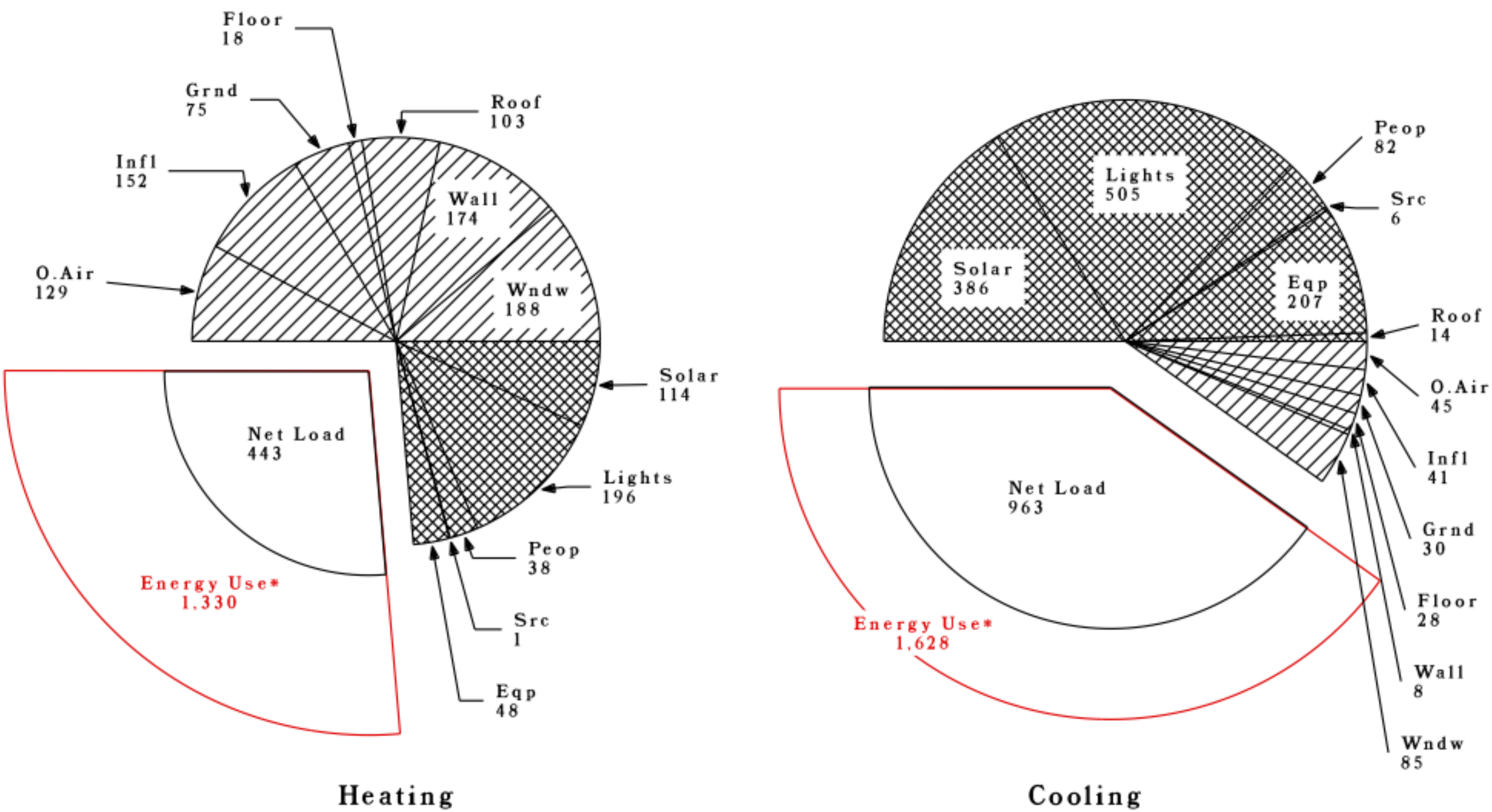
Huang et al. 1999

Building envelopes and energy use: Commercial buildings

- (Another) 1999 study by Lawrence Berkeley National Lab
  - *Commercial Heating and Cooling Loads Component Analysis*
    - Report #LBNL-37208 (Huang and Franconi 1999)

Commercial

Figure 3. Aggregate Component Loads
for All Commercial Buildings (Trillion Btu's)



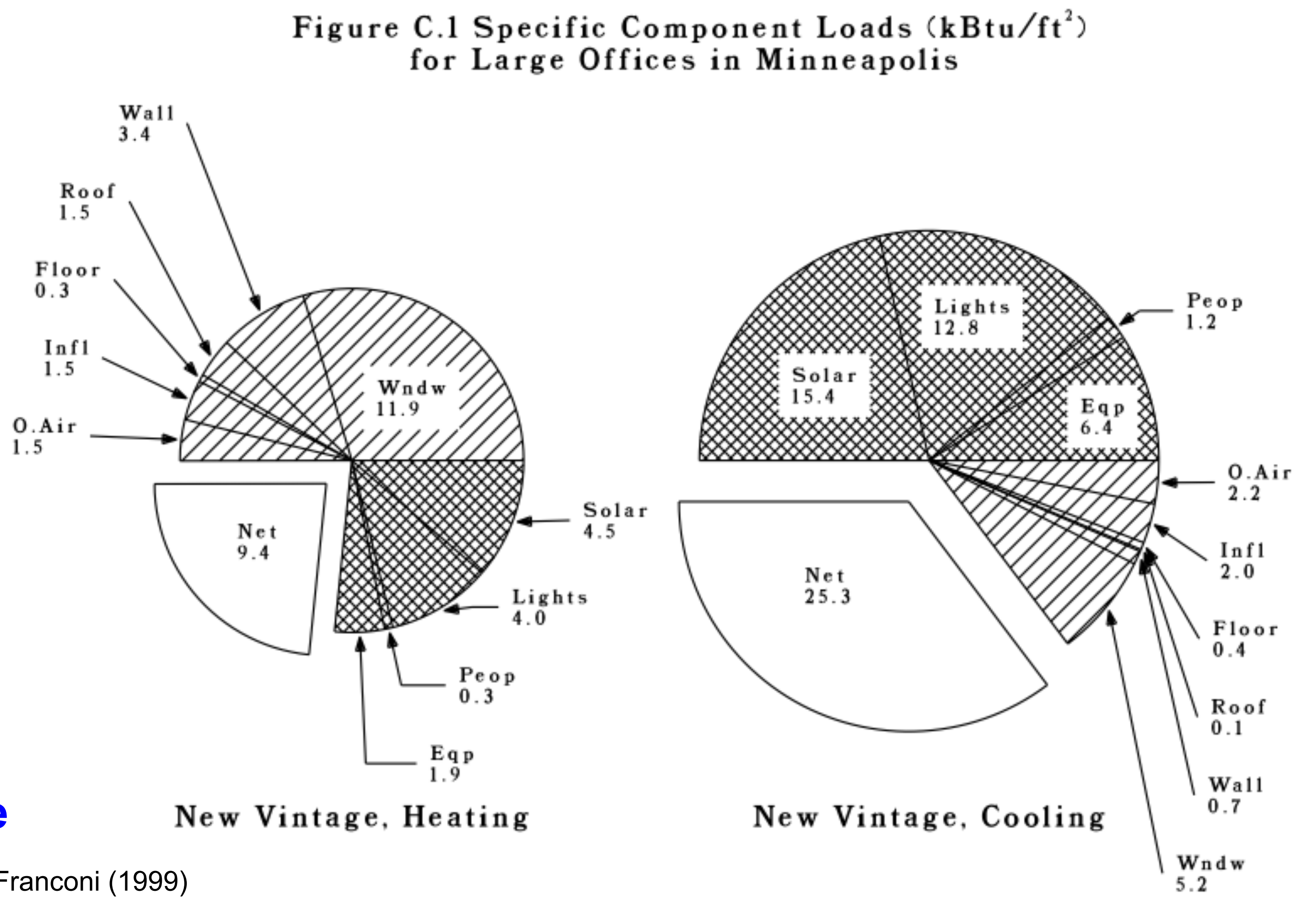
Huang and Franconi (1999)

Building envelopes and energy use: Commercial buildings

- Largest contributors to heating loads in commercial buildings:
  - Windows
  - Walls
  - Infiltration
- Largest contributors to cooling loads in commercial building:
  - Lighting
  - Solar gain
  - Equipment

Building envelopes and energy use: Commercial buildings

- *Commercial Heating and Cooling Loads Component Analysis*
  - Report #LBNL-37208



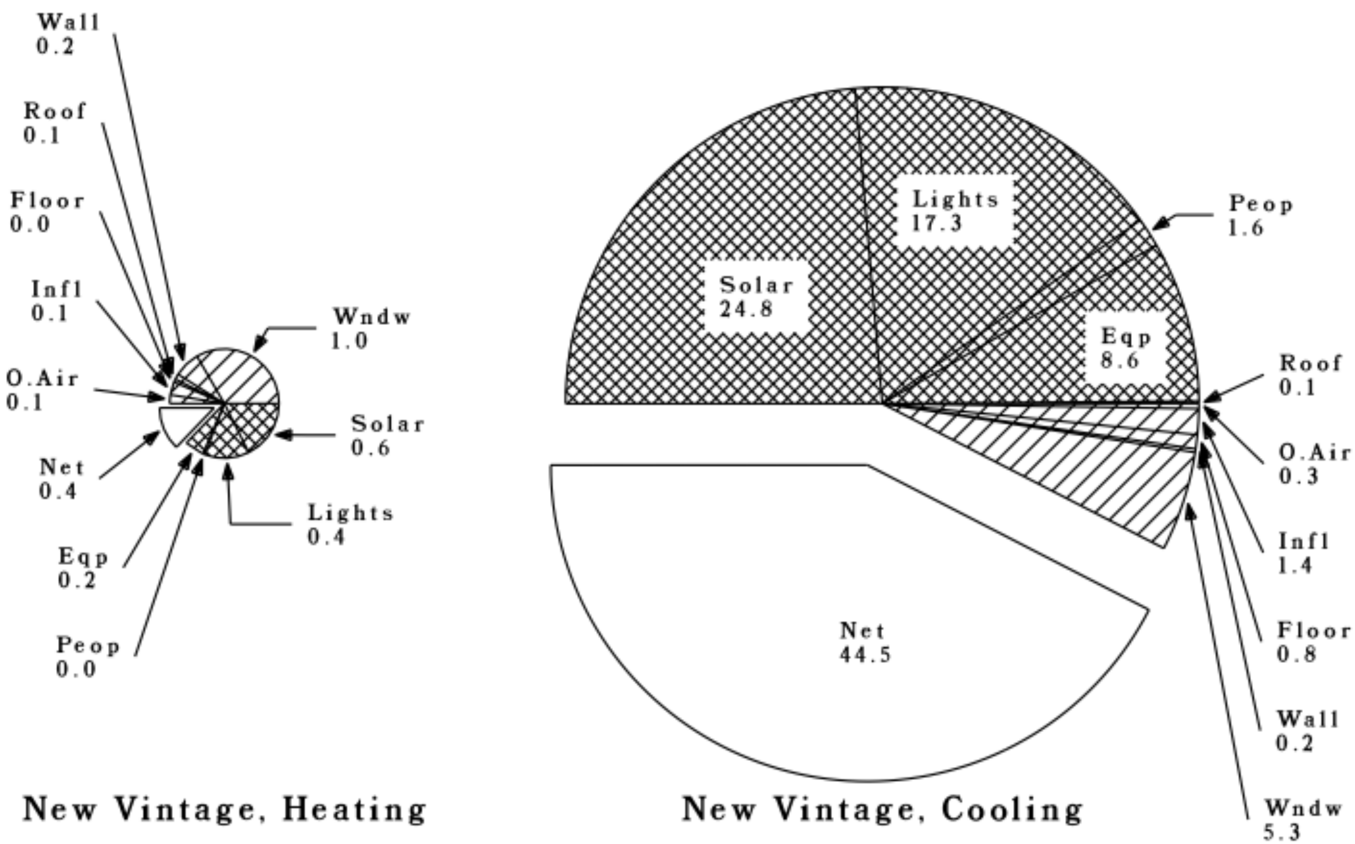
Cold climate

Huang and Franconi (1999)

Building envelopes and energy use: Commercial buildings

– *Commercial Heating and Cooling Loads Component Analysis*
  - Report #LBNL-37208

Figure C.3 Specific Component Loads (kBtu/ft^2) for Large Offices in Houston



Hot climate

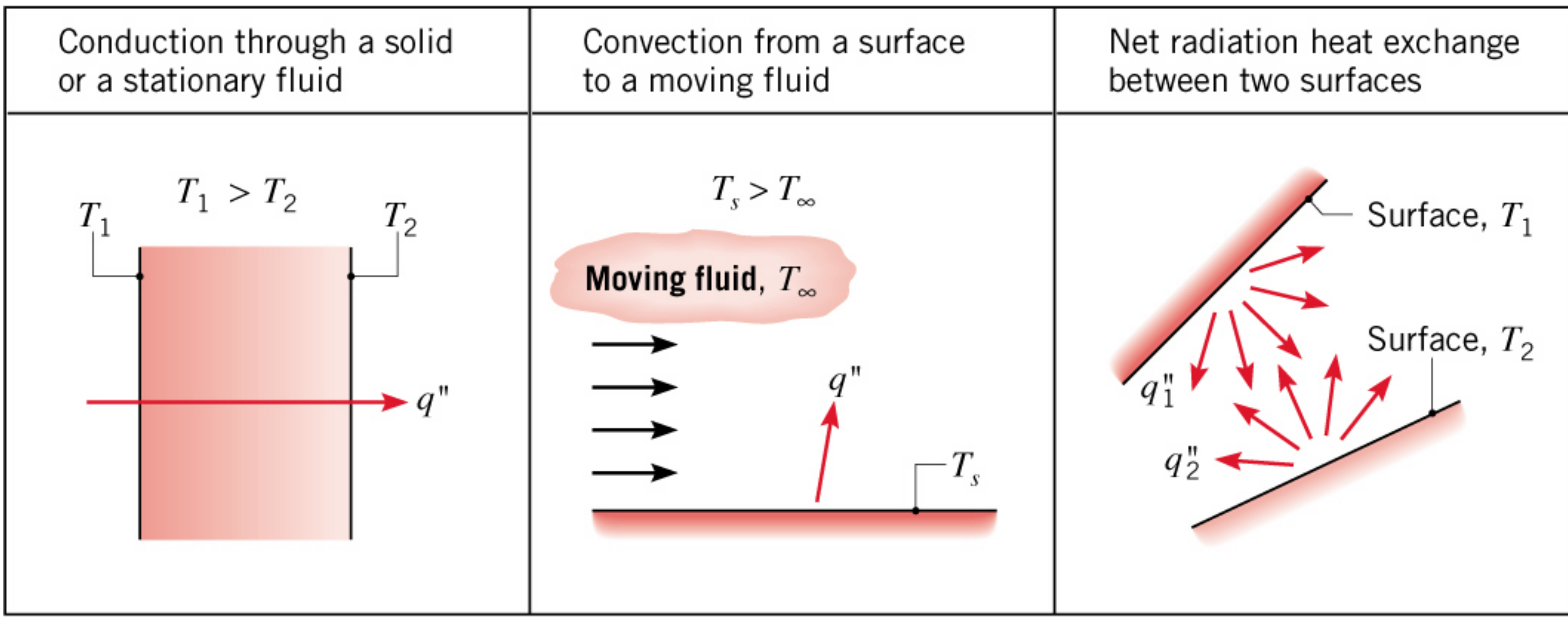
Huang and Franconi (1999)

HEAT, AIR, AND MOISTURE (HAM)

Review of fundamentals from building science

Building enclosure: some primary functions

- Controlling heat transfer
  - Three modes: Conduction, Convection, Radiation
  - Heat energy moves from high temperature to low temperature



Controlling conduction

- Reduce conductive heat transfer through enclosures by increasing the thermal resistance (R-value)
  - Decreasing the U-value

What are some strategies?

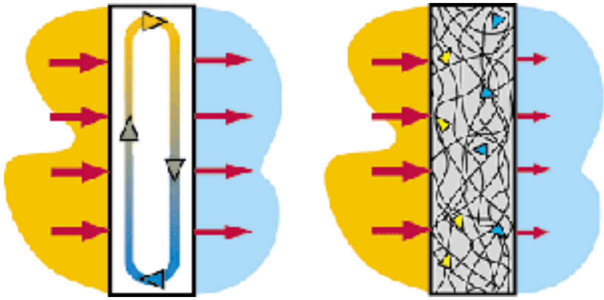
- Use low-conductivity materials
- Proper use/installation of insulation
- Avoiding constructions with thermal bridges

Controlling convection

- Reduce convective heat transfer by reducing air flow and limiting air motion

  What are some strategies?
  - Proper air gap size between elements
  - Installation of air sealants and air barrier materials

  - We will learn how enclosures affect air infiltration and convective heat transfer this semester



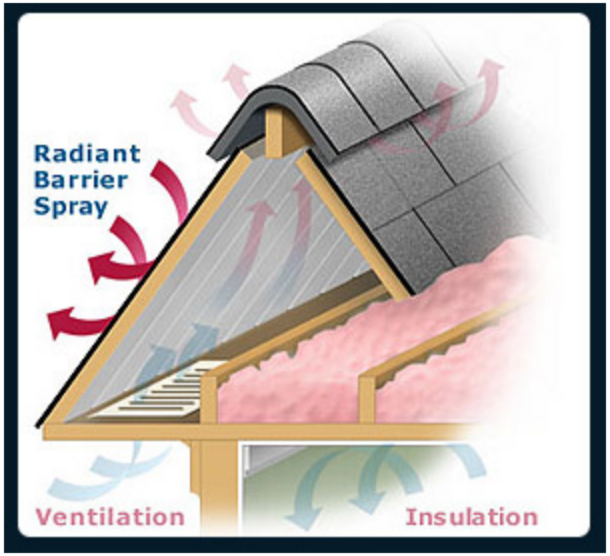
Controlling radiation

- Reduce radiative heat transfer by reducing building exposure to solar radiation and minimizing transmission of solar radiation

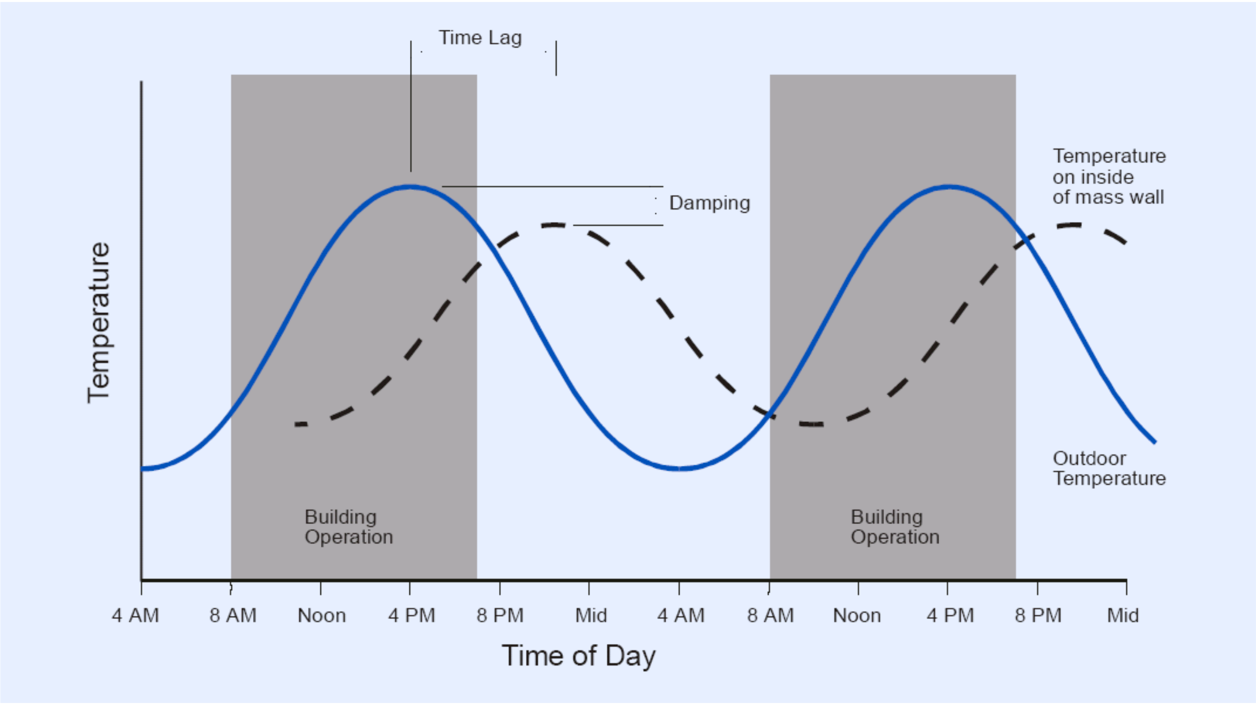
What are some strategies?

- Careful selection of building location and layout
- Careful selection of glazing system and glazing controls
- Use radiant heat barriers (low emissivity)

- We will explore each of these options this semester



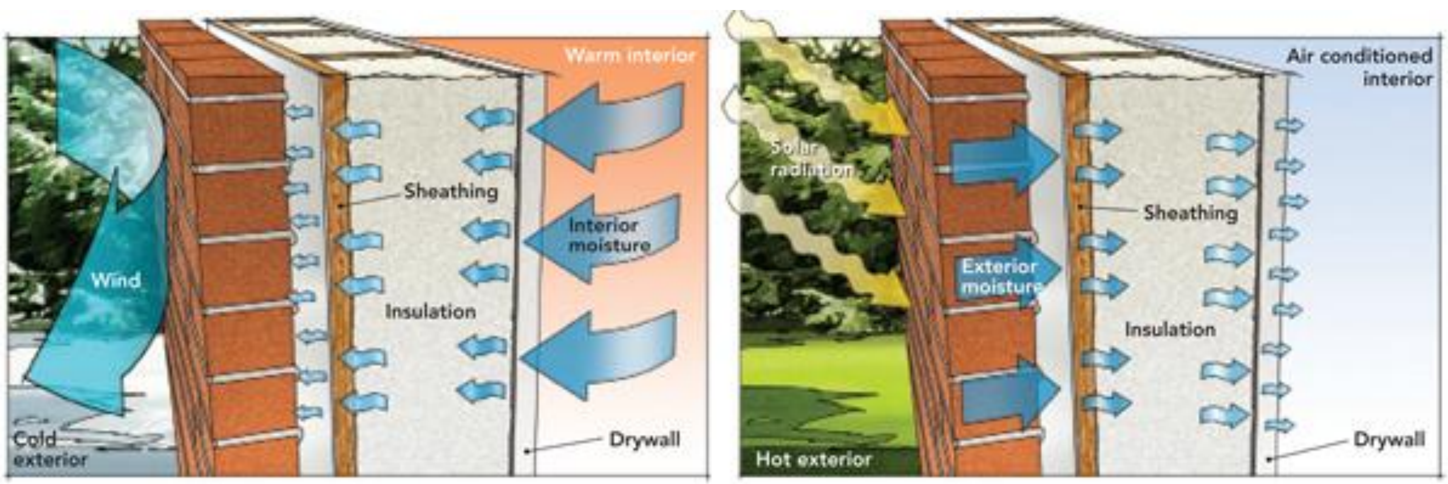
Thermal mass and dynamic heat transfer



- In CAE 331/513, most analysis was at steady state
- In reality, thermally massive materials take 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

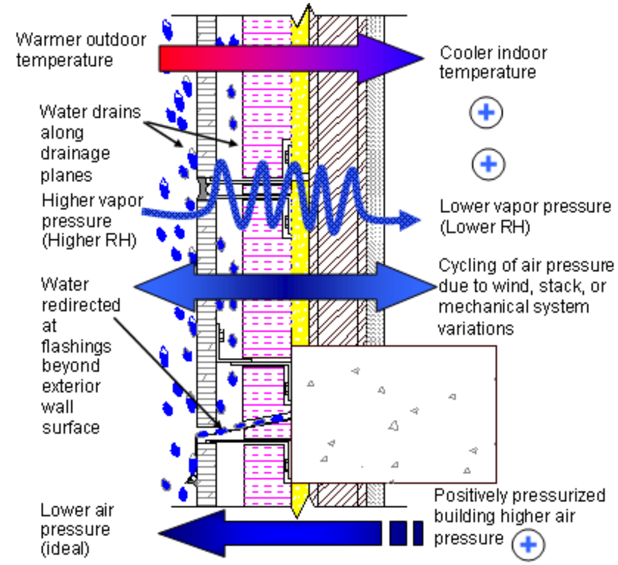
Moisture transfer

- Moisture transfer is the transfer of liquid water and/or 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 (bulk convection)
  - Driven by air leakage into/through enclosure



- Need to ensure that moist air does not contact and condense on cold elements within the enclosure
- If this happens, *these happen:*
  - Chemical deterioration and corrosion
  - Freeze-thaw deterioration
  - Mold and mildew
  - Staining/damage to interior finishes

COURSE DELIVERABLES

Some information on our course projects

- Two course projects

1. Intermediate Group Project:

– Assessment of the enclosure of a building on IIT's main campus (25% of your grade)

– Tentatively due March 29

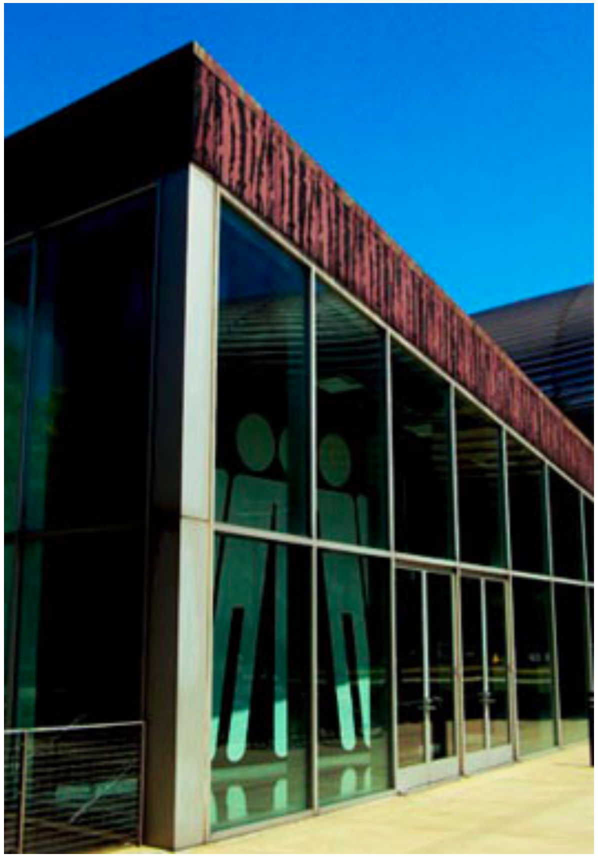
2. Final Individual Project:

– Research and report energy, heat, air, moisture, and other types of performance of "high performance" enclosures (25% of grade)

– Due at the end of the semester

Project 1: Assessment of IIT building enclosures

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



Project 1: Assessment of IIT building enclosures

- Objectives:
  - 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 and other tools
    - "Real" field experience
- Deliverables:
  - Report of findings (I will give you an example)
  - Presentation to the class

Project 1: Assessment of IIT building enclosures

- Tools available for your campus project

Temperature/RH data loggers

Heat flux meter

IR thermometer

IR camera

Solar radiation

Blower door (envelope leakage)

Project 2: High performance enclosure research

- Objectives:
  - Extend what you will learn about HAM and building enclosures and research a “high performance” enclosure construction
    - Literature review, product review, and examples
    - Advantages and disadvantages
    - HAM analysis
    - Energy analysis
    - Cost considerations
    - Practical design considerations
    - Environmental and sustainability impacts

Project 2: High performance enclosure research

- Deliverables:
  - Final report of findings (approx. 8-10 pages)
    - Similar to a conference proceeding

Project 2: High performance enclosure research

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

Green roofs

Green walls

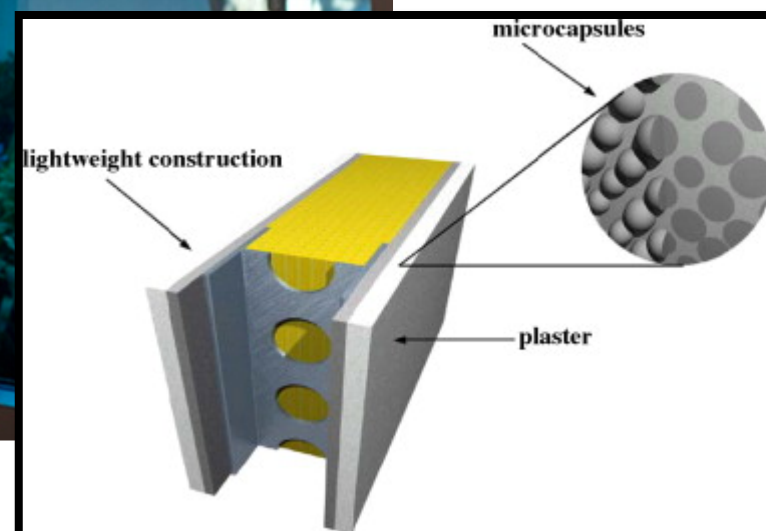
Project 2: High performance enclosure research

Double skin facades

Building integrated photovoltaics

Project 2: High performance enclosure research

Electrochromic windows ("smart glass")



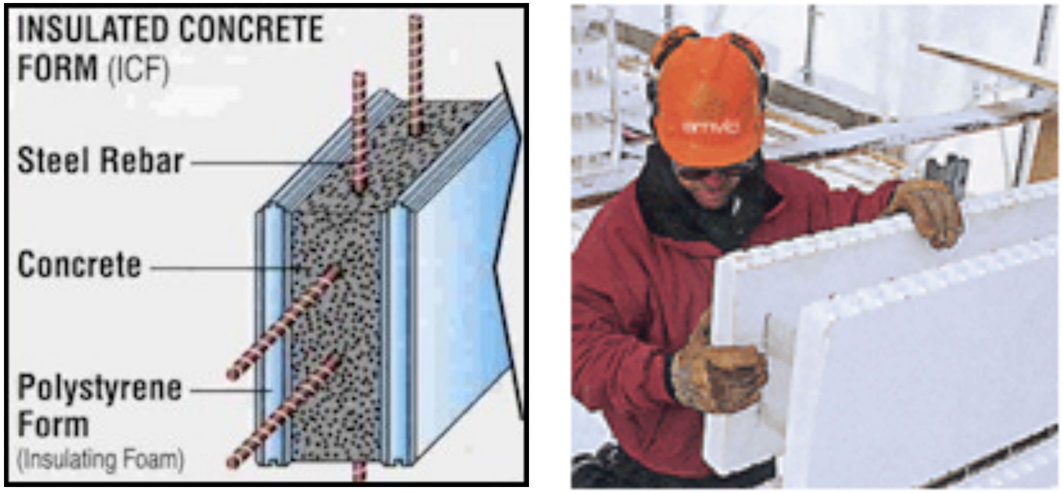
Phase change insulation materials

Project 2: High performance enclosure research

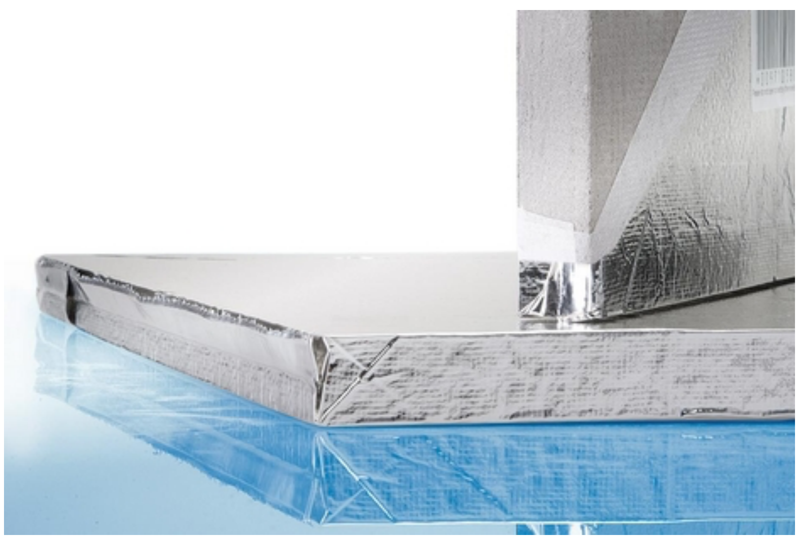
Bio-based insulation materials (mushrooms)

Structural insulated panels (SIPS)

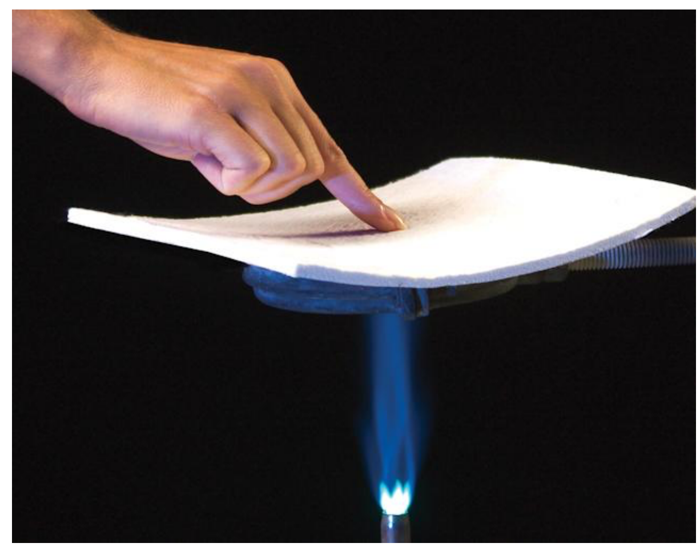
Project 2: High performance enclosure research



Insulated concrete forms (ICFs)



Vacuum insulated panels



Nano-porous aerogels

Project 2: High performance enclosure research

"Cool" roofs (e.g., white roofs)

Straw bale construction

HW topic coverage

- HW1: Building science review; solar radiation; and building energy balances
- HW2: THERM 2-D heat transfer modeling
- HW3: WUFI 1-D moisture transport modeling
- HW4: Commercial building energy simulation
  - eQuest
- HW5: Residential building energy simulation
  - BEopt + EnergyPlus

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

Building Envelope Design Guide (BEDG)

- The National Institute of Building Sciences has a program called Whole Building Design Guide, which also has a Building Envelope Design Guide
  - It's a great resource for all kinds of practical applications in enclosure design

Building Envelope Design Guide

The National Institute of Building Sciences (NIBS) under guidance from the Federal Envelope Advisory Committee has developed this comprehensive guide for exterior envelope design and construction for institutional / office buildings. The Envelope Design Guide (EDG) is continually being improved and updated through the Building Enclosure Councils (BECs). Any edits, revisions, updates or interest in adding new information should be directed to the BEDG Review Committee through the 'Comment' link on this page.

BEDG
BUILDING ENVELOPE DESIGN GUIDE

INTRODUCTION

BELOW GRADE SYSTEMS
- Foundation Walls
- Floor Slabs
- Plaza Decks

WALL SYSTEMS
- Cast-In-Place Concrete
- Exterior Insulation and Finish System (EIFS)
- Masonry
- Panelized Metal
- Precast Concrete
- Thin Stone

FENESTRATION SYSTEMS
- Glazing
- Windows
- Curtain Walls
- Sloped Glazing
- Exterior Doors

ROOFING SYSTEMS

http://www.wbdg.org/design/envelope.php

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*

*Most if not all are available through the Galvin Library

- http://library.iit.edu/
- You should become familiar with peer-reviewed journal articles: http://scholar.google.com

Being review of CAE 331/513 Building Science

ENVIRONMENTAL CONDITIONS

That impact building enclosures

Environmental conditions

- Loads on the enclosure result from indoor/outdoor drivers
  - Temperature, humidity, solar radiation, wind, precipitation

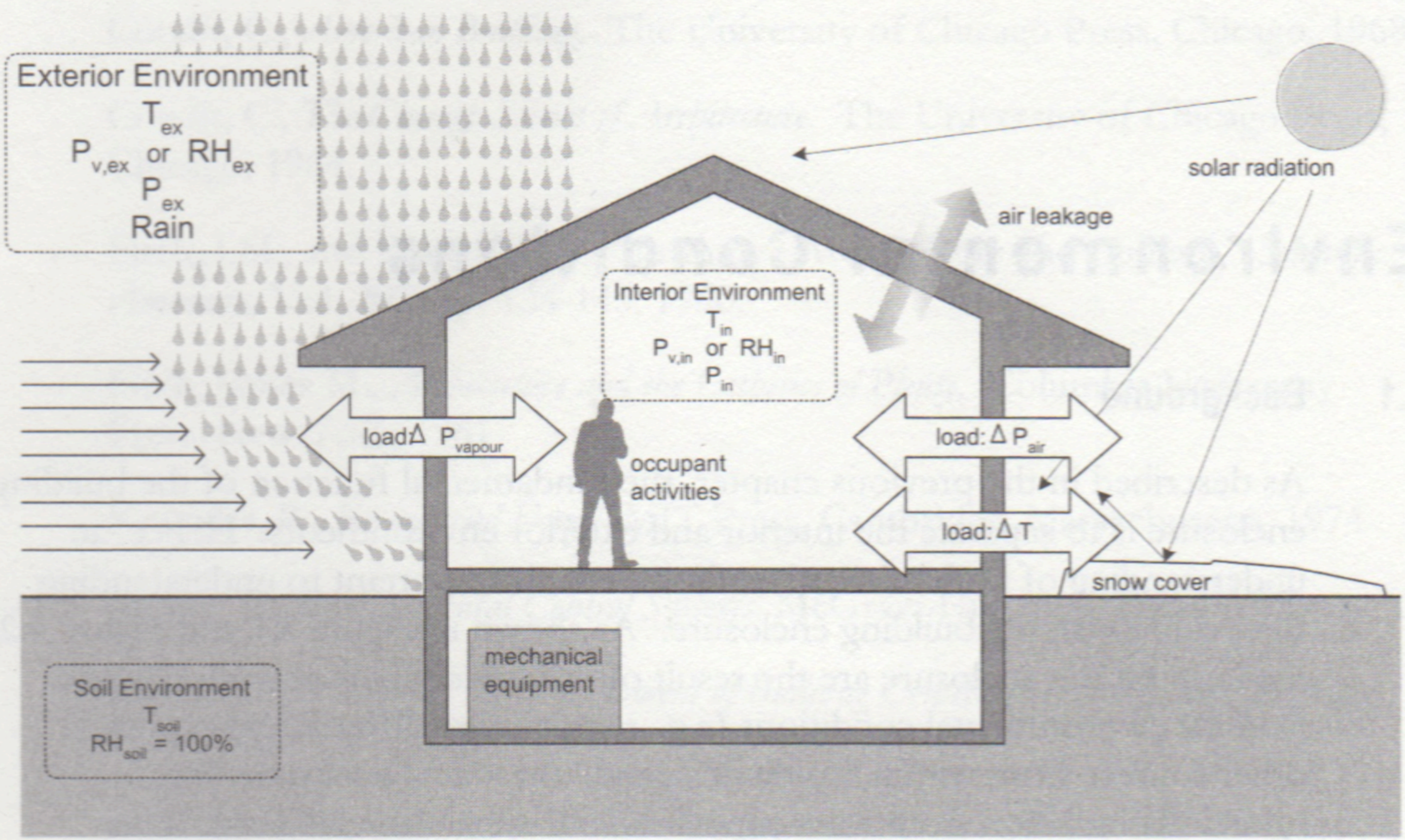


Figure 3.1: Important environmental factors influencing enclosure performance

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 and understand 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

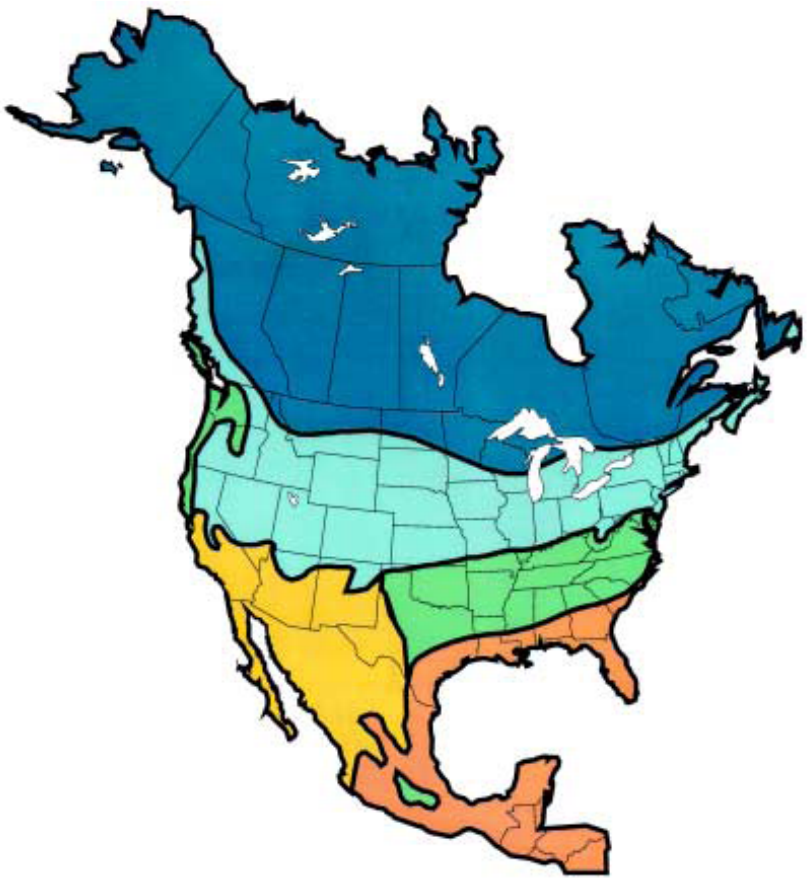
All time scales can be important

Enclosure design and analysis may use more than one time scale

For example:
Peak values are important for HVAC sizing

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)

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

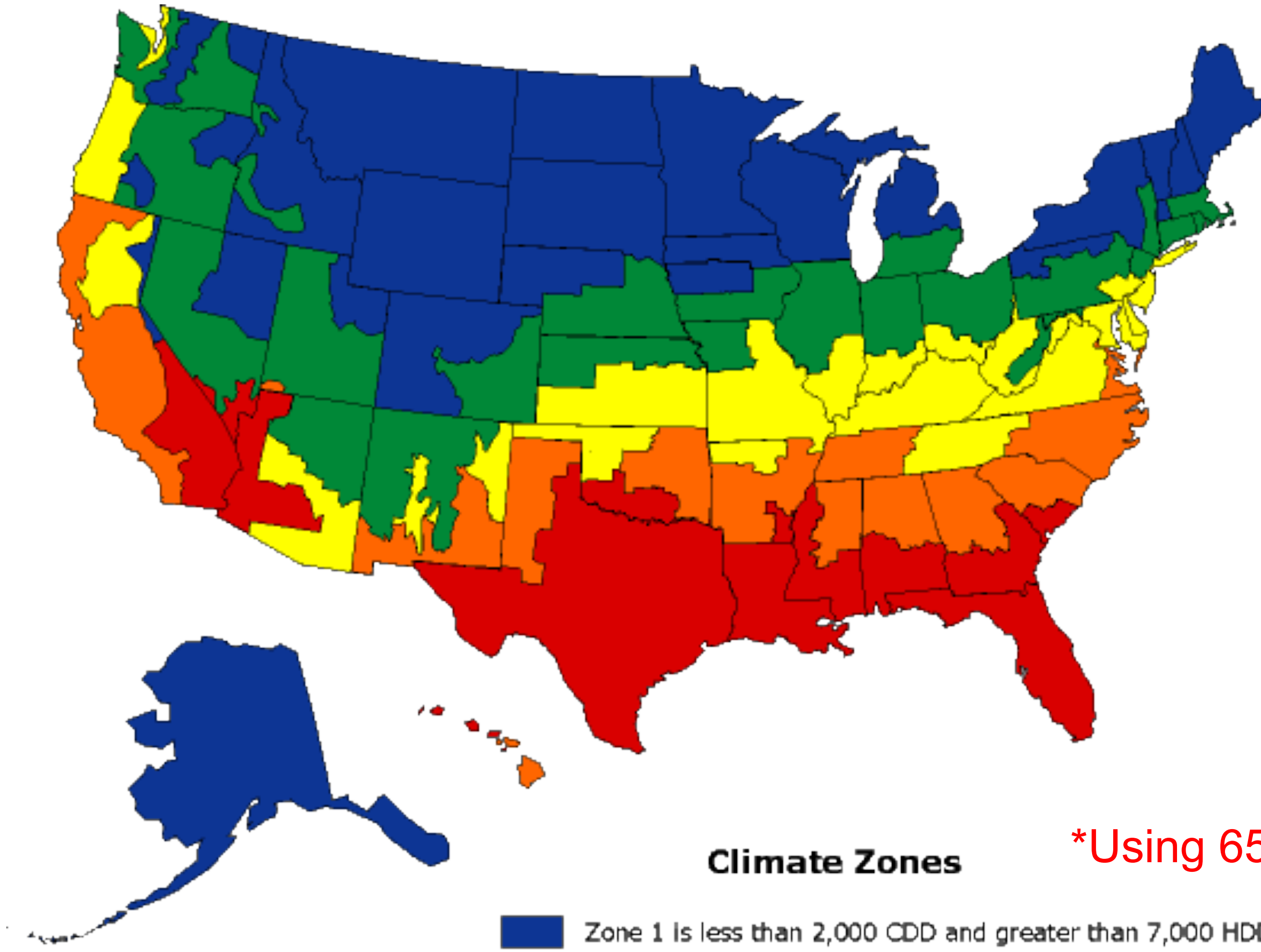
Notes:

- 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

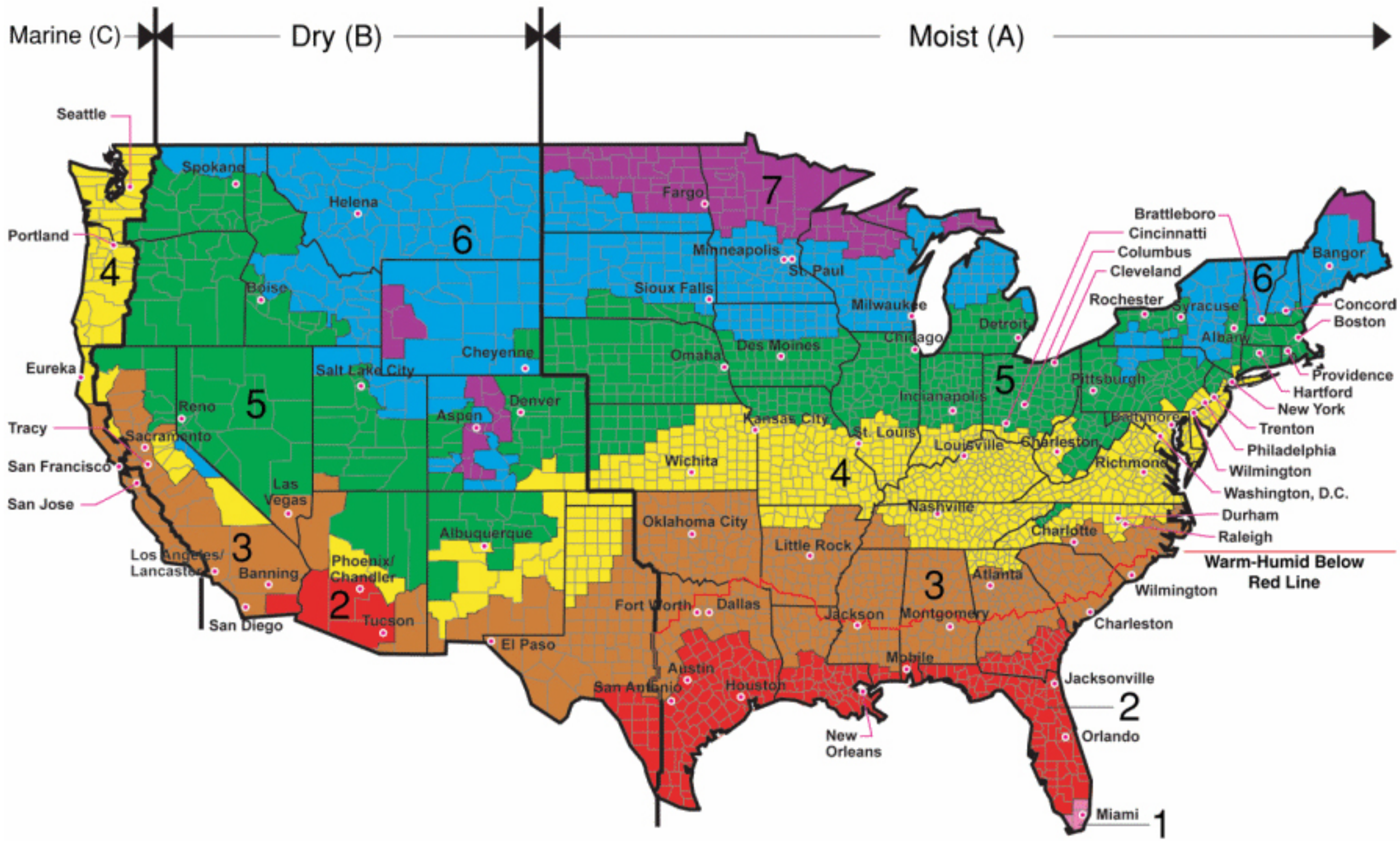


*Using 65°F base

Climate Zones

- Zone 1 is less than 2,000 CDD and greater than 7,000 HDD.
- Zone 2 is less than 2,000 CDD and 5,500-7,000 HDD.
- Zone 3 is less than 2,000 CDD and 4,000-5,499 HDD.
- Zone 4 is less than 2,000 CDD and less than 4,000 HDD.
- Zone 5 is 2,000 CDD or more and less than 4,000 HDD.

ASHRAE Climate Zones



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

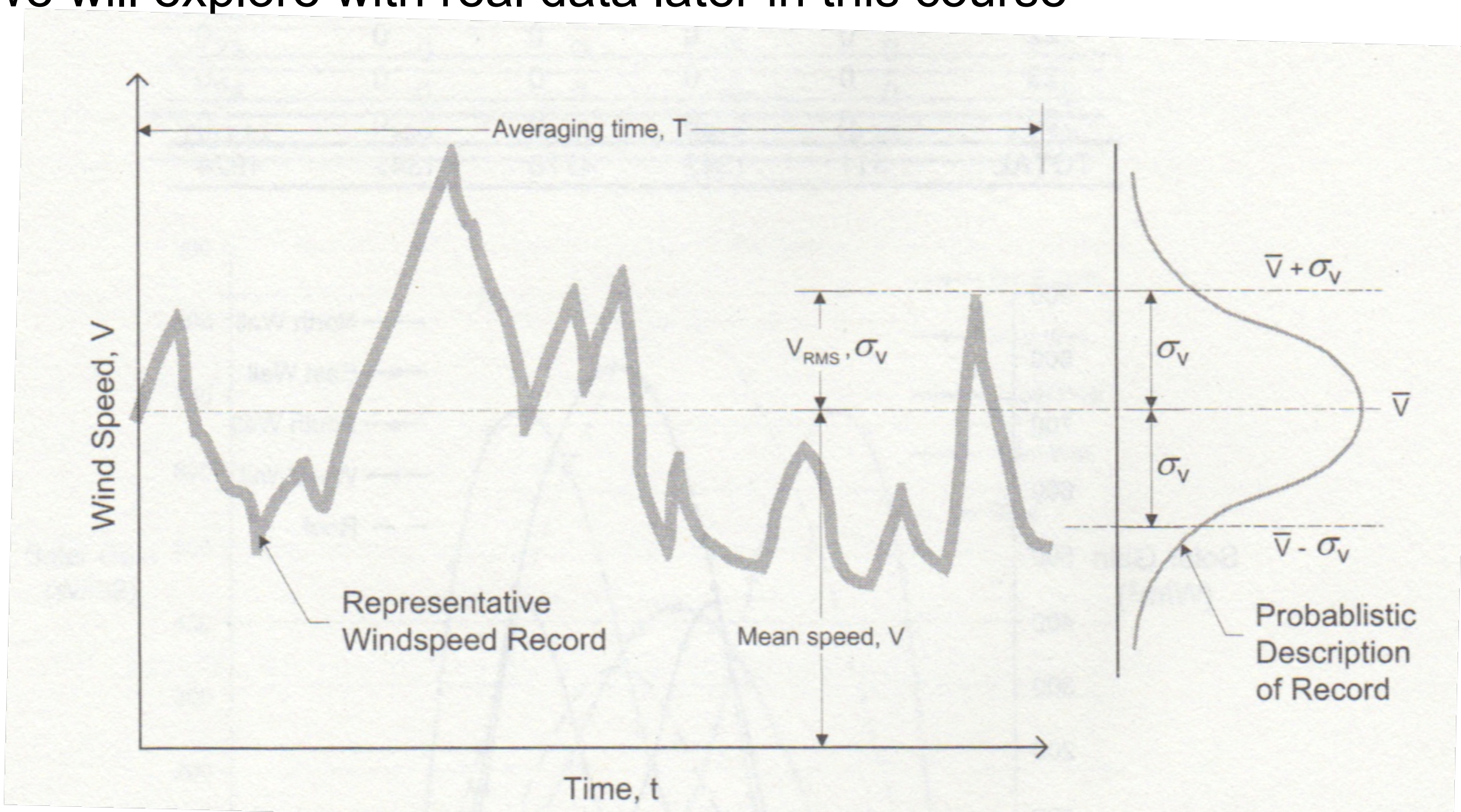
Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

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
  - It starts with relationships between the sun and surfaces on the earth
    - Will cover this in the next couple of lectures

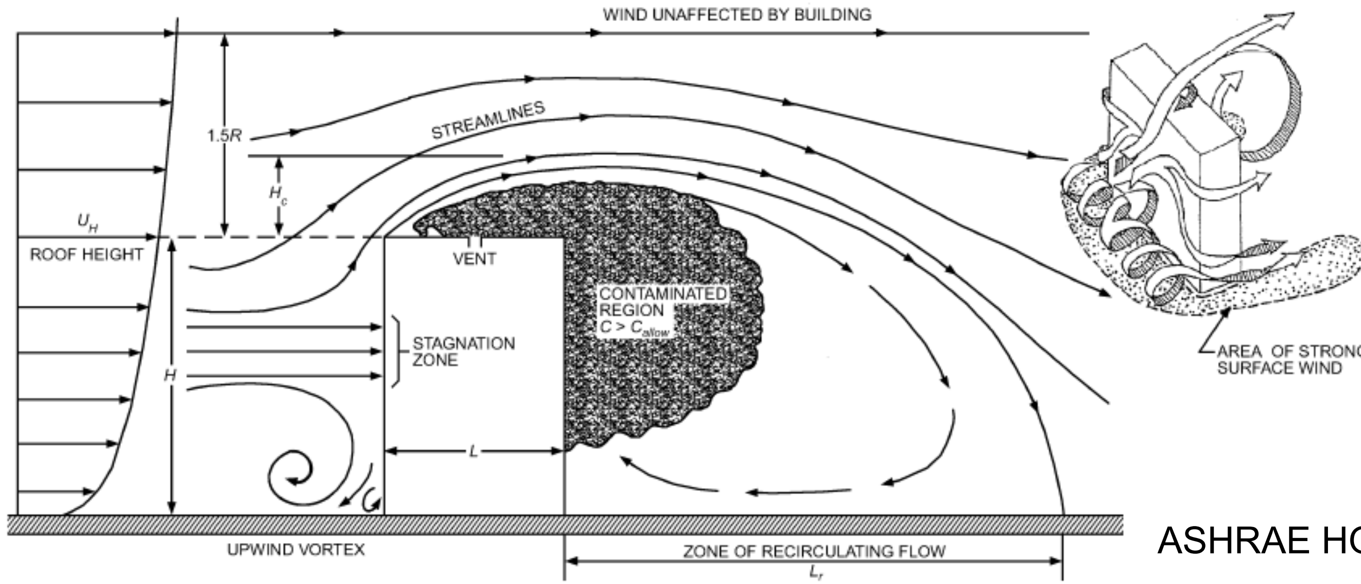
Wind

- 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
  - We will explore with real data later in this course



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

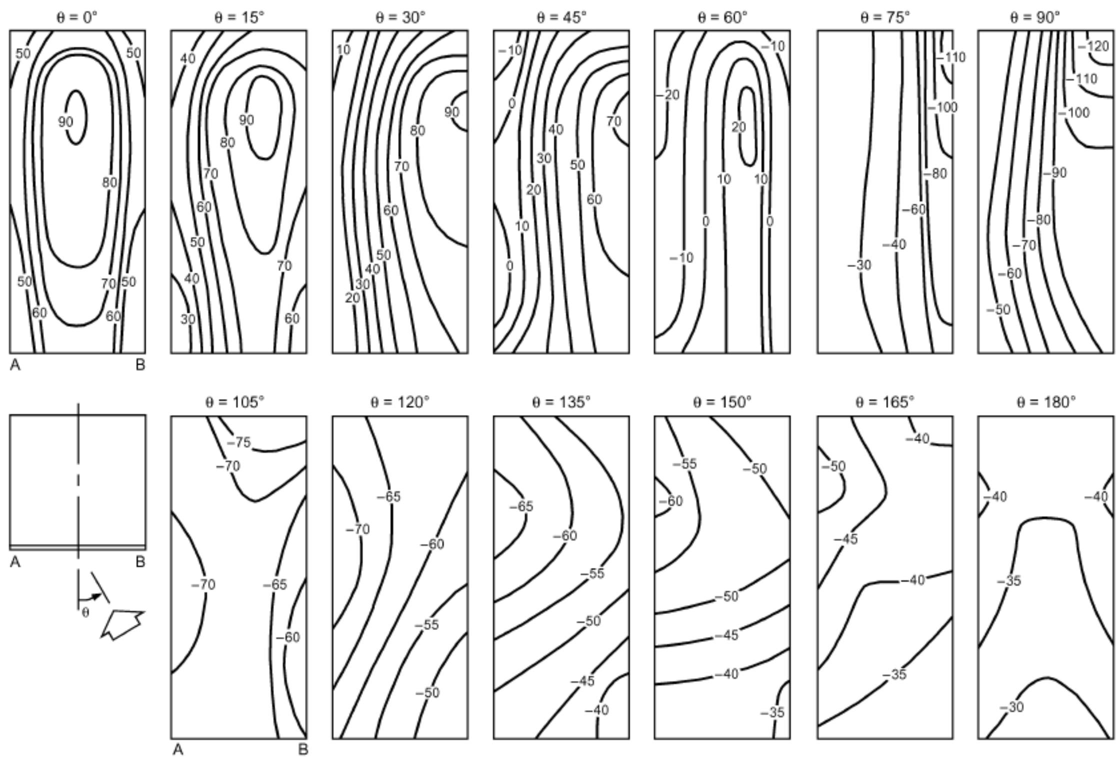
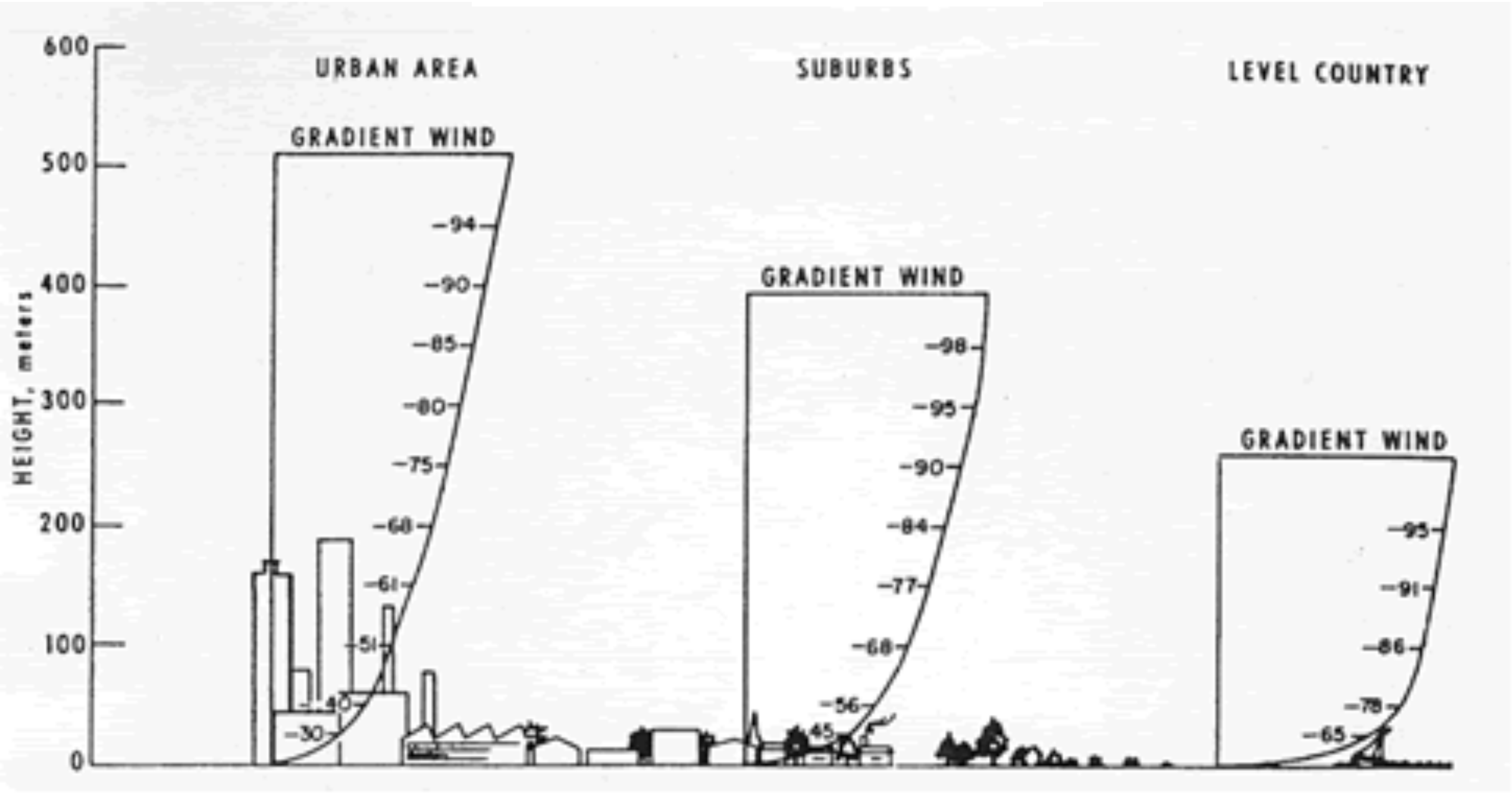


Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

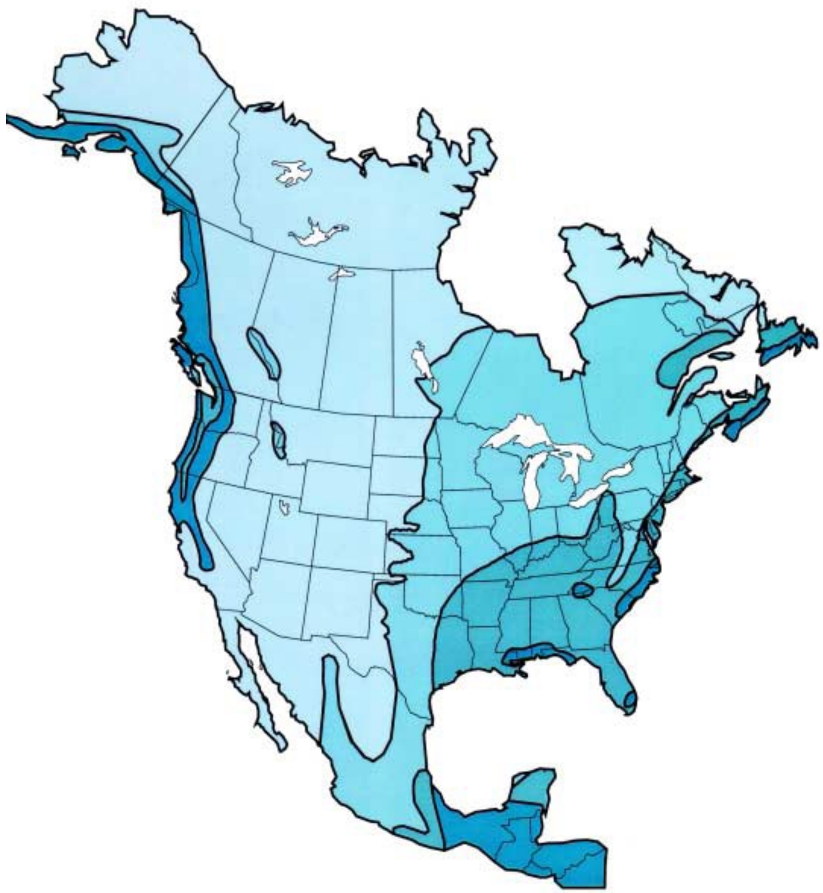
Wind speed gradients

- 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

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

Solar insolation
- Infrared
- Visible light
- Ultraviolet radiation

Wind
- Speed
- Direction
- Resulting ΔP

You should be very familiar with these parameters

HEAT, AIR, AND MOISTURE (HAM) FUNDAMENTALS

Nature of heat, air, and moisture

- **States of matter of relevance**
  - 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
  - Adsorbed compounds
    - Loosely attached to molecules of liquids or solids

Nature of heat, air, and moisture

Heat and energy basics

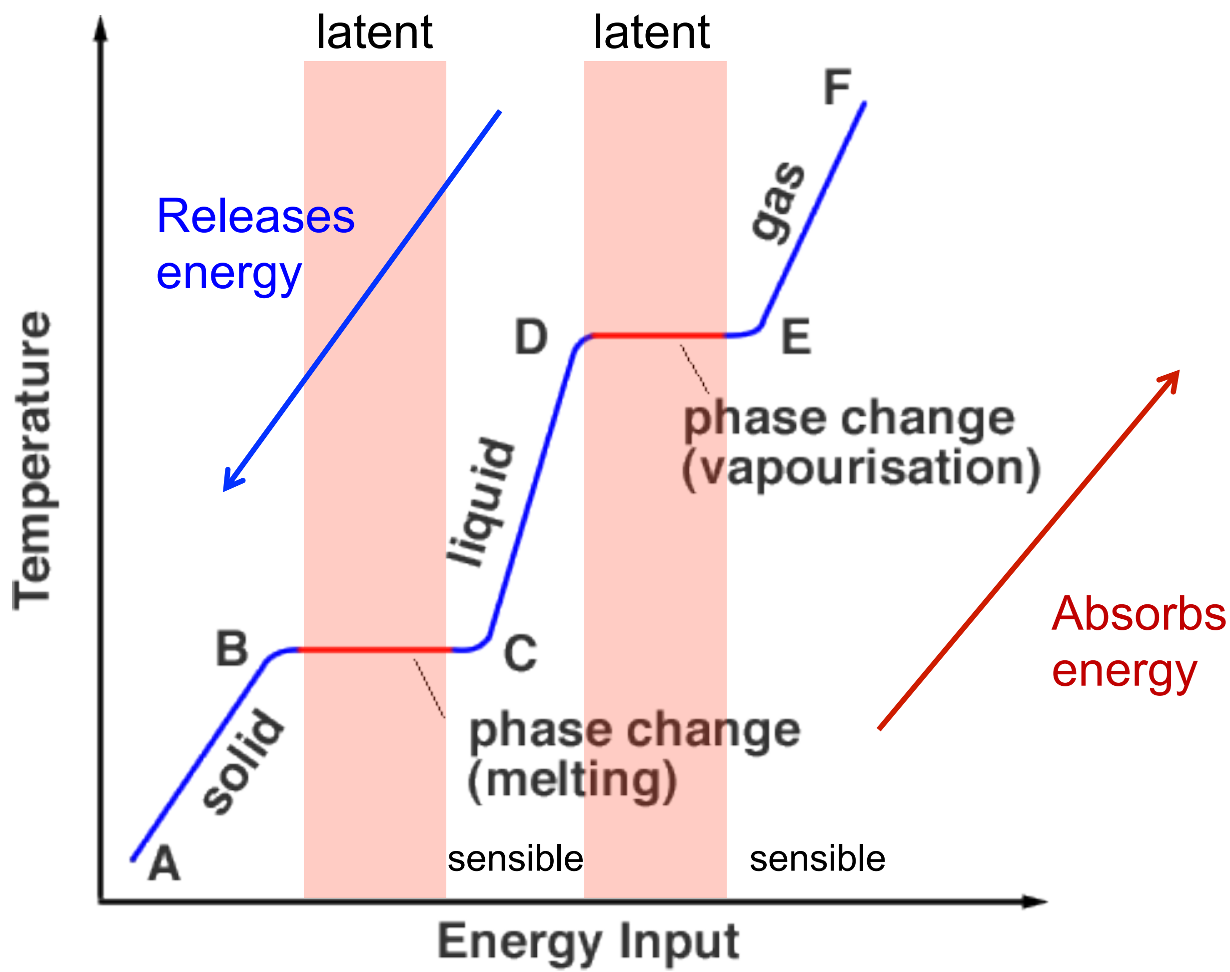
- Sensible energy, J
  - Energy used to increase the velocity or vibrations of molecules
  - i.e., temperature

- Specific heat capacity, J/kgK
  - Sensible energy required to raise a unit mass of material one unit of temperature

- Latent energy, J
  - 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



Psychrometrics: Dry 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?

Psychrometrics: Moist air

- Chemical species in **clean, moist** 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?

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 1 in 2013)
    - IP/SI versions are on Blackboard

Key terms for describing moist air

- To describe and deal with moist air, we need to be able to describe the fractions of dry air and water vapor
- There are several different equivalent measures
  - Which one you use depends on what data you have to start with and what quantity you are trying to find

Key terms to know:

- Dry bulb temperature
- Vapor pressure
- Saturation
- Relative humidity
- Absolute humidity (or humidity ratio)
- Dew point temperature
- Wet bulb temperature
- Enthalpy
- Density
- Specific volume

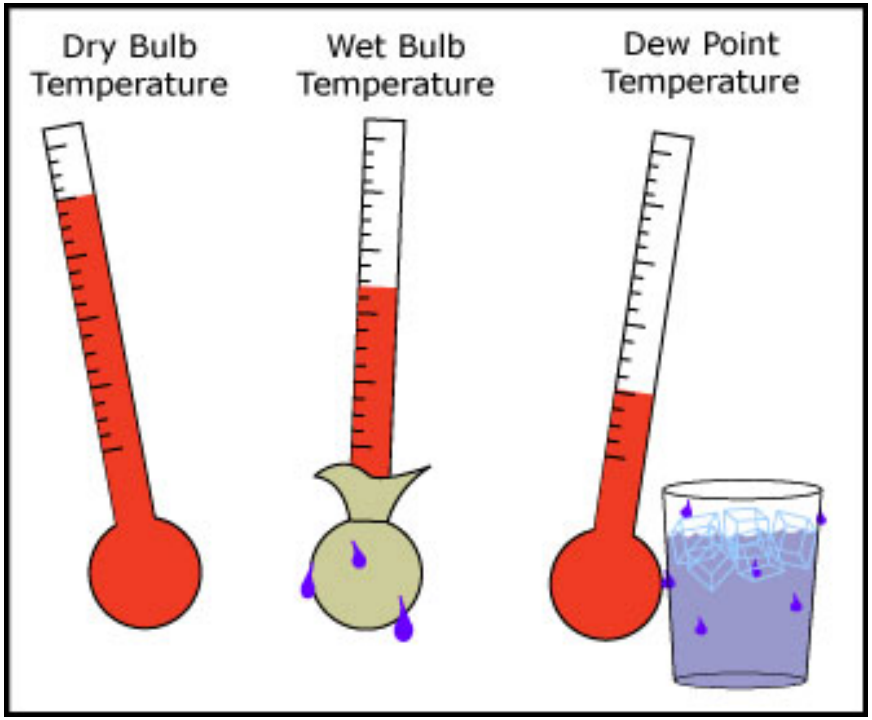
Remember: 3 different temperatures T, T_{dew}, and T_{wb}

The standard temperature, T, we are all familiar with is called the **dry-bulb** temperature, or T_d

- It is a measure of internal energy

We can also define:

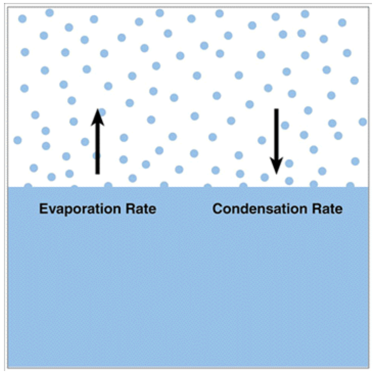
- **Dew-point** temperature, T_{dew}
  - Temperature at which water vapor changes into liquid (condensation)
  - Air is maximally saturated with water vapor
- **Wet-bulb** temperature, T_{wb}
  - The temperature that a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it



Units of Celsius, Fahrenheit, or Kelvin

Key concepts: Vapor pressure and Saturation

- Air can hold moisture (i.e., **water vapor**)
- **Vapor pressure** is a measurement of the amount of water vapor in a volume/parcel of air



$$p_w$$

*Units of pressure, Pa or kPa

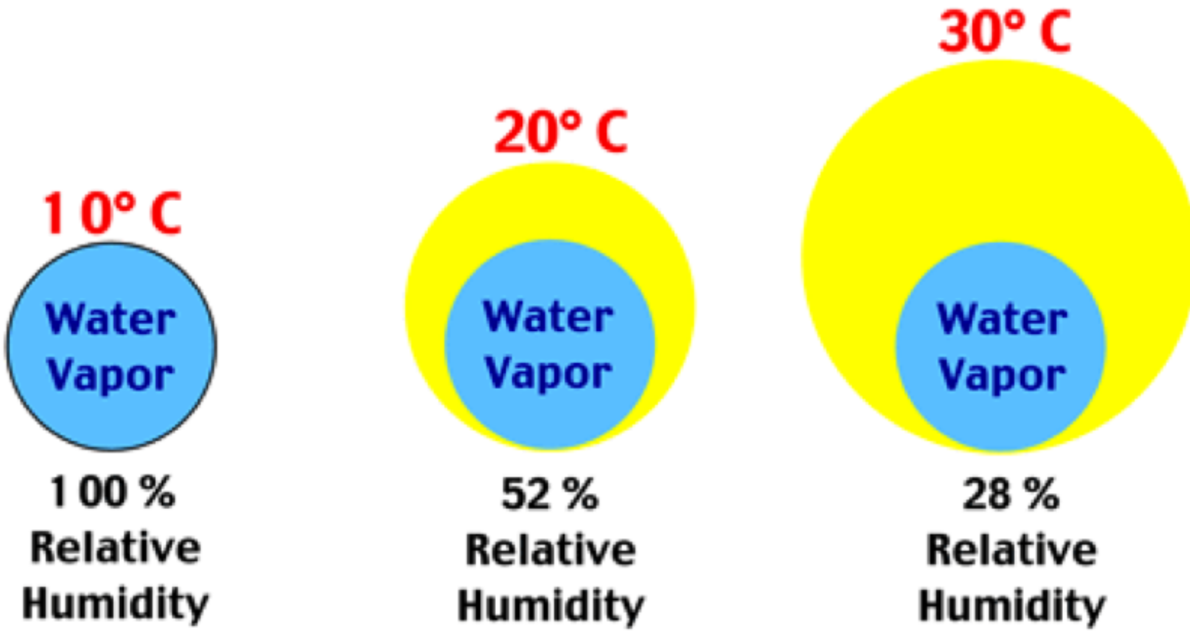
- The amount of moisture air can hold in vapor form before condensation occurs is dependent on temperature
  - We call the limit ***saturation***

$$p_{ws}$$

*Units of pressure, Pa or kPa

Key concept: Relative humidity, ϕ

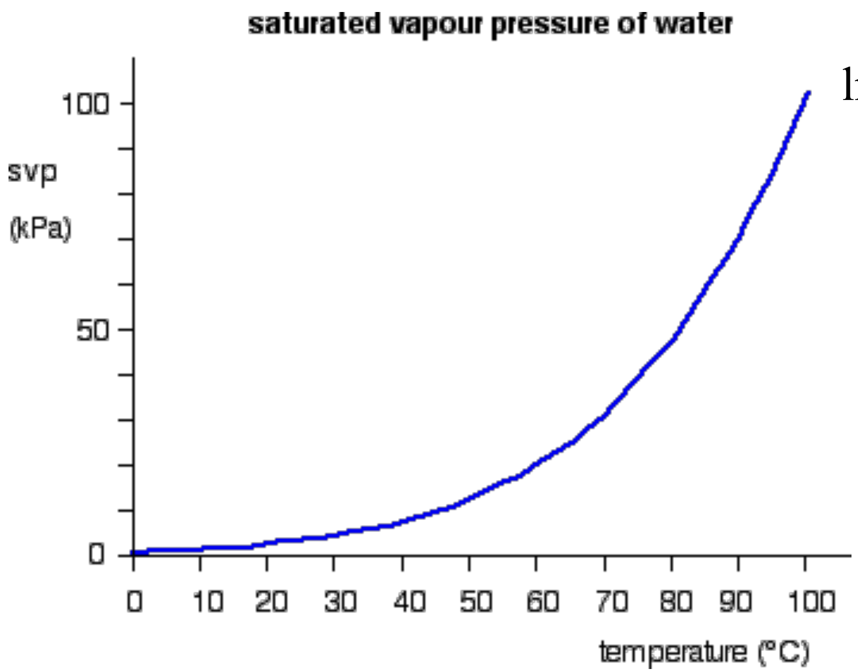
- **Relative humidity** (RH, or ϕ) is the ratio of the vapor pressure of moisture in a sample of air to the *saturation* vapor pressure at the dry bulb temperature of the sample
  - RH is therefore a function of temperature
- Relative humidity ≠ absolute humidity (or humidity ratio)



$$\phi = \frac{p_w}{p_{ws}}$$

Key concept: Saturation vapor pressure, p_{ws}

- The **saturation vapor pressure** is the partial pressure of water vapor at saturation (p_{ws}) *Units of pressure, Pa or kPa
  - Cannot absorb any more moisture at that temperature
- We can look up p_{ws} in tables (as a function of T)
  - Table 3 in Ch.1 of 2013 ASHRAE Fundamentals
- We can also use empirical equations:



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

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

Key concept: Humidity ratio, W

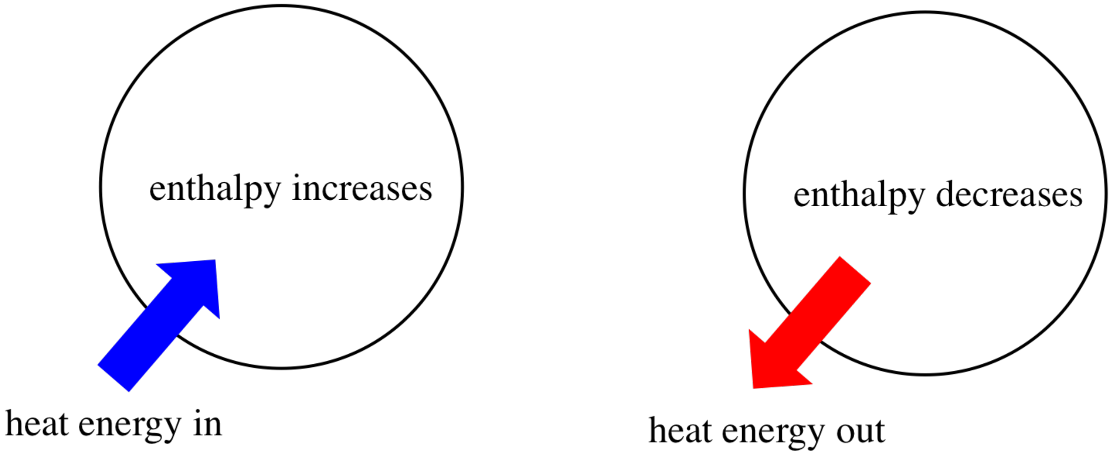
- The **humidity ratio** is a direct measure of the moisture content of a parcel of air
- Simply, the humidity ratio is the mass quantity of water vapor that exists in a mass parcel of air
  - Units of mass of water vapor per mass of dry air
    - kg/kg (kg_w/kg_{da})
    - g/kg (g_w/g_{da})

$$W = \frac{\text{mass of water vapor}}{\text{mass of dry air}} \quad \left[\frac{kg_w}{kg_{da}}\right]$$

$$W = \frac{m_w}{m_{da}} = \frac{MW_w p_w}{MW_{da} p_{da}} = 0.622 \frac{p_w}{p_{da}} = 0.622 \frac{p_w}{p - p_w} \quad \left[\frac{kg_w}{kg_{da}}\right]$$

Key concept: Enthalpy

- **Enthalpy** is a measure of the amount of energy in a system
  - Units of Joules (specific enthalpy in J/kg)
- The enthalpy of moist air is the total enthalpy of the dry air and the water vapor mixture per mass of moist air
- Includes:
  - Enthalpy of dry air, or sensible heat
  - Enthalpy of evaporated water, or latent heat



Enthalpy, *h*

- The enthalpy of a mixture of perfect gases equals the sum of the individual partial enthalpies of the components
- Therefore, the enthalpy (h) for moist air is: $$h = h_{da} + Wh_g$$

  h = enthalpy for moist air [kJ/kg]
  h_g = specific enthalpy for saturated water vapor (i.e., h_{ws}) [kJ/kg_w]
  h_{da} = specific enthalpy for dry air (i.e., h_{ws}) [kJ/kg_{da}]

- Some approximations: $h_{da} \approx 1.006T$ $\quad h_g \approx 2501 + 1.86T$

$$h \approx 1.006T + W(2501 + 1.86T)$$

*where T is in °C

Key concept: Density and specific volume

Specific volume

- Specific volume is the volume of unit mass of dry air at a given temperature, expressed as m^3/kg_{da} (inverse of dry density)

$$\upsilon = \frac{\text{volume of dry air}}{\text{mass of dry air}} \quad [\frac{m^3}{kg_{da}}]$$

Air density

- Density is a measure of the mass of moist air per unit volume of air
- Includes mass of dry air + water vapor

$$\rho = \frac{\text{mass of moist air}}{\text{volume of moist air}} \quad [\frac{kg}{m^3}]$$

Specific volume, v, and density, ρ

- The specific volume of moist air (or the volume per unit mass of air, m^3/kg) can be expressed as:

$$v = \frac{R_{da}T}{p - p_w} = \frac{R_{da}T(1 + 1.6078W)}{p}$$

where

v = specific volume, m^3/kg_{da}
t = dry-bulb temperature, °C
W = humidity ratio, kg_w/kg_{da}
p = total pressure, kPa

$$v \approx 0.287042(T + 273.15)(1 + 1.6078W) / p$$

- If we have v we can also find moist air density, ρ (kg/m^3):

$$\rho = \frac{m_{da} + m_w}{V} = \frac{1}{v}\left(1 + W\right)$$

Dew-point temperature, T_{dew}

The dew point temperature, T_{dew}, is the air temperature at which the current humidity ratio W is equal to the saturation humidity ratio W_s at the same temperature

i.e. $W_s(p, T_{dew}) = W$

When the air temperature is lowered to the dew-point at constant pressure, the relative humidity rises to 100% and condensation occurs

T_{dew} is a direct measure of the humidity ratio W since $W = W_s$ at $T = T_{dew}$

Dew-point temperature, T_{dew}

- Dew-point temperature, T_{dew}

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
α = $\ln p_w$
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

Note:
These constants are only for SI units
IP units are different

Wet-bulb temperature, T_{wb}

- Wet-bulb temperature, T_{wb}
- Requires iterative solver… find the T_{wb} that satisfies the following equation (above freezing):

$$W = \frac{(2501 - 2.326T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2501 + 1.86T - 4.186T_{wb}} = \text{actual } W$$

- And for T below freezing:

$$W = \frac{(2830 - 0.24T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2830 + 1.86T - 2.1T_{wb}} = \text{actual } W$$

*Where T_{wb} and T are in Kelvin

Obtaining these data from ASHRAE Tables

ASHRAE HoF Ch. 1 (2013) Table 2 gives us W_s, v_{da} , and v_s directly at different temperatures:

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressu

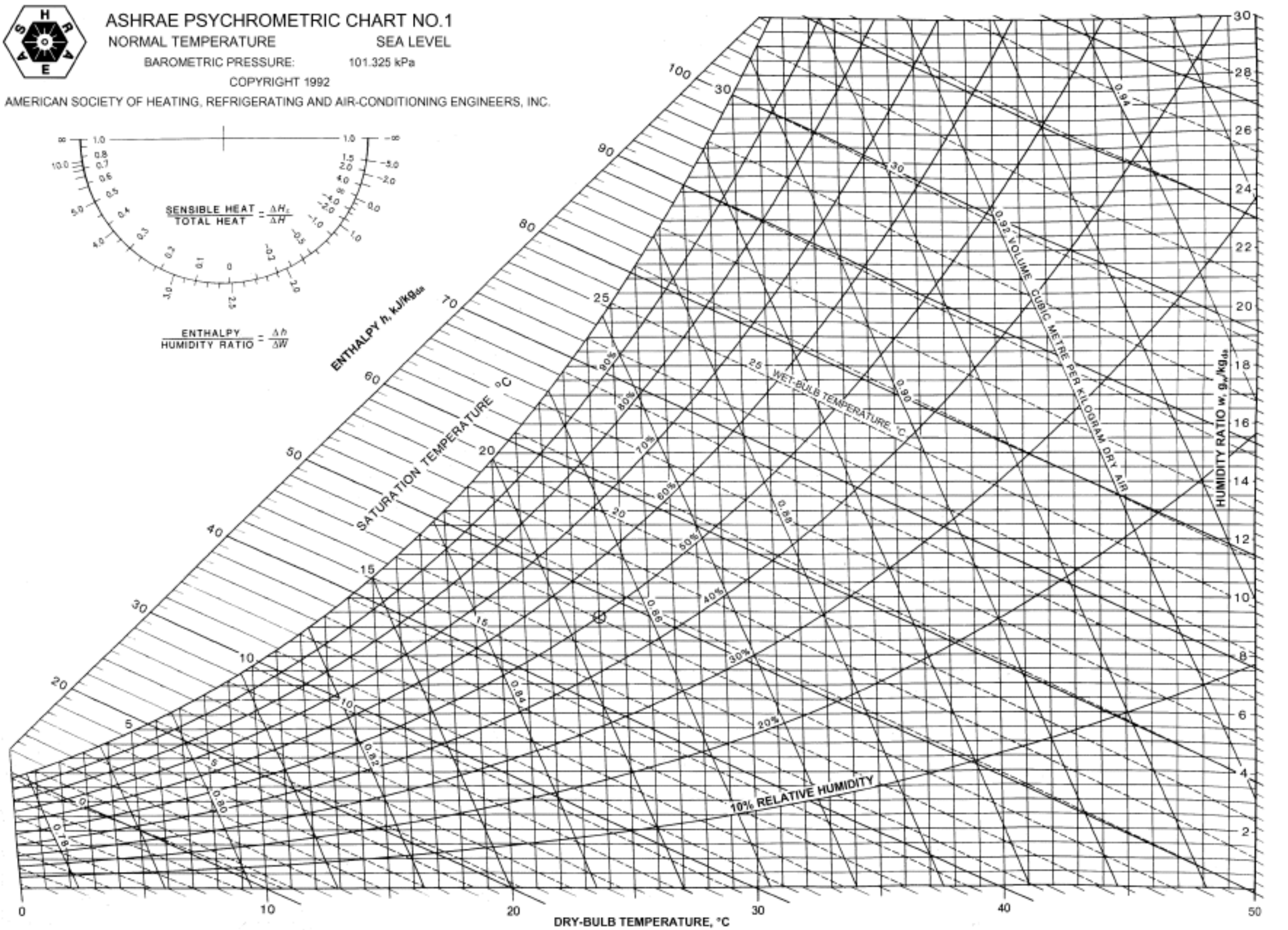
Temp., °C	Humidity Ratio	Specific Volume, m³/kg$_{da}$			Specific Enthalpy, kJ/kg$_{da}$		
t	W_s, kg$_w$/kg$_{da}$	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s
15	0.010694	0.8159	0.0140	0.8299	15.087	27.028	42.115
16	0.011415	0.8188	0.0150	0.8338	16.093	28.873	44.966
17	0.012181	0.8216	0.0160	0.8377	17.099	30.830	47.929
18	0.012991	0.8245	0.0172	0.8416	18.105	32.906	51.011
19	0.013851	0.8273	0.0184	0.8457	19.111	35.107	54.219
20	0.014761	0.8301	0.0196	0.8498	20.117	37.441	57.558
21	0.015724	0.8330	0.0210	0.8540	21.124	39.914	61.037
22	0.016744	0.8358	0.0224	0.8583	22.130	42.533	64.663

Obtaining these data from ASHRAE Tables

ASHRAE HoF Ch. 1 (2013) Table 3 gives us p_{ws} at different temperatures:

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w			Specific Enthalpy, kJ/kg_w		
		Sat. Liquid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Sat. Liquid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g
3	0.7581	0.001000	168.013	168.014	12.60	2493.80	2506.40
4	0.8135	0.001000	157.120	157.121	16.81	2491.42	2508.24
5	0.8726	0.001000	147.016	147.017	21.02	2489.05	2510.07
6	0.9354	0.001000	137.637	137.638	25.22	2486.68	2511.91
7	1.0021	0.001000	128.927	128.928	29.43	2484.31	2513.74
8	1.0730	0.001000	120.833	120.834	33.63	2481.94	2515.57
9	1.1483	0.001000	113.308	113.309	37.82	2479.58	2517.40
10	1.2282	0.001000	106.308	106.309	42.02	2477.21	2519.23


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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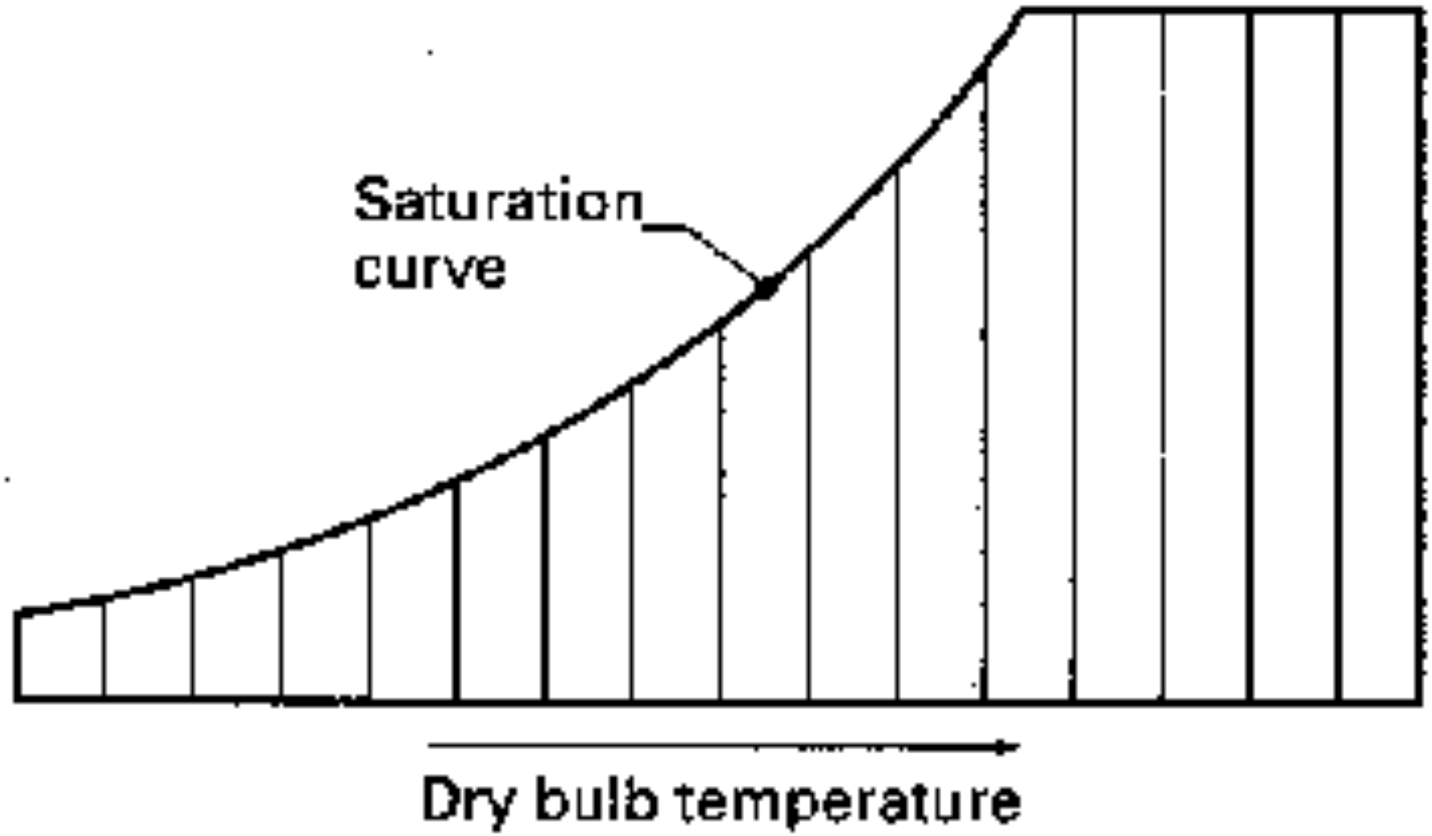
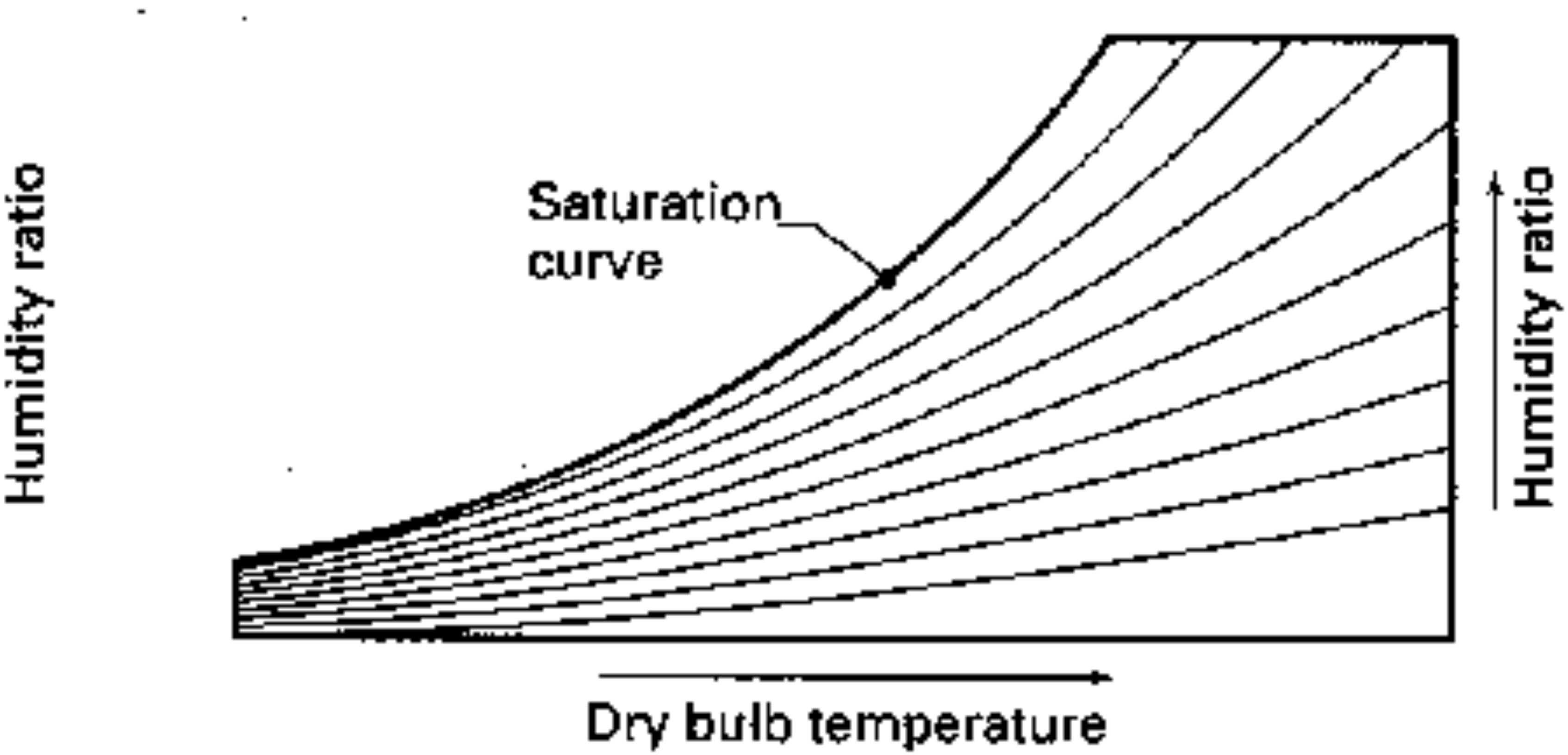
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C

Psychrometric chart: Lines of constant dry bulb *T*

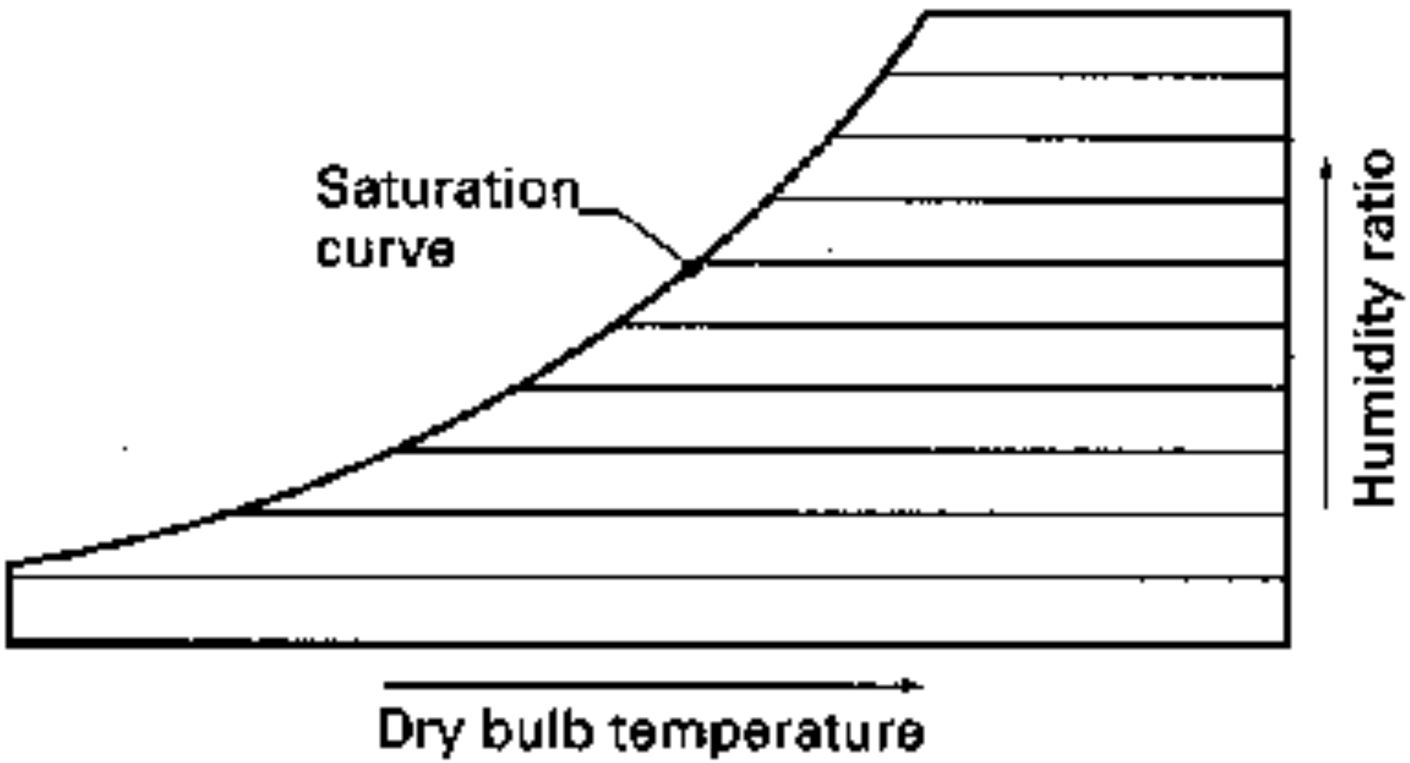


T and RH



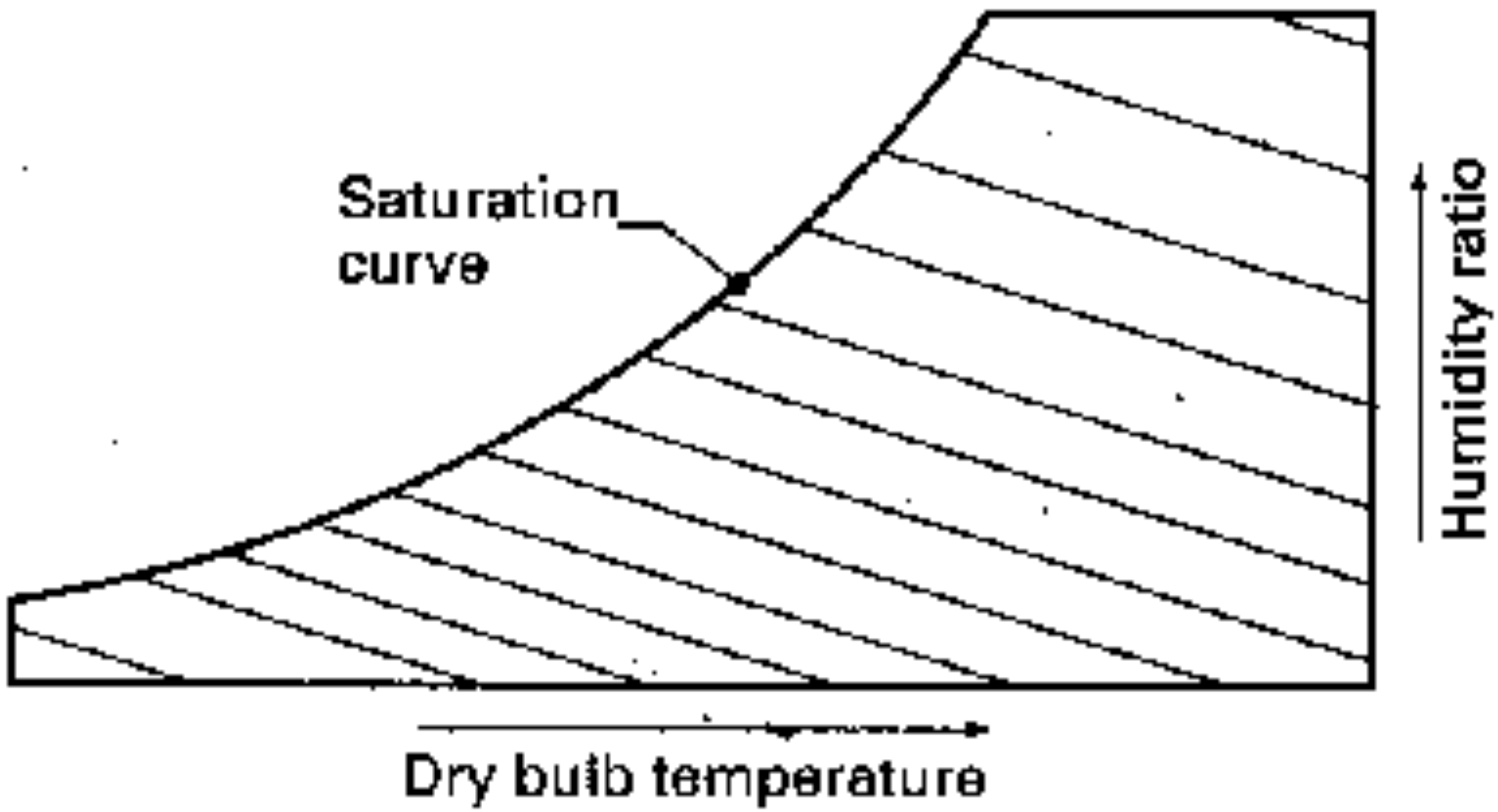
Lines of constant relative humidity

Humidity Ratio, *W*, and dry bulb *T*

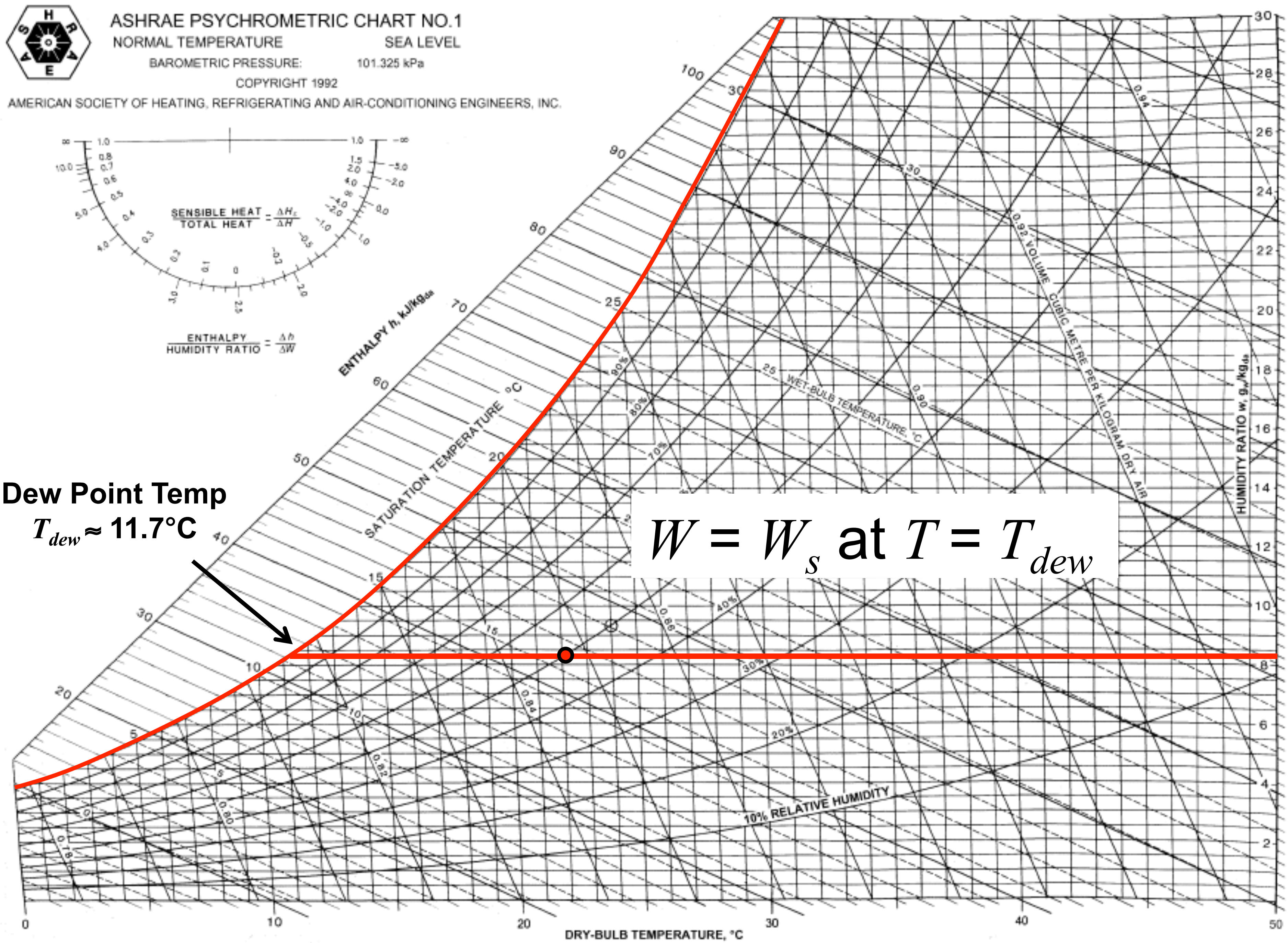


Lines of constant absolute humidity

Psychrometric chart: Lines of constant wet bulb



Lines of constant wet bulb



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NORMAL TEMPERATURE
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BAROMETRIC PRESSURE: 101.325 kPa
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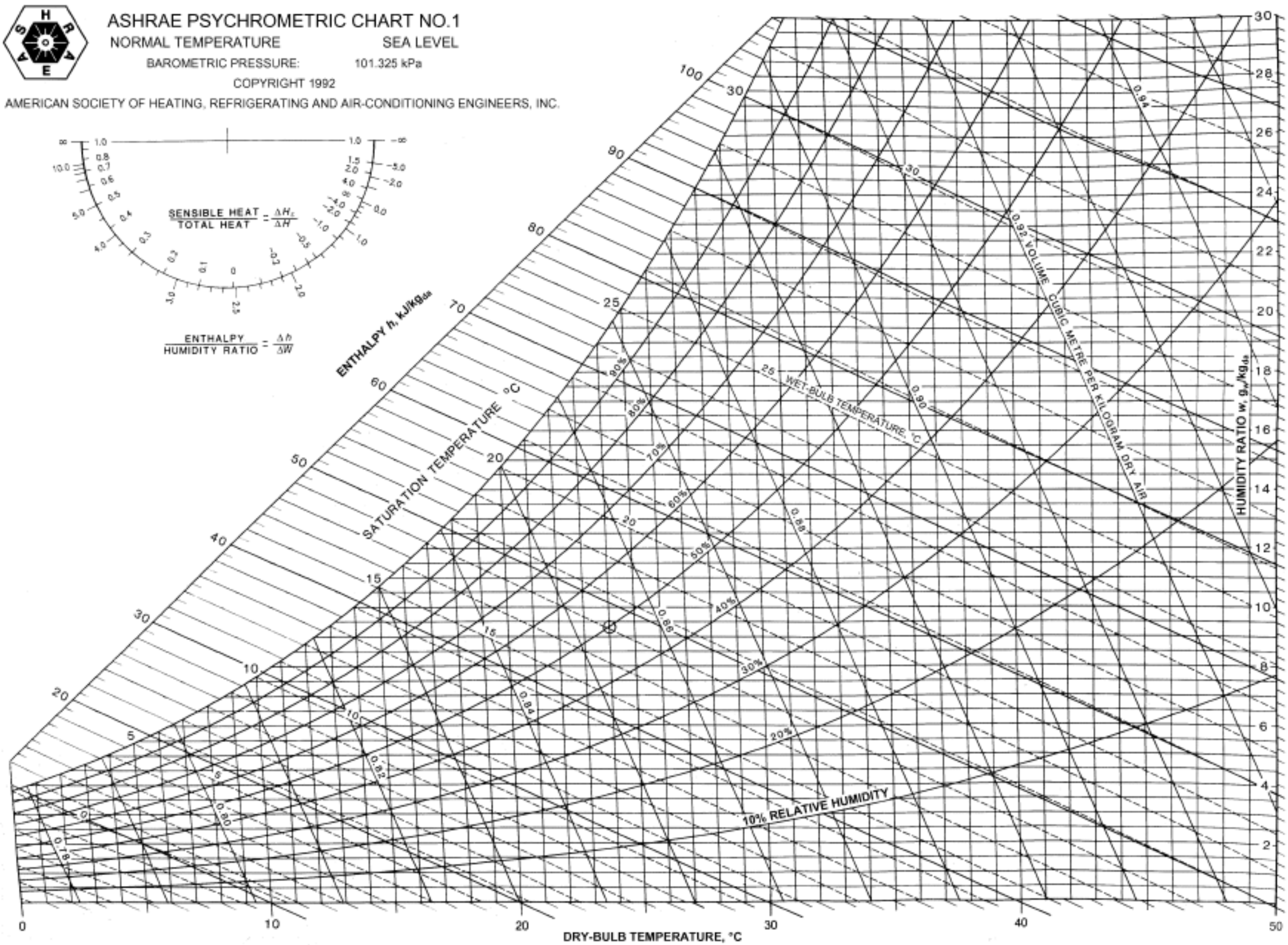
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Dew Point Temp
$T_{dew} \approx 11.7°C$
$W = W_s$ at $T = T_{dew}$


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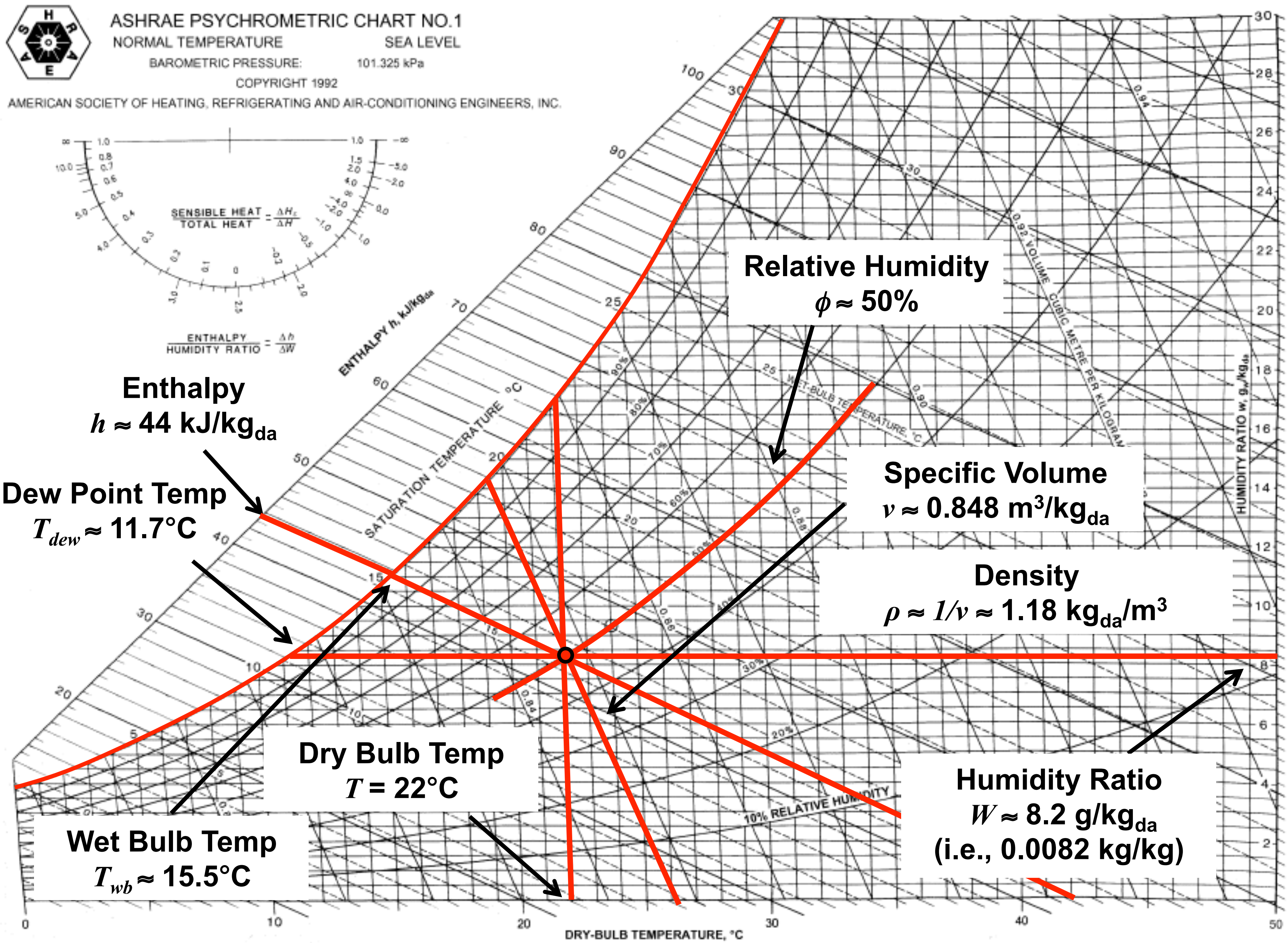
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
20%
30%
40%
50%
60%
70%
80%
90%
HUMIDITY RATIO w, gw/kg da
DRY-BULB TEMPERATURE, °C
0
10
20
30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


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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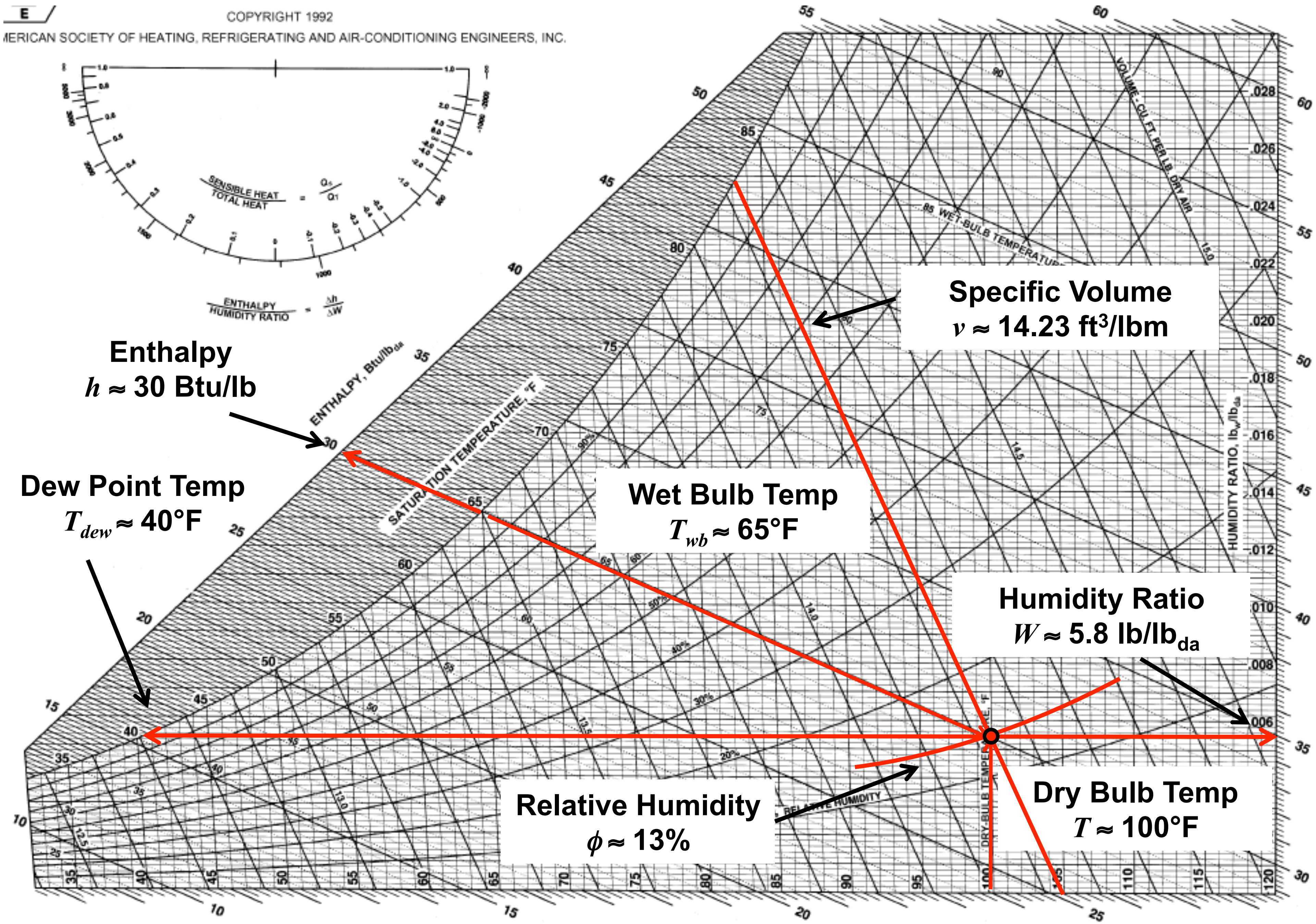
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
Relative Humidity
φ ≈ 50%
Enthalpy
h ≈ 44 kJ/kgda
Dew Point Temp
Tdew ≈ 11.7°C
Specific Volume
v ≈ 0.848 m3/kgda
Density
ρ ≈ 1/v ≈ 1.18 kgda/m3
Dry Bulb Temp
T = 22°C
Wet Bulb Temp
Twb ≈ 15.5°C
Humidity Ratio
W ≈ 8.2 g/kgda
(i.e., 0.0082 kg/kg)



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SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Enthalpy
h ≈ 30 Btu/lb
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
Dew Point Temp
Tdew ≈ 40°F
Wet Bulb Temp
Twb ≈ 65°F
Specific Volume
v ≈ 14.23 ft3/lbm
85 WET-BULB TEMPERATURE
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
Humidity Ratio
W ≈ 5.8 lb/lbda
Relative Humidity
φ ≈ 13%
RELATIVE HUMIDITY
Dry Bulb Temp
T ≈ 100°F
DRY BULB TEMPERATURE, °F

Helpful data for air

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

Temperature [°C]	Dry Density [kg/m³]	Saturation Vapor Pressure [Pa]	Saturation Humidity Ratio [g/kg]	Saturation Humidity Ratio [g/m³]
-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

Next lecture (Jan 19)

- Review of building science and heat transfer
- No class January 26 (ASHRAE conference in Orlando)