CAE 331/513
Building Science
Fall 2013

Lecture 5: September 23, 2013
Finish psychrometrics and thermal comfort
HVAC thermodynamic and psychrometric processes

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Scheduling/deliverables

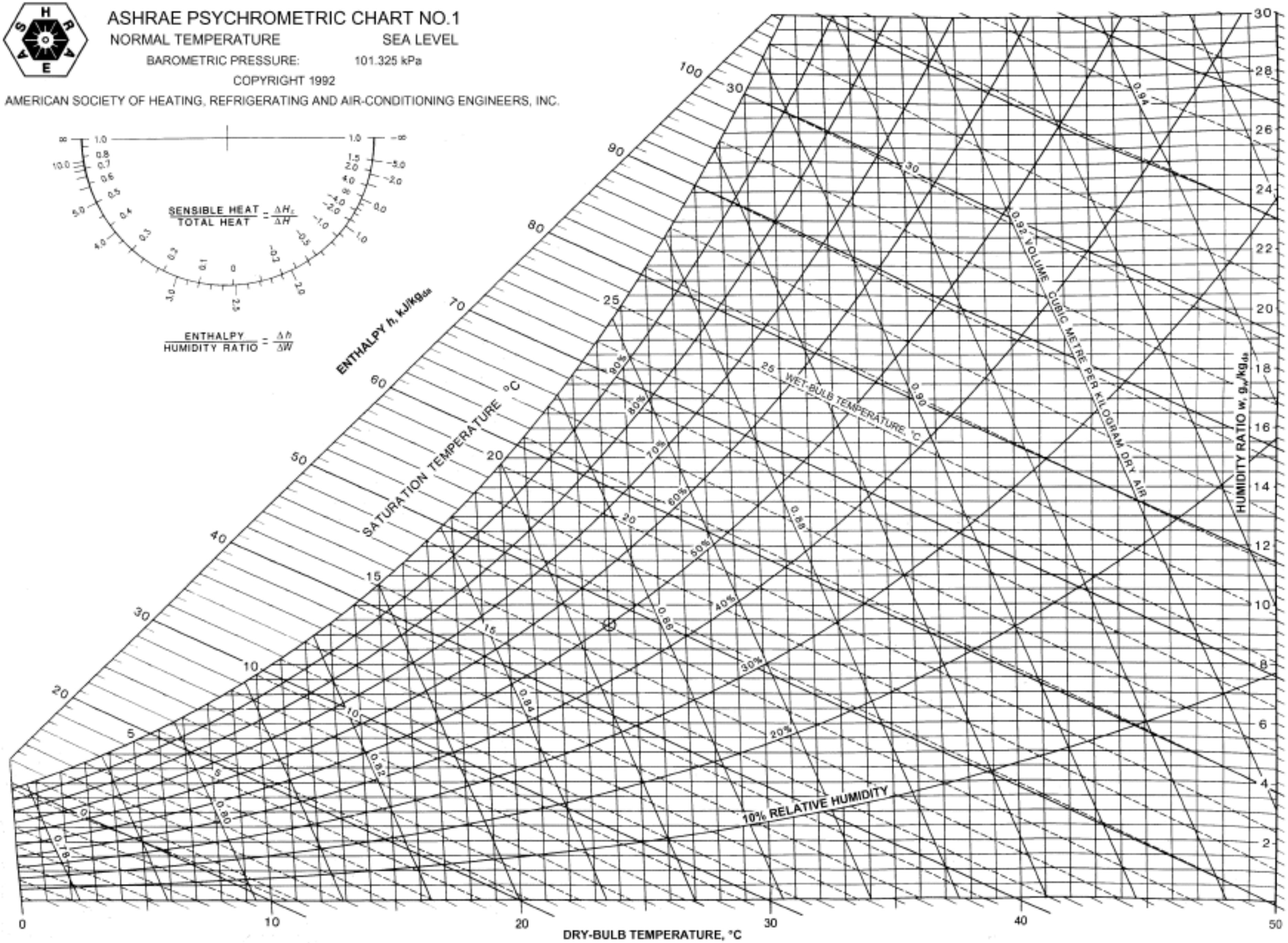
- Graduate students' blog post #3 is due today
- HW 3 (psychrometric chart) is due Monday September 30th
  - I will miss Monday's lecture on 9/20
    - AAAR conference in Portland, OR
  - Turn your HW in to our TA:
    - Elizabeth Hausheer ehaushee@hawk.iit.edu
    - Her mailbox is in CAEE office (Alumni 228) near Prof Snyder's office
- We also do not have class on the following Monday, Oct. 7th
  - Make-up class on Tuesday Oct. 8th?

Last time

- Finished solar radiation
  - I_{solar}
  - Sol-air temperatures
  - Building energy balance
- Heat transfer through windows
  - U values
  - SHGC
  - IAC (shading)
- Introduced Psychrometrics

Today's objectives

- Revisit Psychrometrics
- Human thermal comfort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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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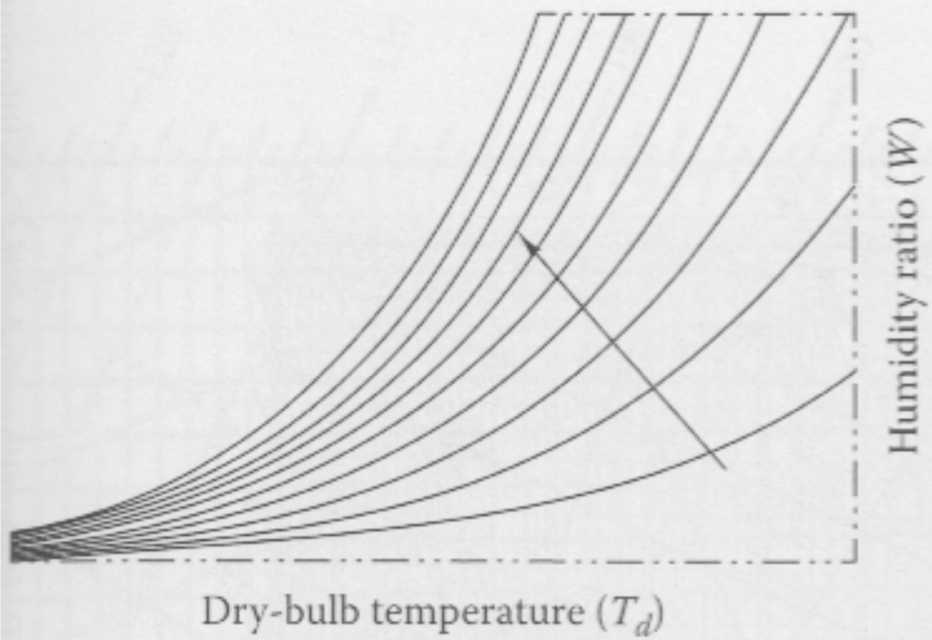
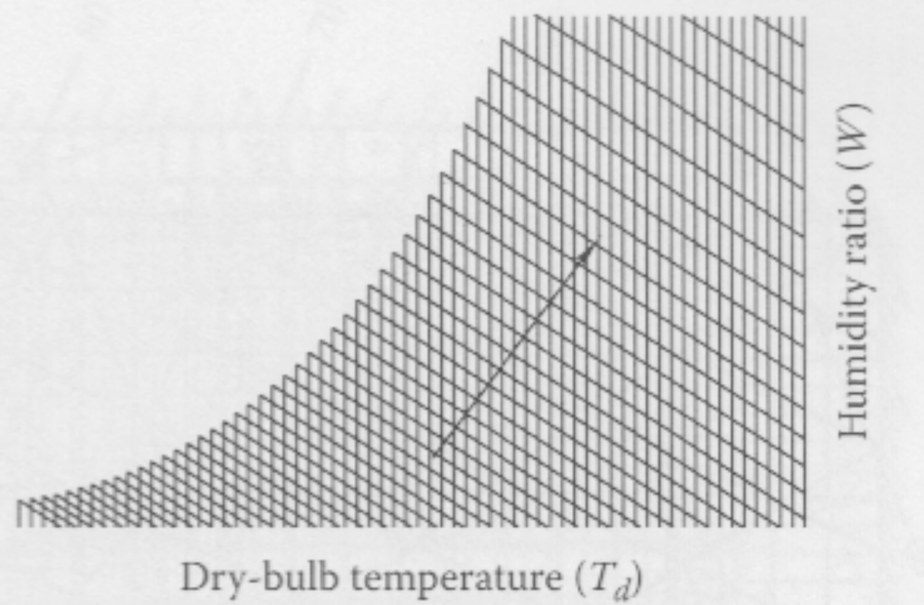
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kg da
DRY-BULB TEMPERATURE, °C

Deciphering the psychrometric chart

Lines of constant RH

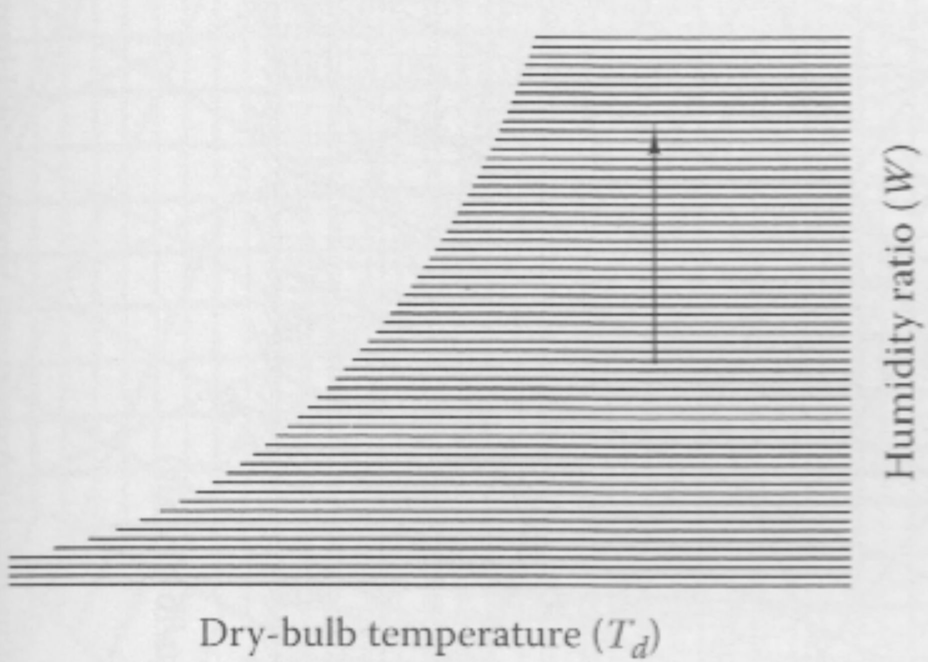


Lines of constant wet-bulb and dry-bulb

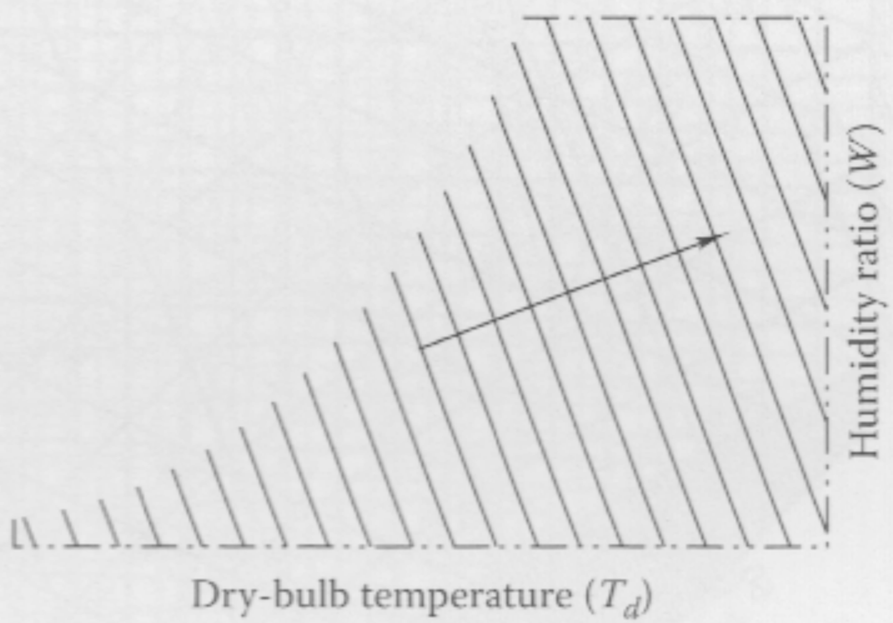


Deciphering the psychrometric chart

Lines of constant humidity ratio

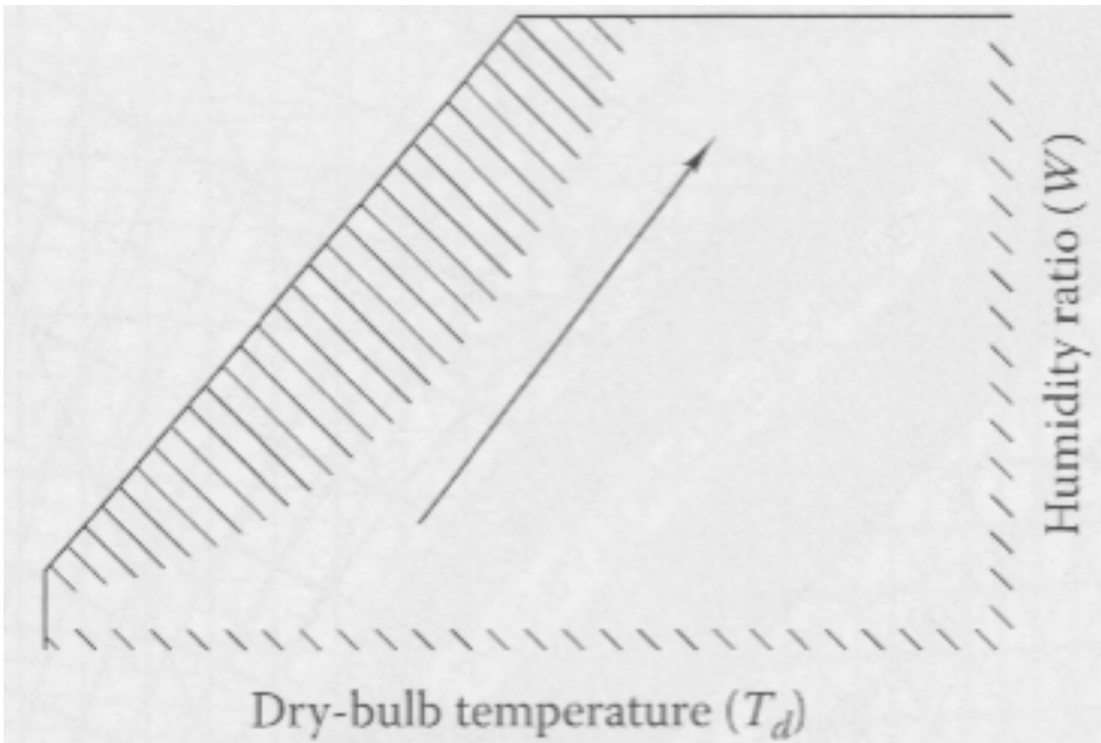


Lines of constant specific volume



Deciphering the psychrometric chart

Lines of constant enthalpy



Revisit example from last class

Moist air exists at 30°C dry-bulb temperature with a 15°C dew point temperature

Find the following:

(a) the humidity ratio, W

(b) degree of saturation, μ

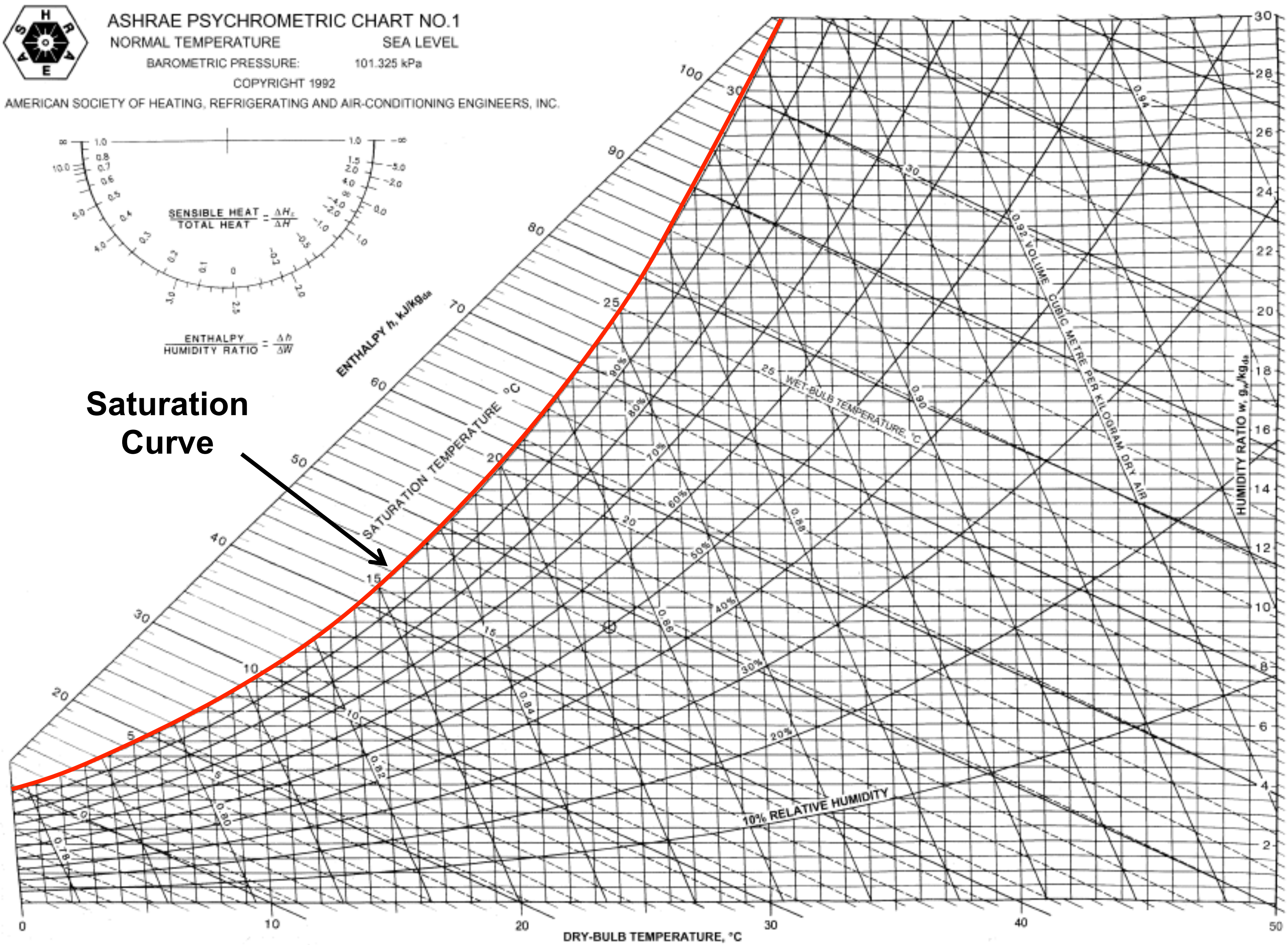
(c) relative humidity, ϕ

(d) enthalpy, h

(e) specific volume, v

(f) density, ρ

(g) wet-bulb temperature, T_{wb}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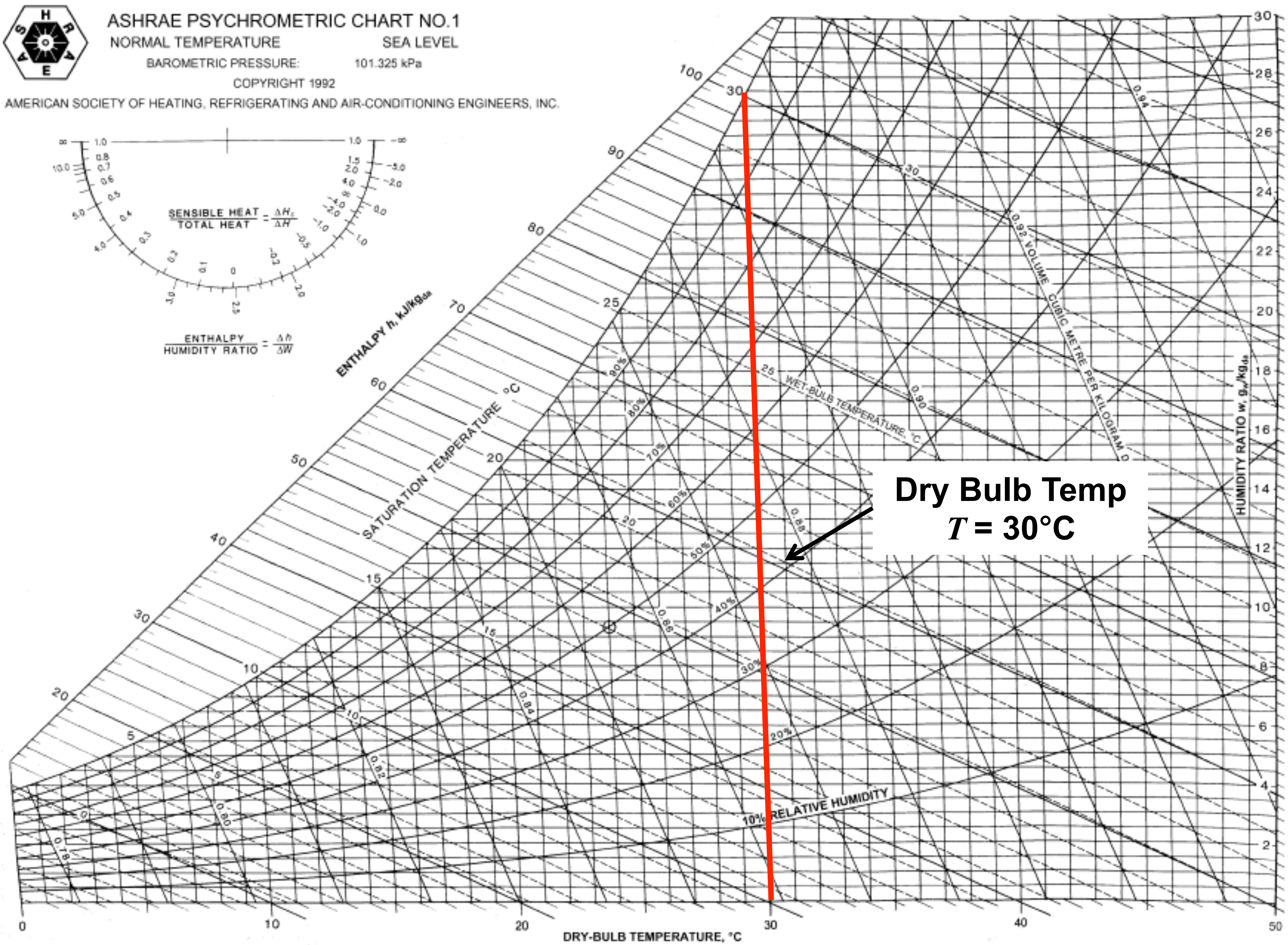
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g_w/kg_da
DRY-BULB TEMPERATURE, °C
Saturation Curve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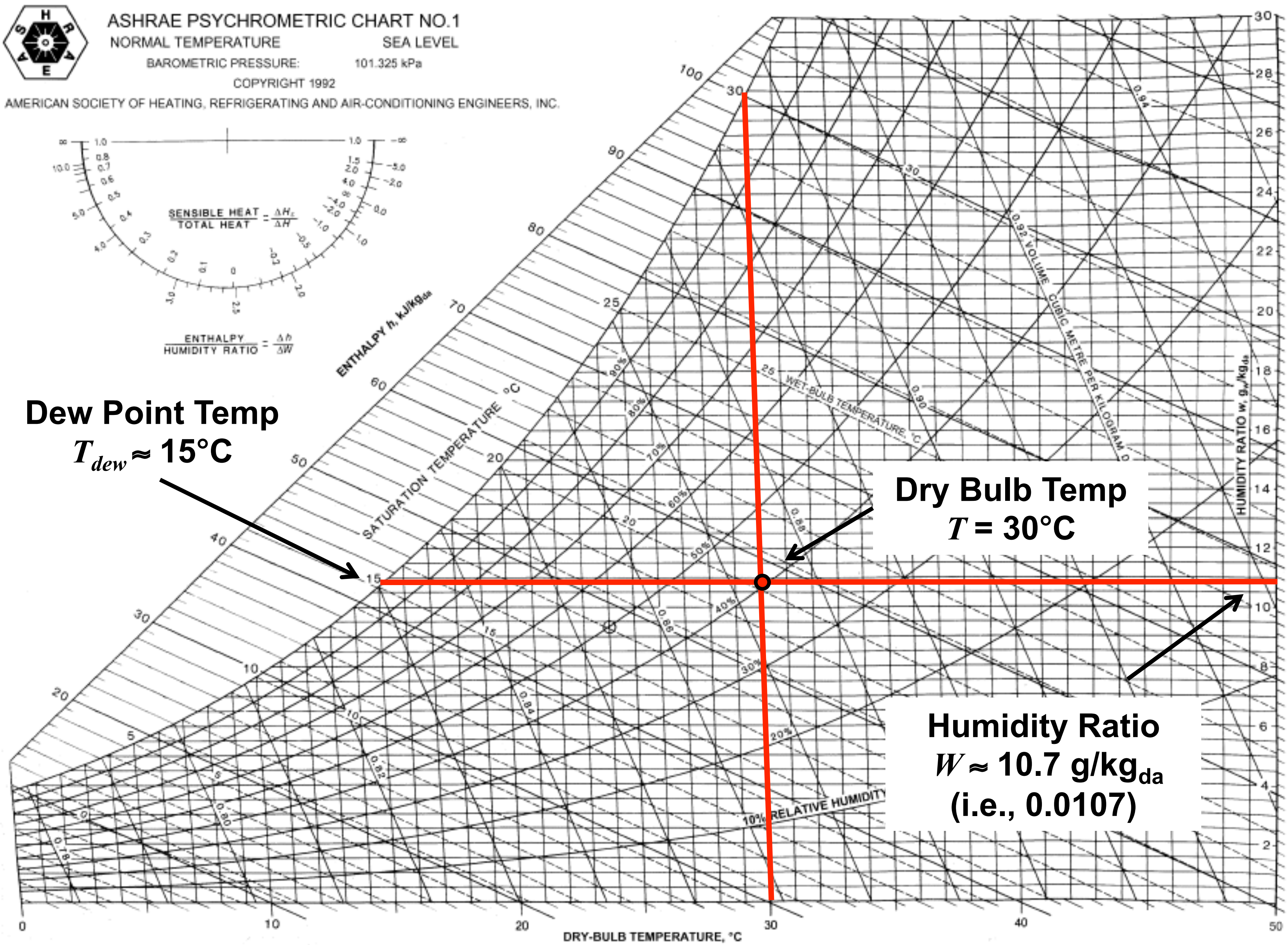
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C
Dry Bulb Temp
T = 30°C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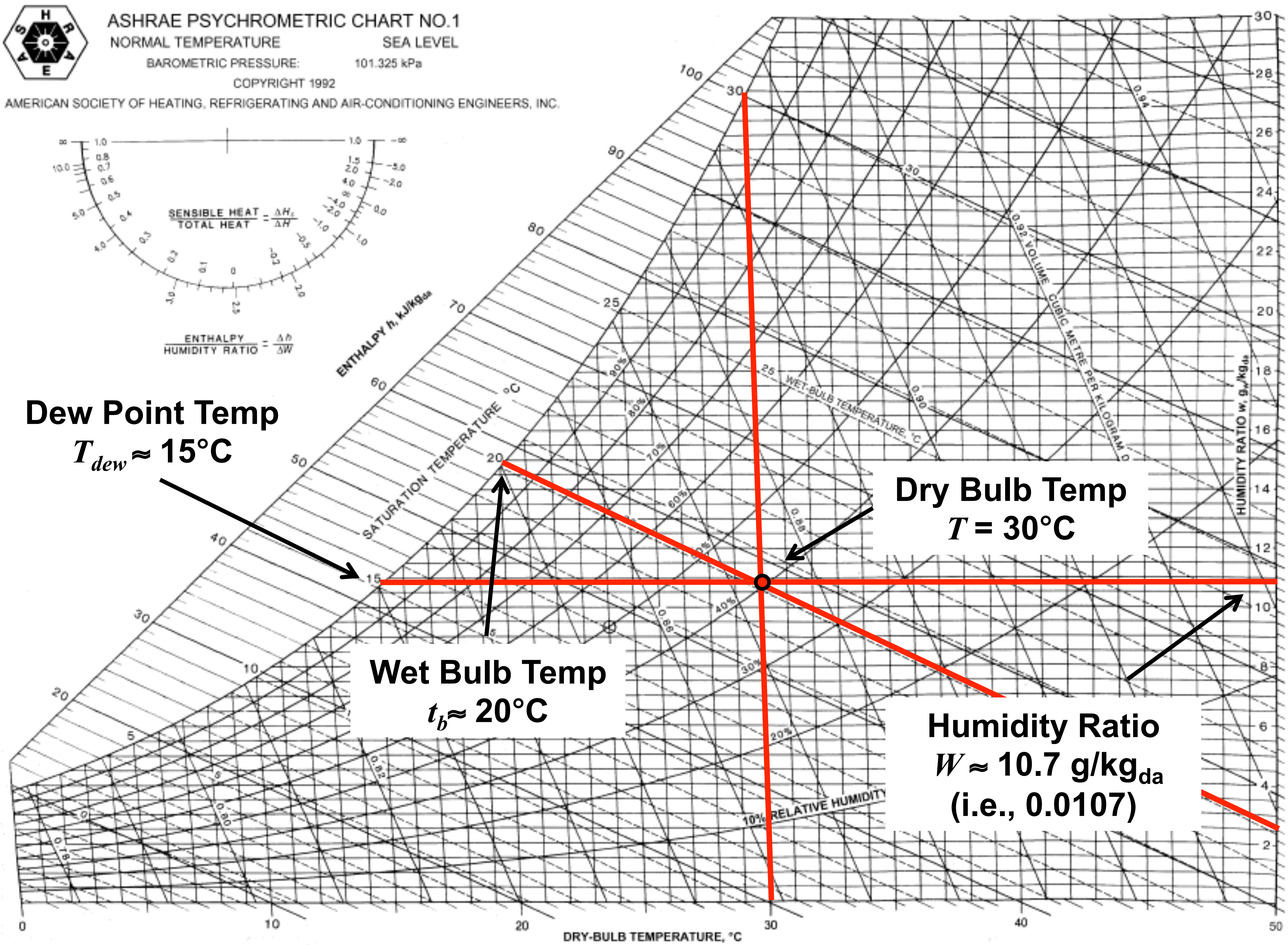
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO W, gw/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Dew Point Temp
T dew ≈ 15°C
Dry Bulb Temp
T = 30°C
Humidity Ratio
W ≈ 10.7 g/kg da
(i.e., 0.0107)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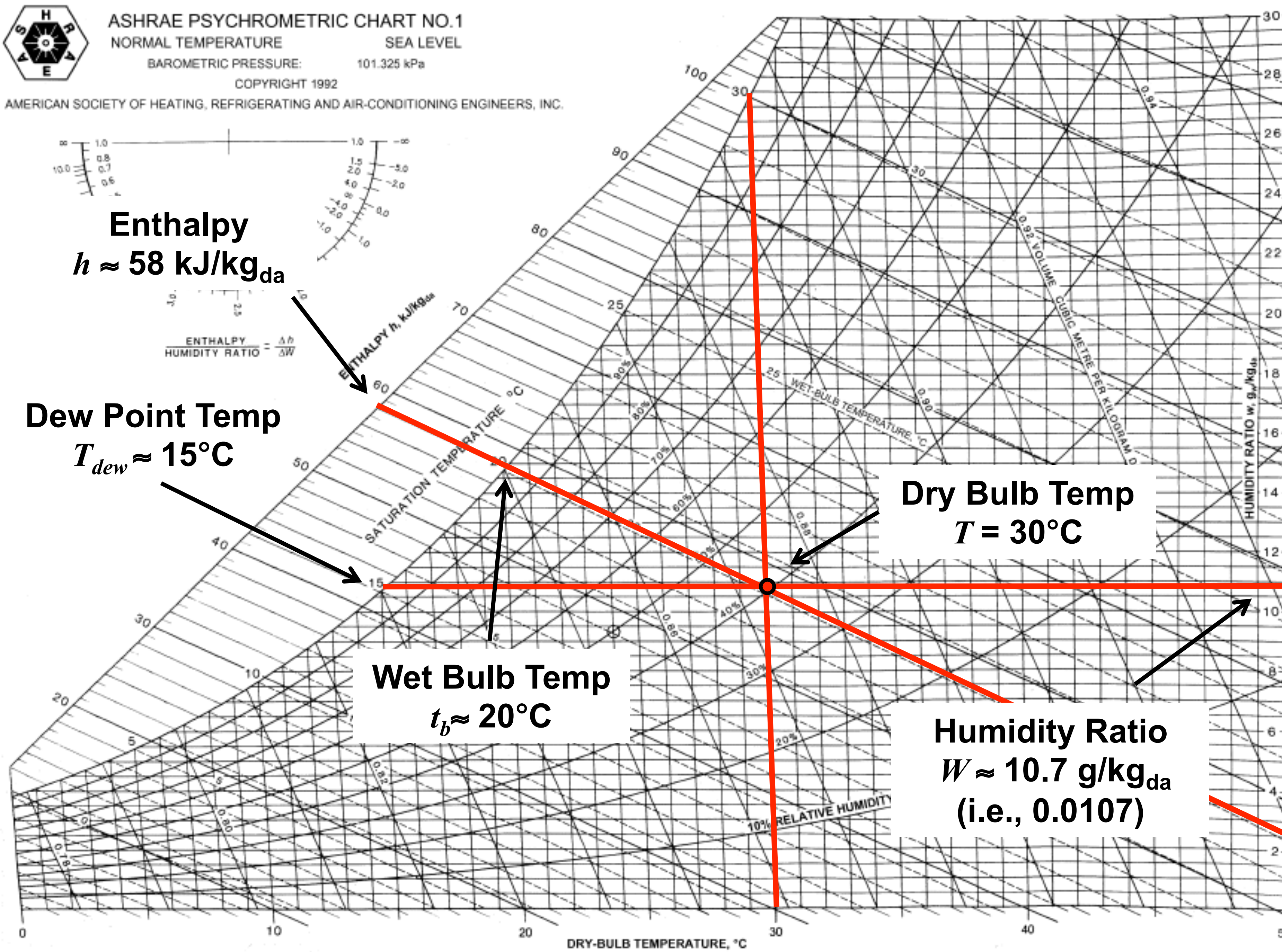
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Dew Point Temp
$T_{dew} \approx 15°C$
Wet Bulb Temp
$t_b \approx 20°C$
Dry Bulb Temp
$T = 30°C$
Humidity Ratio
$W \approx 10.7\ g/kg_{da}$
(i.e., 0.0107)



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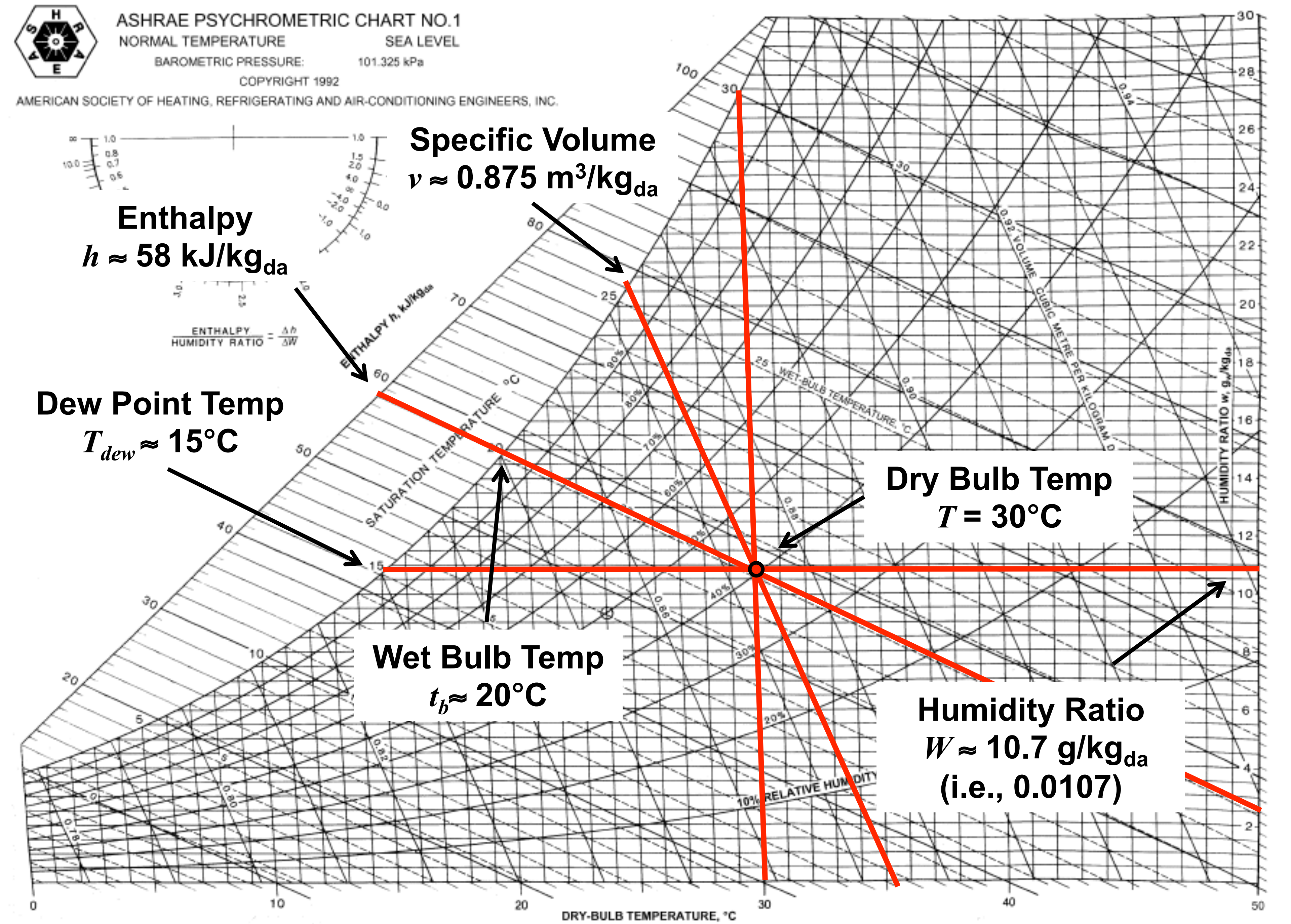
Enthalpy
h ≈ 58 kJ/kg_da
Dew Point Temp
T_dew ≈ 15°C
Wet Bulb Temp
t_b ≈ 20°C
Dry Bulb Temp
T = 30°C
Humidity Ratio
W ≈ 10.7 g/kg_da
(i.e., 0.0107)
ENTHALPY h, kJ/kg_da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, g_w/kg_da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
ENTHALPY / HUMIDITY RATIO = Δh / ΔW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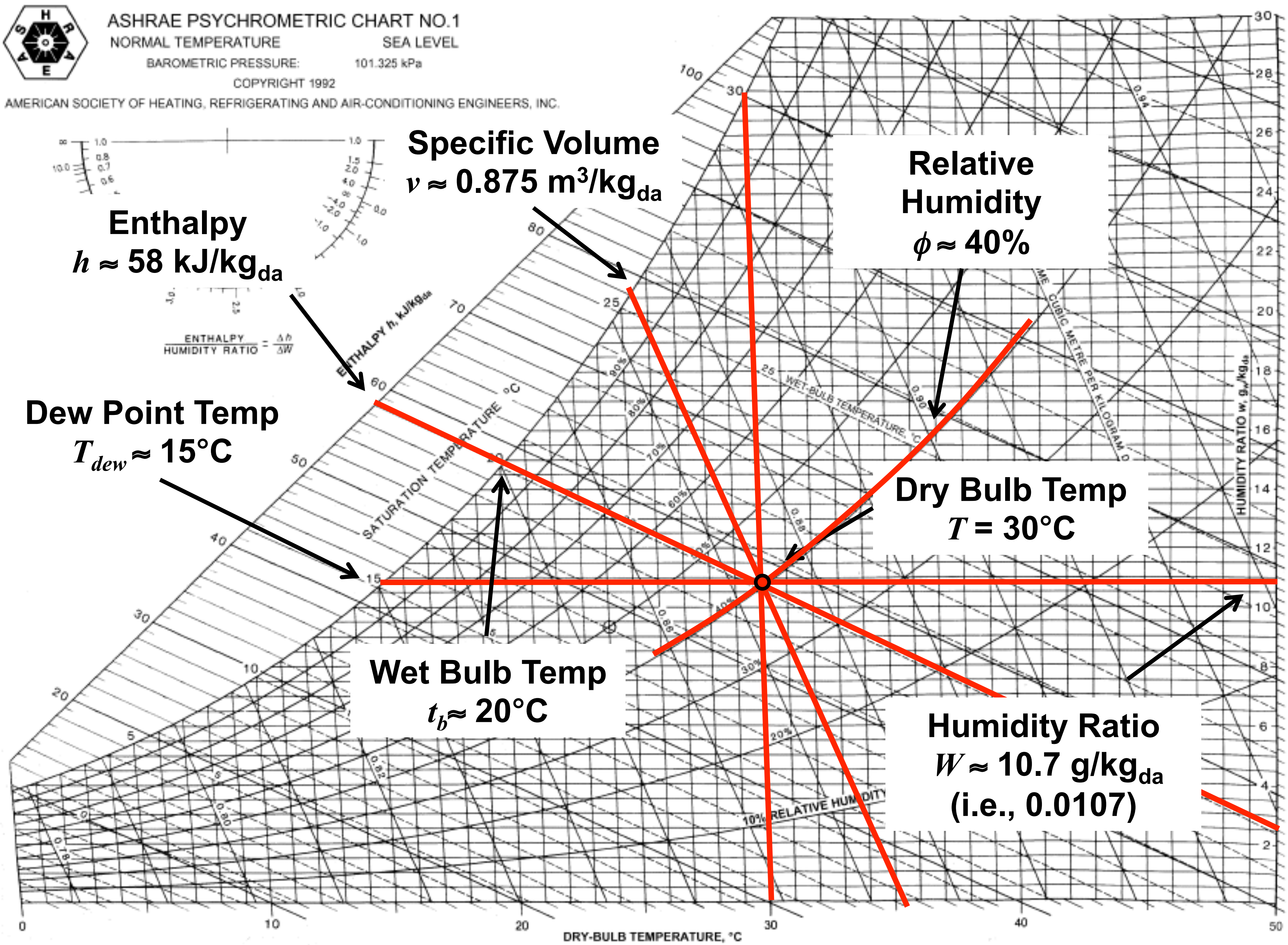
Specific Volume
$v \approx 0.875$ m^3/kg$_{da}$
Enthalpy
$h \approx 58$ kJ/kg$_{da}$
Dew Point Temp
$T_{dew} \approx 15$°C
Dry Bulb Temp
$T = 30$°C
Wet Bulb Temp
$t_b \approx 20$°C
Humidity Ratio
$W \approx 10.7$ g/kg$_{da}$
(i.e., 0.0107)
ENTHALPY h, kJ/kg$_{da}$
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DA
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g$_w$/kg$_{da}$
DRY-BULB TEMPERATURE, °C
ENTHALPY / HUMIDITY RATIO = Δh / ΔW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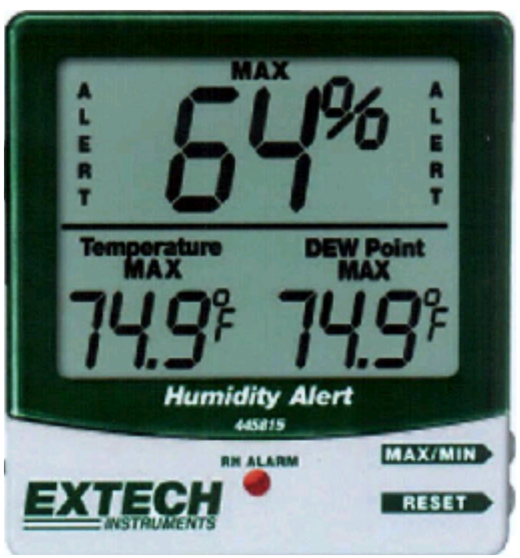
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Specific Volume
$v \approx 0.875\ m^3/kg_{da}$
Relative Humidity
$\phi \approx 40\%$
Enthalpy
$h \approx 58\ kJ/kg_{da}$
Dew Point Temp
$T_{dew} \approx 15°C$
Dry Bulb Temp
$T = 30°C$
Wet Bulb Temp
$t_b \approx 20°C$
Humidity Ratio
$W \approx 10.7\ g/kg_{da}$
(i.e., 0.0107)
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
CUBIC METRE PER KILOGRAM
HUMIDITY RATIO W, gw/kgda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C

Relative humidity, ϕ (RH)

- The relative humidity ratio, ϕ, is the mole fraction of water vapor (x_w) relative to the water vapor that would be in the mixture if it were saturated at the given T and P (x_{ws})
- Relative humidity is a common measure that relates well to how we perceive moisture in air



$$\phi = \left[\frac{x_w}{x_{ws}}\right]_{T,P} = \frac{p_w}{p_{ws}}$$

Humidity ratio, W

- The humidity ratio, W, is ratio of the mass of water vapor to mass of dry air in a given volume
  - We use W when finding other mixture properties
  - Note 1: W is small (W < 0.04 for any real building conditions)
  - Note 2: W is sometimes expressed in grains/lb where 1 lb = 7000 grains (try not to ever use this)

UNITS

$$W = \frac{m_w}{m_{da}} = \frac{MW_w p_w}{M_{da} p_{da}} = 0.622 \frac{p_w}{p_{da}} = 0.622 \frac{p_w}{p - p_w} \quad [\frac{\text{kg}_\text{w}}{\text{kg}_\text{da}}]$$

Saturation humidity ratio, W_s

- At a given temperature T and pressure P there is a maximum W that can be obtained
- If we try to add any more moisture, it will just condense out
  - It is when the partial pressure of vapor has reached the saturation pressure
- This maximum humidity ratio is called the saturation humidity ratio, W_s
  - From our previous equation we can write:

$$W_s = 0.622 \frac{p_s}{p_{da}} = 0.622 \frac{p_s}{p - p_s}$$

Degree of saturation, μ

- The degree of saturation, μ (dimensionless), is the ratio of the humidity ratio W to that of a saturated mixture W_s at the same T and P
  - Note that μ and ϕ are not quite the same
  - Their values are very similar at lower temperatures but may differ a lot at higher temperatures

$$\mu = \left[\frac{W}{W_s}\right]_{T,P}$$

$$\mu = \frac{\phi}{1 + (1-\phi)W_s / (0.6295)}$$

$$\phi = \frac{\mu}{1 - (1-\mu)p_{ws} / p}$$

Specific volume, *v*

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

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

where

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

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

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

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

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:

$$h = h_{da} + W h_g$$

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:

$$h_{da} \approx 1.006T \qquad h_g \approx 2501 + 1.86T$$

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

*where T is in °C

Thermodynamic properties of common gases

TABLE 3.1
Properties of Common Gases

Gas	Molecular Weight	c_p Btu/(lb$_m$ · °F)	c_p kJ/(kg · C)	c_v Btu/(lb$_m$ · °F)	c_v kJ/(kg · °C)	R ft·lb/(lb$_m$ · °R)	R J/(kg · K)
Air	28.97	0.240	1.005	0.1715	0.718	53.35	287.1
Hydrogen (H_2)	2.016	3.42	14.32	2.43	10.17	767.0	4127
Helium (He)	4.003	1.25	5.234	0.75	3.14	386.3	2078
Methane (CH_4)	16.04	0.532	2.227	0.403	1.687	96.4	518.7
Water vapor (H_2O)	18.02	0.446	1.867	0.336	1.407	85.6	460.6
Acetylene (C_2H_2)	26.04	0.409	1.712	0.333	1.394	59.4	319.6
Carbon monoxide (CO)	28.01	0.249	1.043	0.178	0.745	55.13	296.6
Nitrogen (N_2)	28.02	0.248	1.038	0.177	0.741	55.12	296.6
Ethane (C_2H_6)	30.07	0.422	1.767	0.357	1.495	51.3	276
Oxygen (O_2)	32.00	0.219	0.917	0.156	0.653	48.24	259.6
Argon (A)	39.94	0.123	0.515	0.074	0.310	38.65	208
Carbon dioxide (CO_2)	44.01	0.202	0.846	0.156	0.653	35.1	188.9
Propane (C_3H_8)	44.09	0.404	1.692	0.360	1.507	35.0	188.3
Isobutane(C_4H_{10})	58.12	0.420	1.758	0.387	1.62	26.6	143.1

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 $T = T_{dew}$

Equations for T_{dew}

- Dew-point temperature, T_{dew}

Between dew points of 0 and 93°C,

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984} \quad (39)$$

Below 0°C,

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \quad (40)$$

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

Equations for T_{wb}

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

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

- And below freezing:

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

Revisit example from last class: Solutions

Moist air exists at 30°C dry-bulb temperature with a 15°C dew point temperature

Find the following:

(a) the humidity ratio, W

(b) degree of saturation, μ

(c) relative humidity, ϕ

(d) enthalpy, h

(e) specific volume, v

(f) density, ρ

(g) wet-bulb temperature, T_{wb}

Solution: Humidity ratio

$$W = 0.622 \left. \frac{p_w}{p - p_w} \right|_{@T=30°C}$$

- Assume p = 101.325 kPa
- For a known T_{dew} = 15°C, we know that the actual humidity ratio in the air, W, is by definition the same as the saturation humidity ratio, W_s, at an air temperature of 15°C

$$W_{@T=30°C} = W_{s@T=15°C} = 0.622 \left. \frac{p_{ws}}{p - p_{ws}} \right|_{@T=15°C}$$

Temp., °C t	Absolute Pressure p_{ws}, kPa
14	1.5989
15	1.7057

$p_{ws@15C}$ = 1.7057 kPa

$$W_{@T=30°C} = W_{s@T=15°C} = 0.622 \frac{1.7057}{101.325 - 1.7057} = 0.01065 \frac{\text{kg}_\text{w}}{\text{kg}_\text{da}}$$

Solution: Degree of saturation

$$\mu = \left[\frac{W}{W_s}\right]_{@T=30^\circ C}$$

- Need the saturation humidity ratio @ T = 30°C:

$$W_{s@T=30^\circ C} = 0.622 \left.\frac{p_{ws}}{p - p_{ws}}\right|_{@T=30^\circ C}$$

Temp., °C t	Absolute Pressure p_{ws}, kPa
30	4.2467
31	4.4966

$p_{ws@15C}$ = 4.2467 kPa

$$W_{s@T=30^\circ C} = 0.622 \frac{4.2467}{101.325 - 4.2467} = 0.02720 \frac{\text{kg}_\text{w}}{\text{kg}_\text{da}}$$

$$\mu = \frac{W}{W_s} = \frac{0.01065}{0.02720} = 0.39$$

Solution: Relative humidity

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

- From previous:

$$p_{@T=30^\circ C} = p_{ws@T=15^\circ C} = 1.7057\,kPa$$

$$p_{ws@T=30^\circ C} = 4.2467\,kPa$$

$$\phi = \frac{1.7057}{4.2467} = 0.40 = 40\%$$

Solution: Enthalpy

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

*where T is in °C

$$h \approx 1.006(30) + (0.01065)(2501 + 1.86(30)) = 57.4\,\frac{\text{kJ}}{\text{kg}}$$

Solution: Specific volume and density

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

$$v \approx 0.287042(30 + 273.15)(1 + 1.6078(0.01065)) / (101.325)$$

$$v \approx 0.873 \frac{\text{m}^3}{\text{kg}_{\text{da}}}$$

$$\rho = \frac{1}{v}\left(1 + W\right) = \frac{1}{0.873}\left(1 + 0.01065\right) = 1.157 \frac{\text{kg}}{\text{m}^3}$$

Solution: Wet-bulb temperature

- Wet-bulb temperature is the T_{wb} that fits this equation:

$$W = \frac{(2501 - 2.326T_{wb})W_{s@T_{wb}} - 1.006(T - T_{wb})}{2501 + 1.86T - 4.186T_{wb}} = 0.01065$$

where: $T = 30°C$ $\quad W_{s@T_{wb}=?} = 0.622 \left. \frac{p_{ws}}{p - p_{ws}} \right|_{@T_{wb}=?}$

$T_{wb} = ?°C$

Procedure:

- Guess T_{wb}, calculate pws for that T, calculate W_s for that T
  - Repeat until W calculated based on those values (and original T) in equation above is equal to actual W (0.01065 in our case)

$$\boxed{T_{wb} = 20.1°C}$$

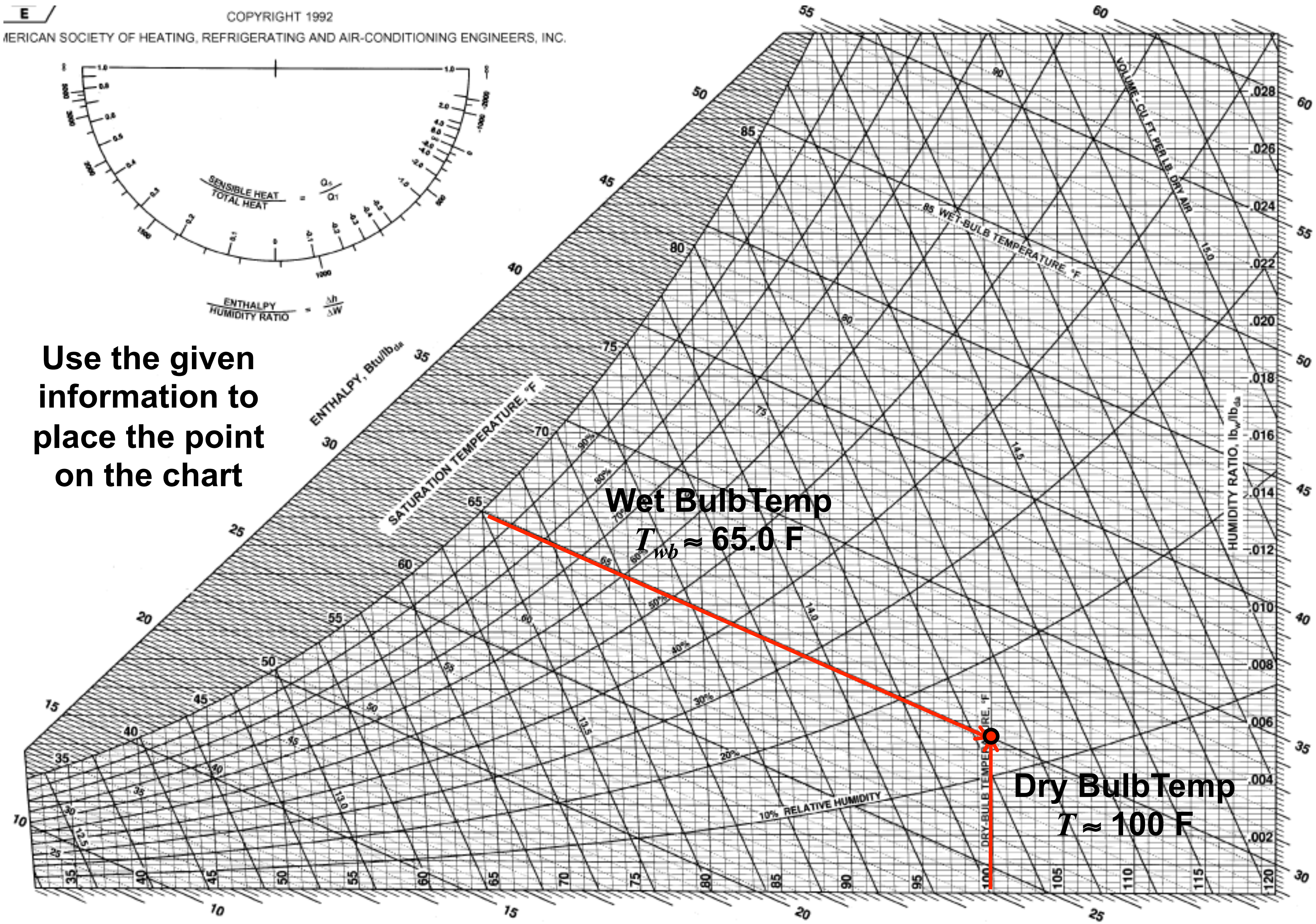
Psychrometrics: IP units example

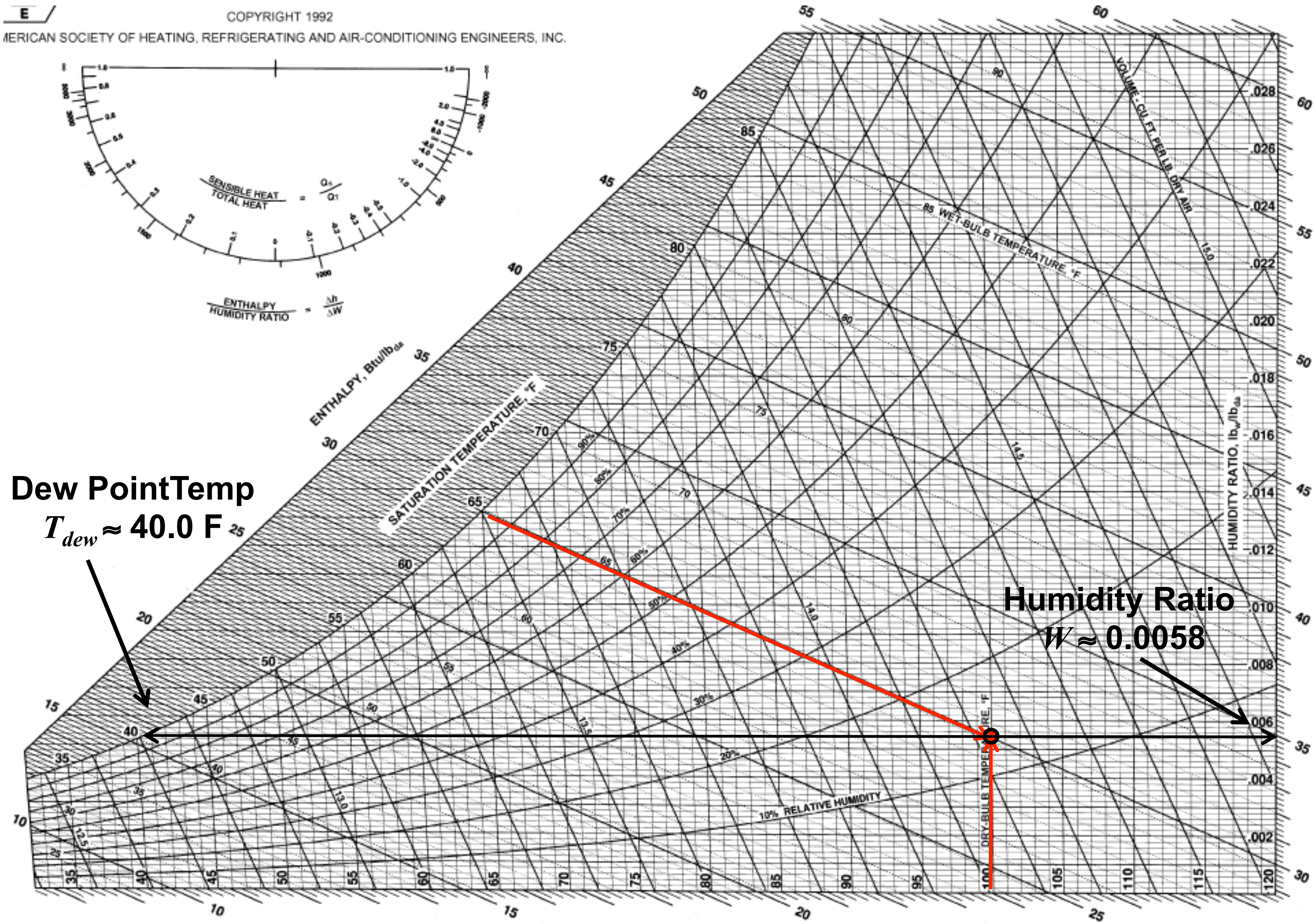
- Moist air exists at 100°F dry bulb, 65°F wet bulb and 14.696 psia

Find:

a) Humidity ratio
b) Enthalpy
c) Dew-point temperature
d) Relative humidity
e) Specific volume

Use the given information to place the point on the chart





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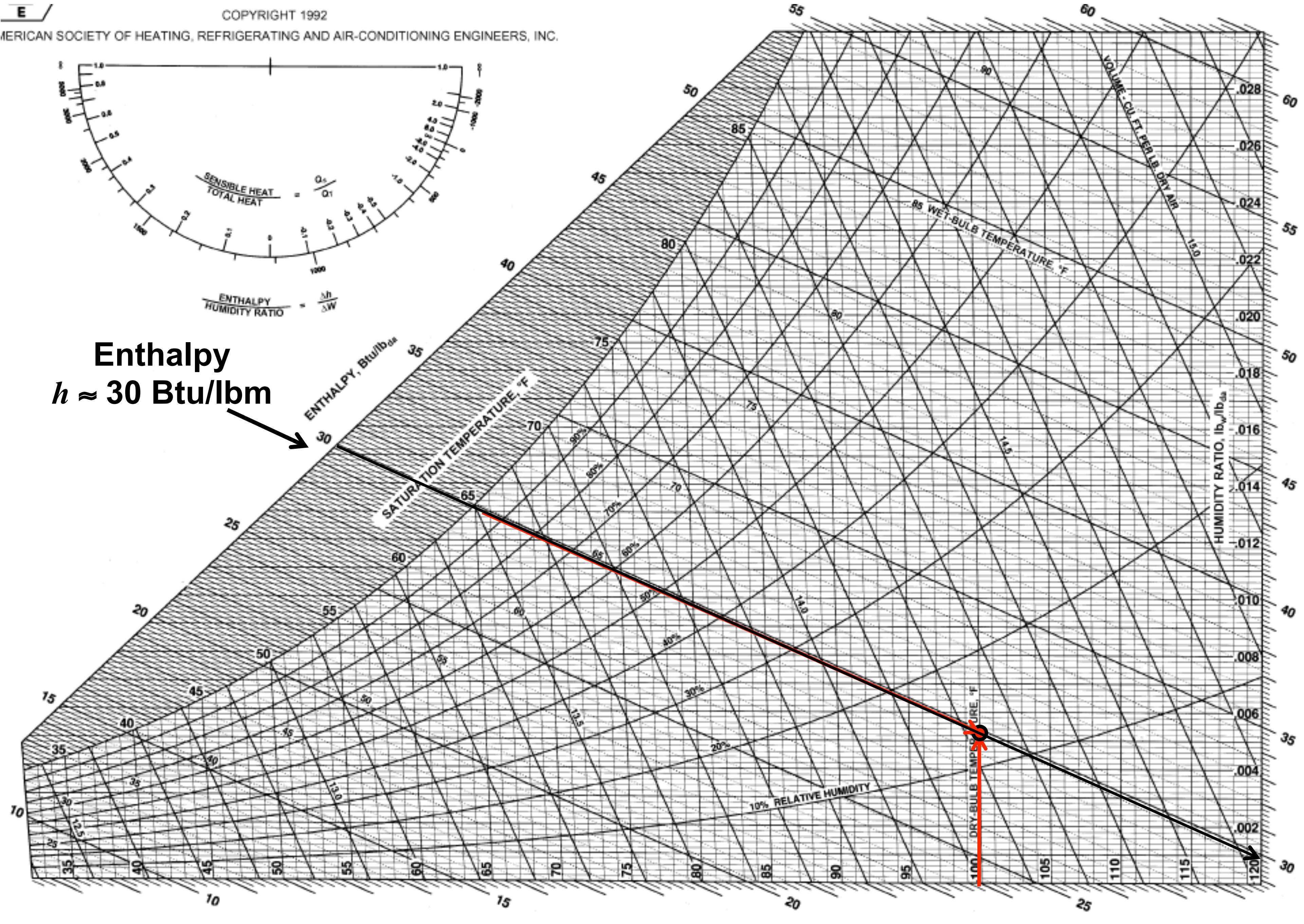
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb_w/lb_da
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Dew PointTemp
T_dew ≈ 40.0 F
Humidity Ratio
W ≈ 0.0058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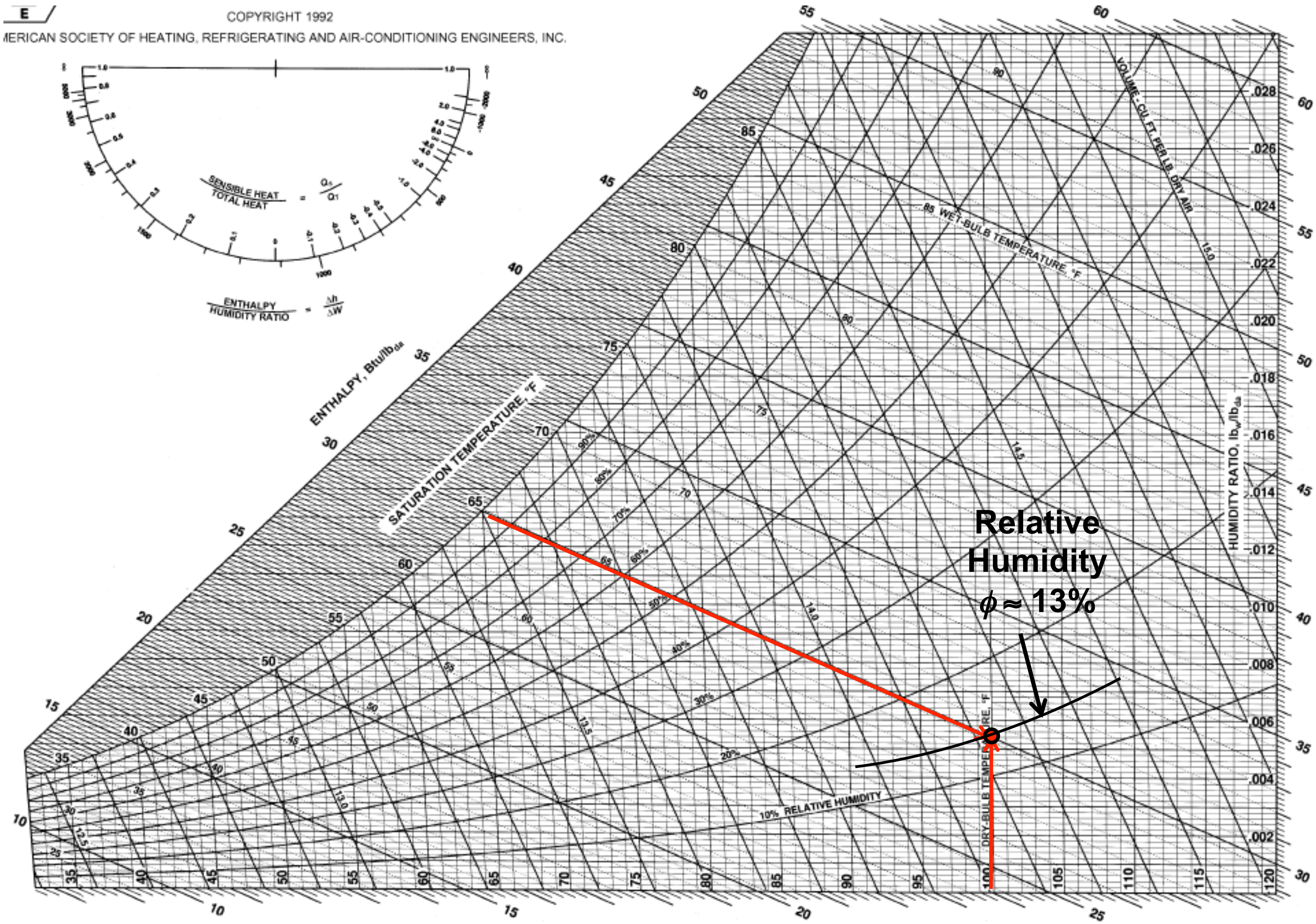
MERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Enthalpy
h ≈ 30 Btu/lbm
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU. FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °F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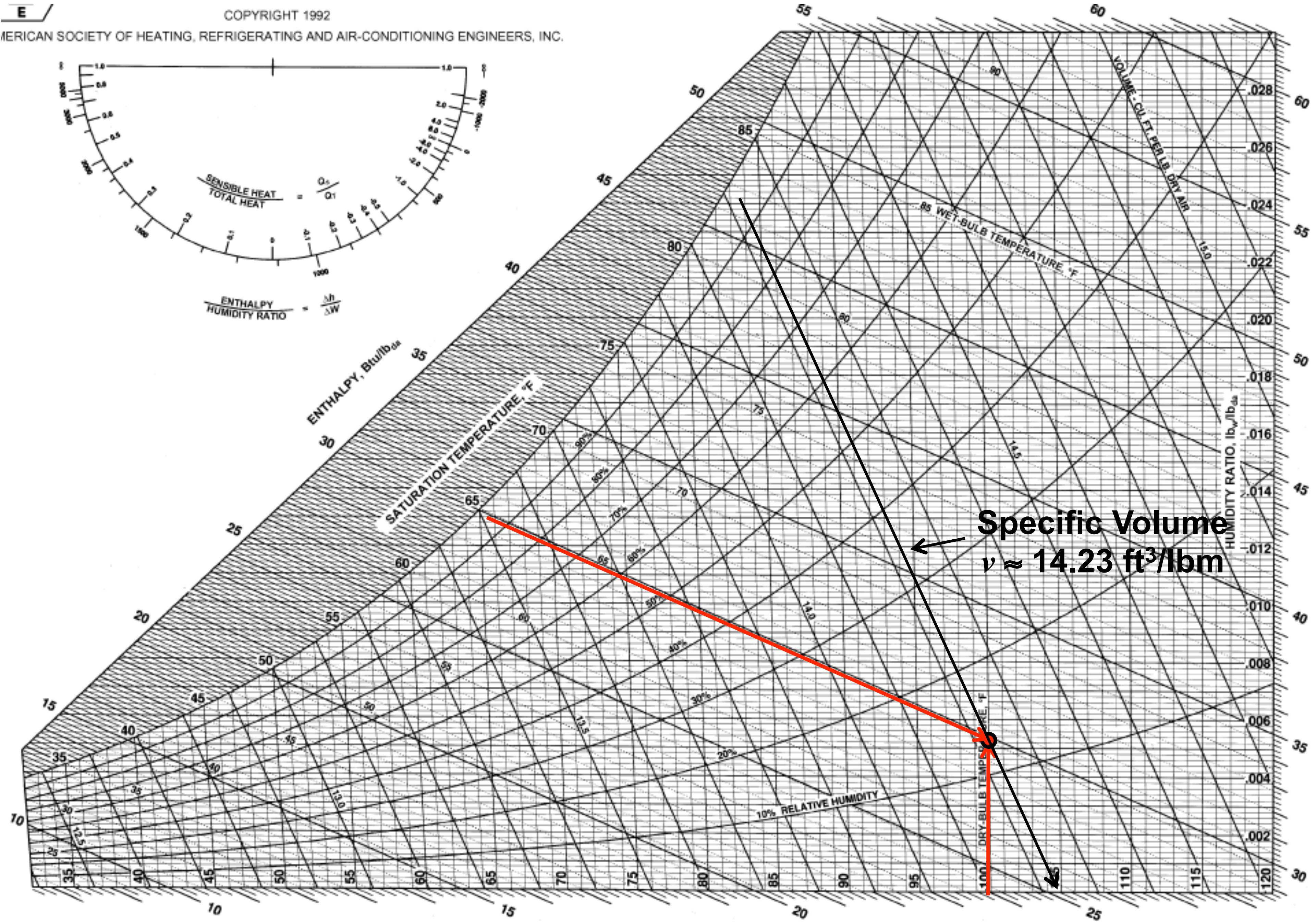
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME, CU. FT. PER LB. DRY AIR
HUMIDITY RATIO, lb_w/lb_da
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
Relative
Humidity
ϕ ≈ 13%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SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
Specific Volume
v ≈ 14.23 ft³/lbm

Psychrometric software

- Psych and Psychpro
  - Very popular psych chart and analysis software
  - I think at least one of these is in the AM 217 lab
- There are a bunch of online calculators as well
  - http://www.sugartech.co.za/psychro/
- And smart phone apps too
- You can also make your own (i.e., in Excel)
  - You will have a HW problem where you have to do this

PSYCHROMETRIC PROCESSES

Use of the psychrometric chart for *processes*

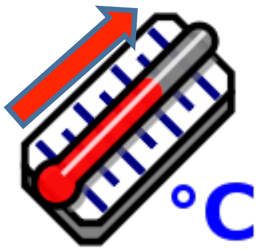
We can use the psychrometric chart not only to describe states of moist air, but for a number of processes that are important for building science

Examples:

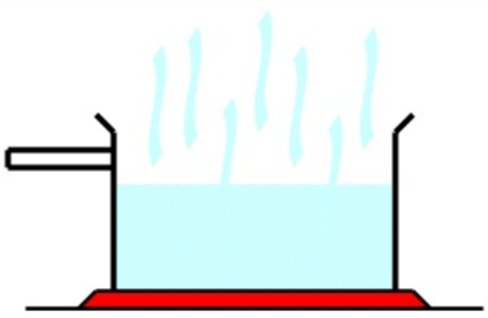
- Sensible cooling
- Sensible + latent cooling
- Adiabatic saturation
- Warming and humidification of cold, dry air
- Cooling and dehumidification of warm, humid air
- Evaporative cooling
- Mixing of airstreams

Sensible and latent heat

- Sensible heat transfer
  - Increases or decreases temperature of a substance without undergoing a phase change



- Latent heat transfer
  - Heat transfer required to change the phase of a substance
  - Phase change involves great heat transfer so latent heat transfer values can get very large



Sensible heat transfer equation

$$\dot{q}_{sens} = \dot{m} c_p (T_{exit} - T_{inlet}) = \dot{V} \rho c_p (T_{exit} - T_{inlet})$$

$\dot{q}_{sens}$ = Rate of sensible heat xfer [Btu/hr or ton or W]

$\dot{m}$ = mass rate of air flow [lbm/hr or kg/s]

$\dot{V}$ = volumetric flow rate of air [ft^3/hr or cfm or m^3/s]

ρ = density of air [lbm/ft^3 or kg/m^3]

c_p = specific heat of air [Btu/(lbm-F) or J/(kg-K)]

T_{exit}, T_{inlet} = exit and inlet temperature [°F or °C]

$\dot{q}_{sens} > 0$ for heating

$\dot{q}_{sens} < 0$ for cooling

Latent heat transfer equation

$$\dot{q}_{lat} = \dot{m}_w h_{fg}$$

$\dot{q}_{lat}$ = rate of latent heat Xfer [Btu/hr or ton or W]

$\dot{q}_{lat}$ is positive for humidification processes

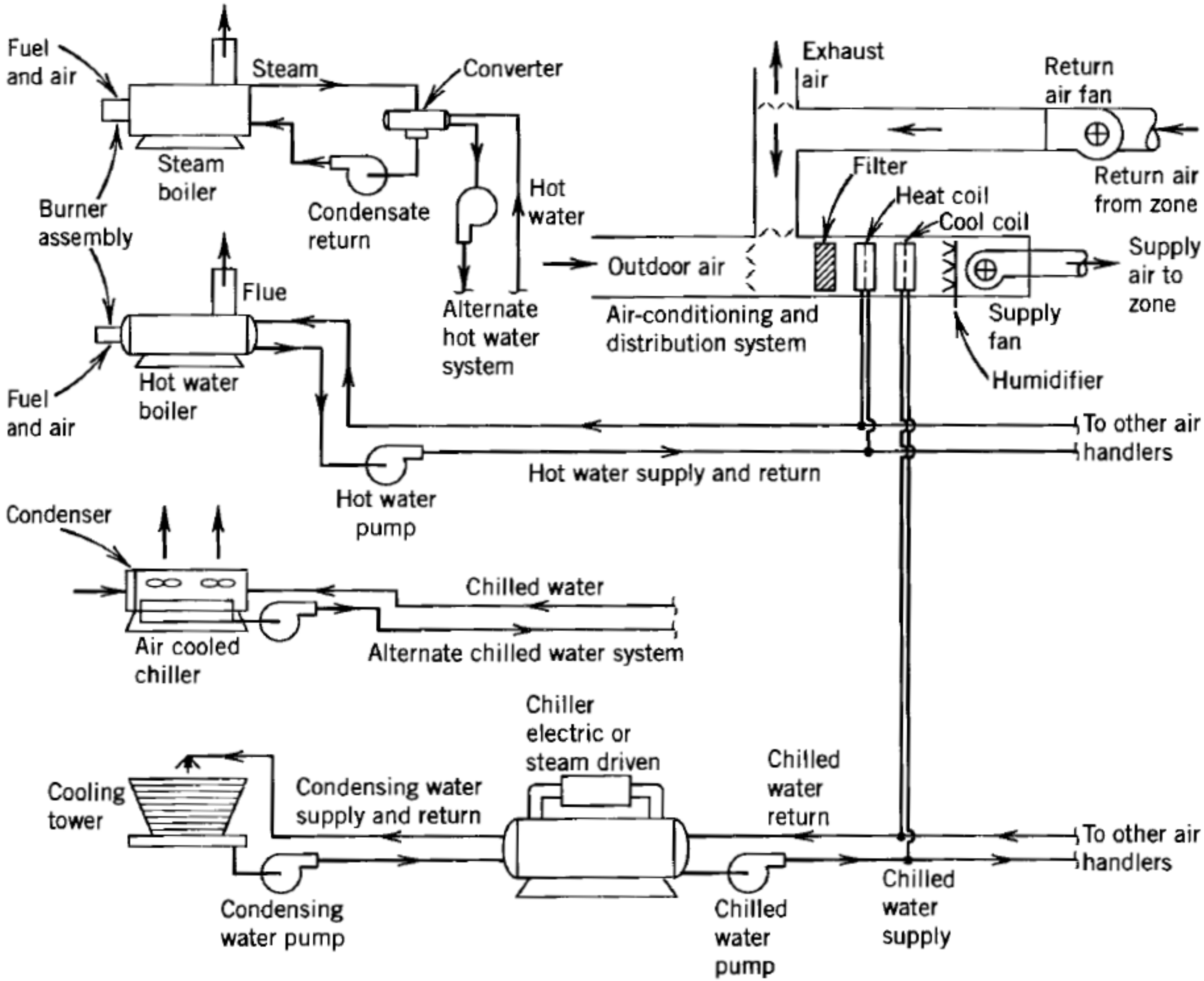
$\dot{m}_w$ = rate of evaporation/condensation [lbm/hr or kg/s]

h_{fg} = enthalpy of vaporization [Btu/lbm or J/kg]

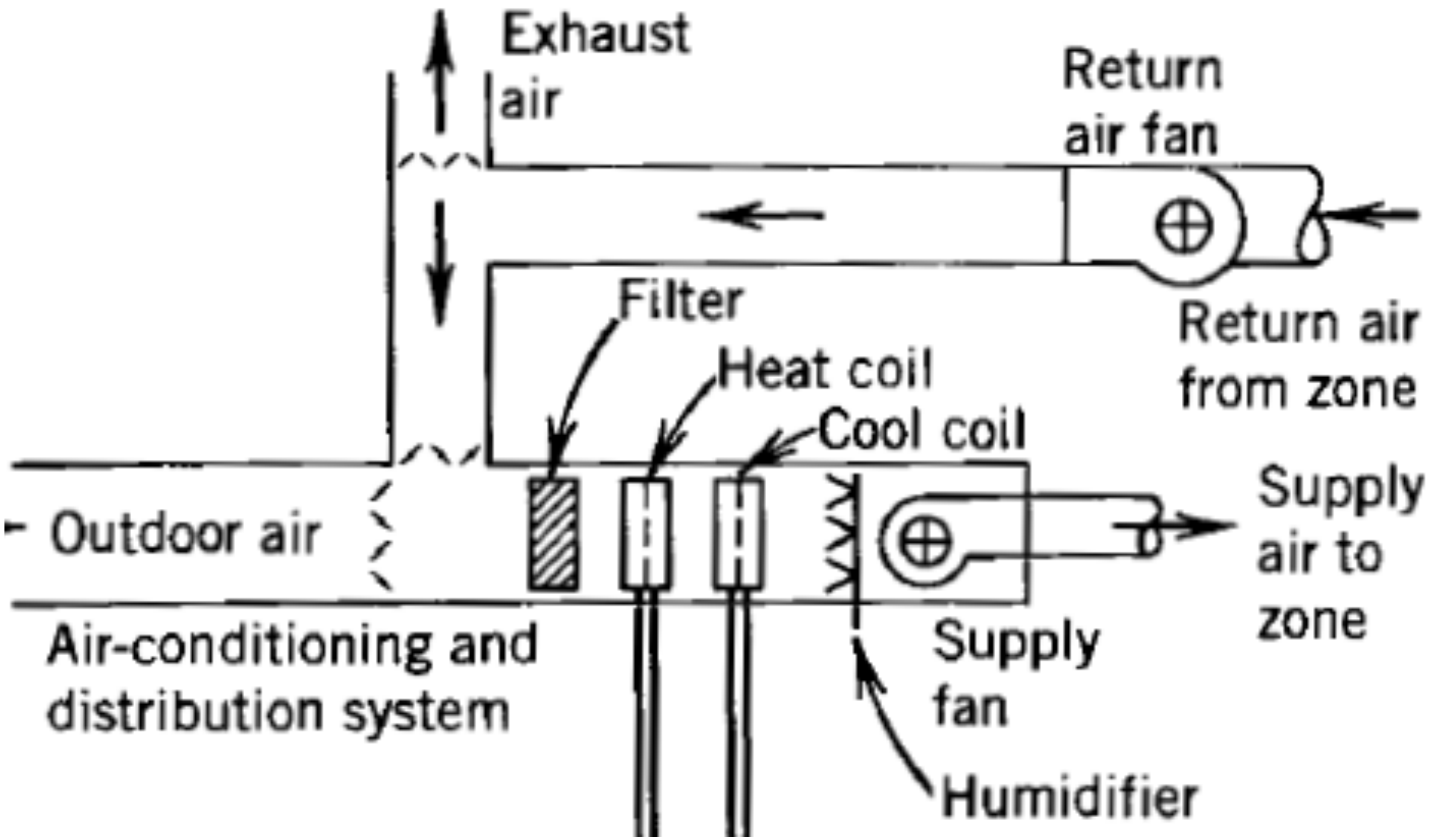
also called latent heat of vaporization

(h_{fg} = 2260 kJ/kg for water)

Where do we use psych processes? HVAC systems



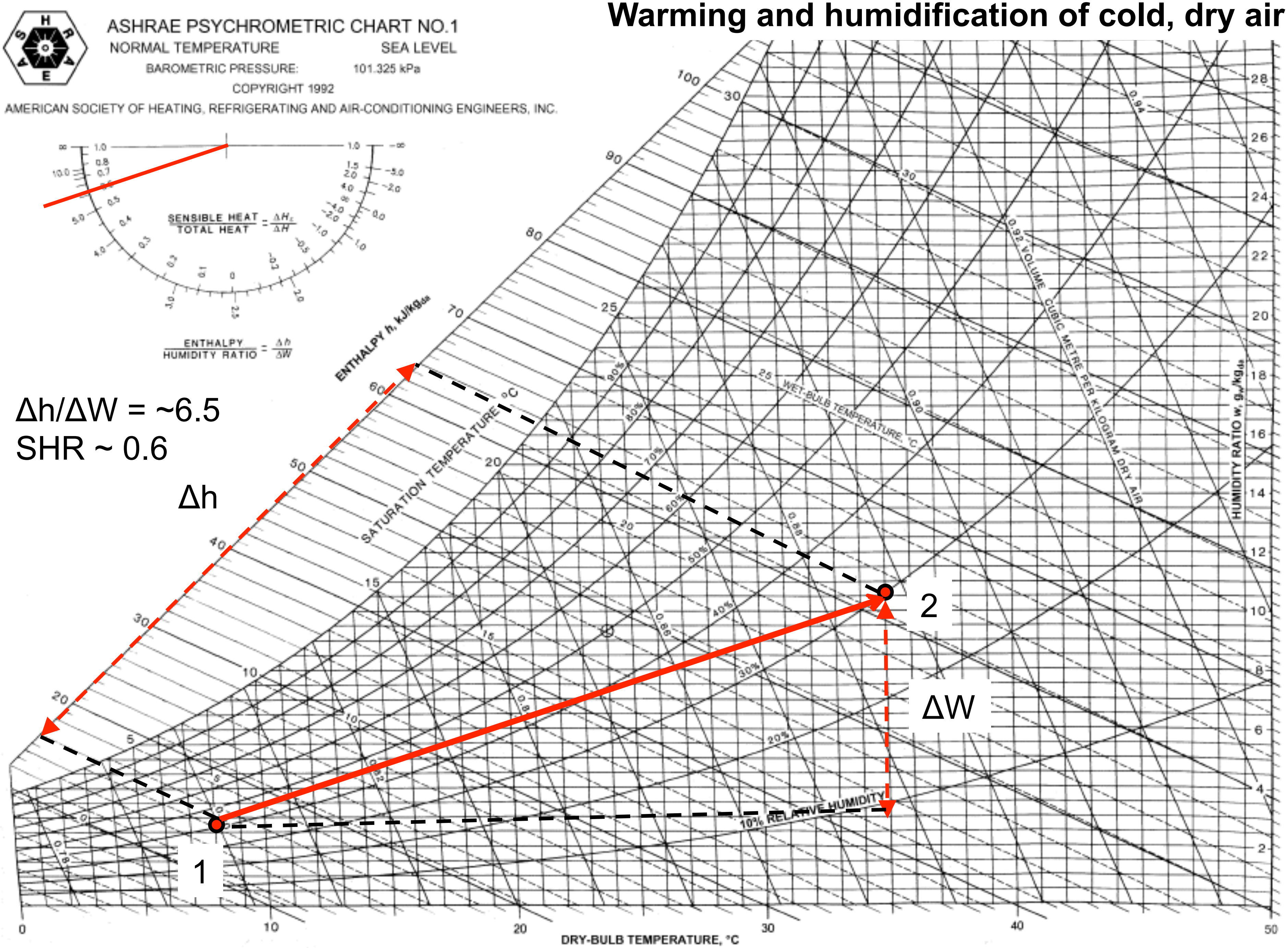
Typical air distribution system



Warming and humidification of cold, dry air

- Example: Heating and humidifying coils
- Adding moisture and heat
  - Sensible + latent heating

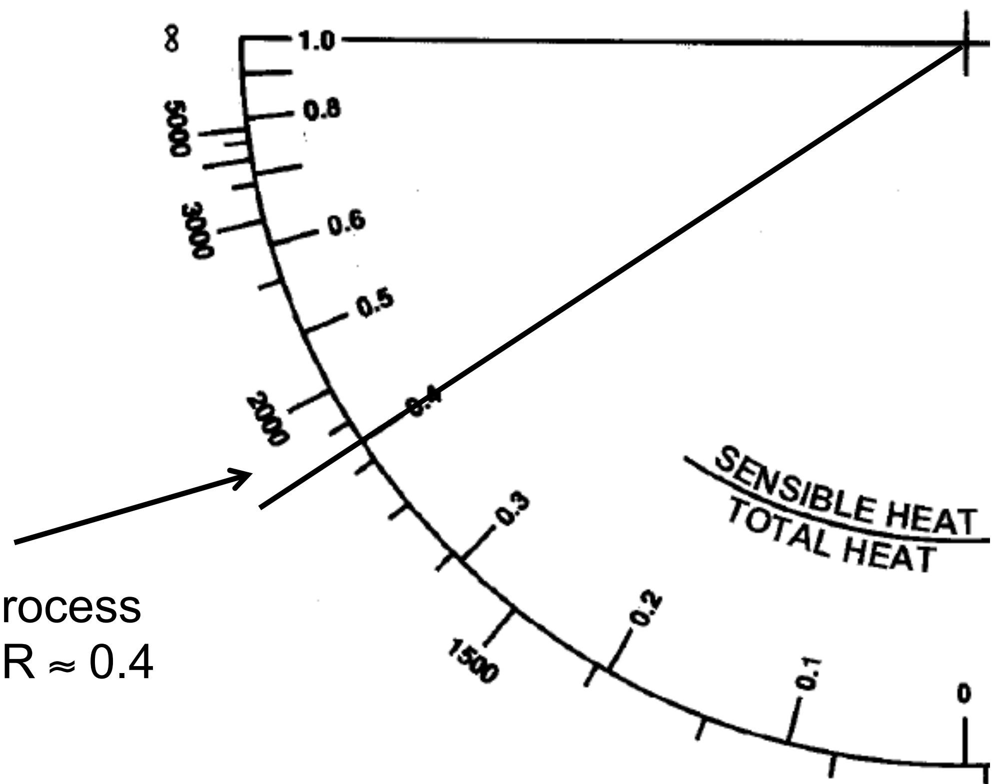
Warming and humidification of cold, dry air



Sensible heat ratio (SHR)

- The sensible heat ratio is defined as:

$$SHR = \frac{\dot{q}_{sens}}{\dot{q}_{total}} = \frac{\dot{q}_{sens}}{\dot{q}_{sens} + \dot{q}_{latent}} \rightarrow \frac{\Delta h}{\Delta W}$$

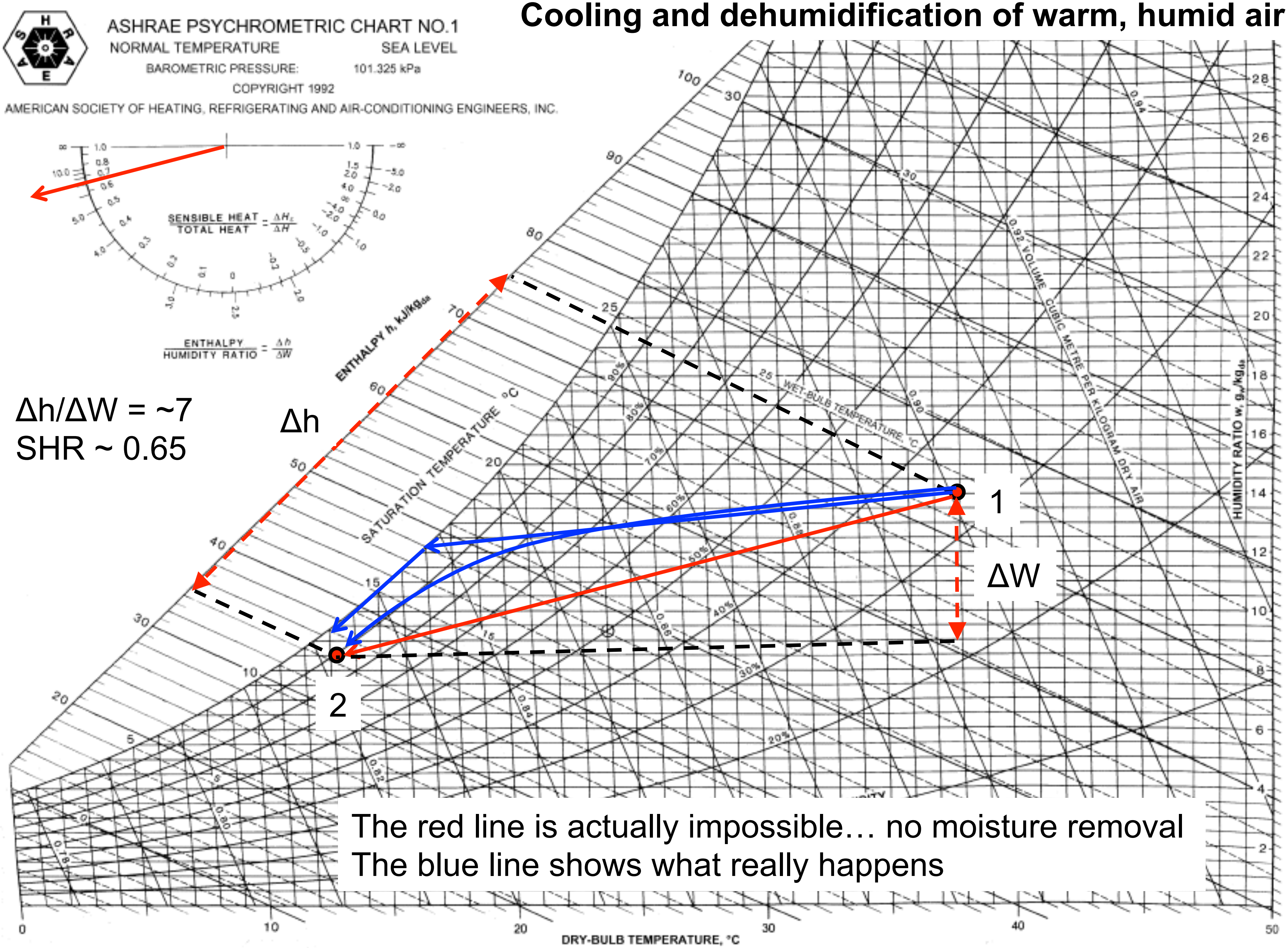


Here is a process with an SHR ≈ 0.4

Cooling and dehumidification of warm, humid air

- Example: Cooling coil
- Removing both moisture and heat
  - Sensible + latent cooling

Cooling and dehumidification of warm, humid air



The red line is actually impossible… no moisture removal

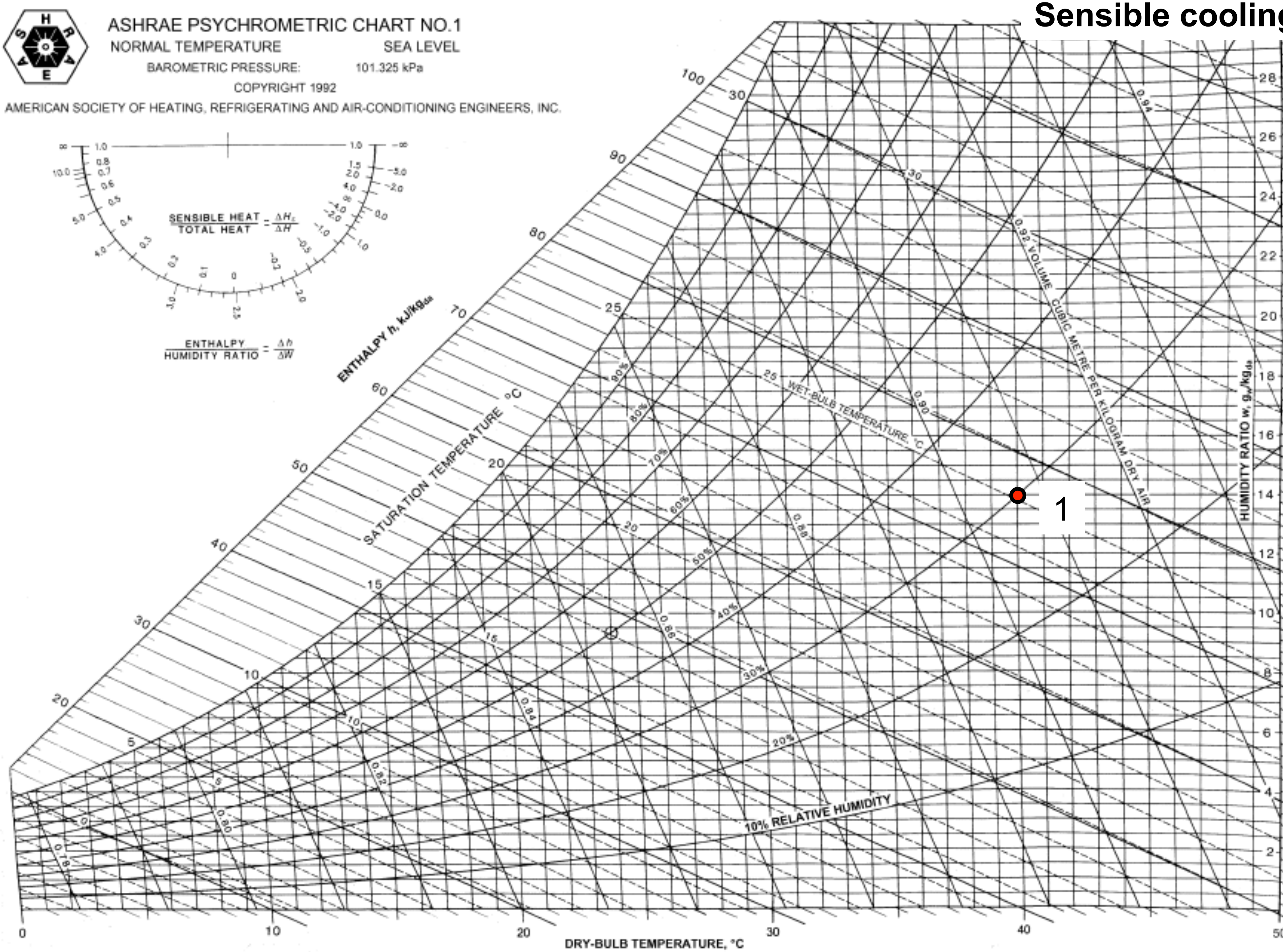
The blue line shows what really happens

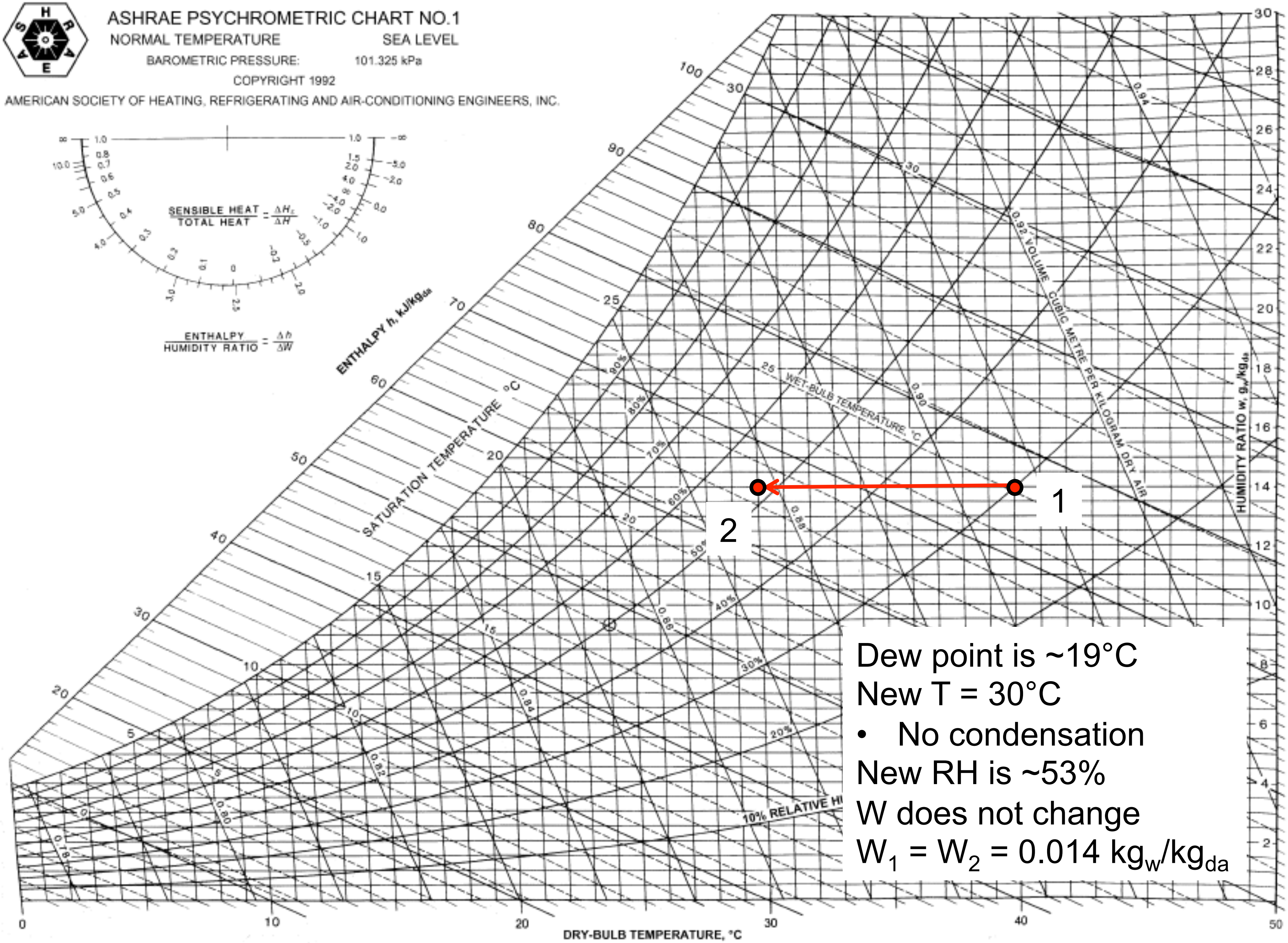
Example: Sensible cooling

- Moist air is cooled from 40°C and 30% RH to 30°C
- Does the moisture condense?
- What are values of RH at W at the process end point?

- What is the rate of sensible heat transfer if the airflow rate is 1000 ft^3/min?

Sensible cooling





Dew point is ~19°C

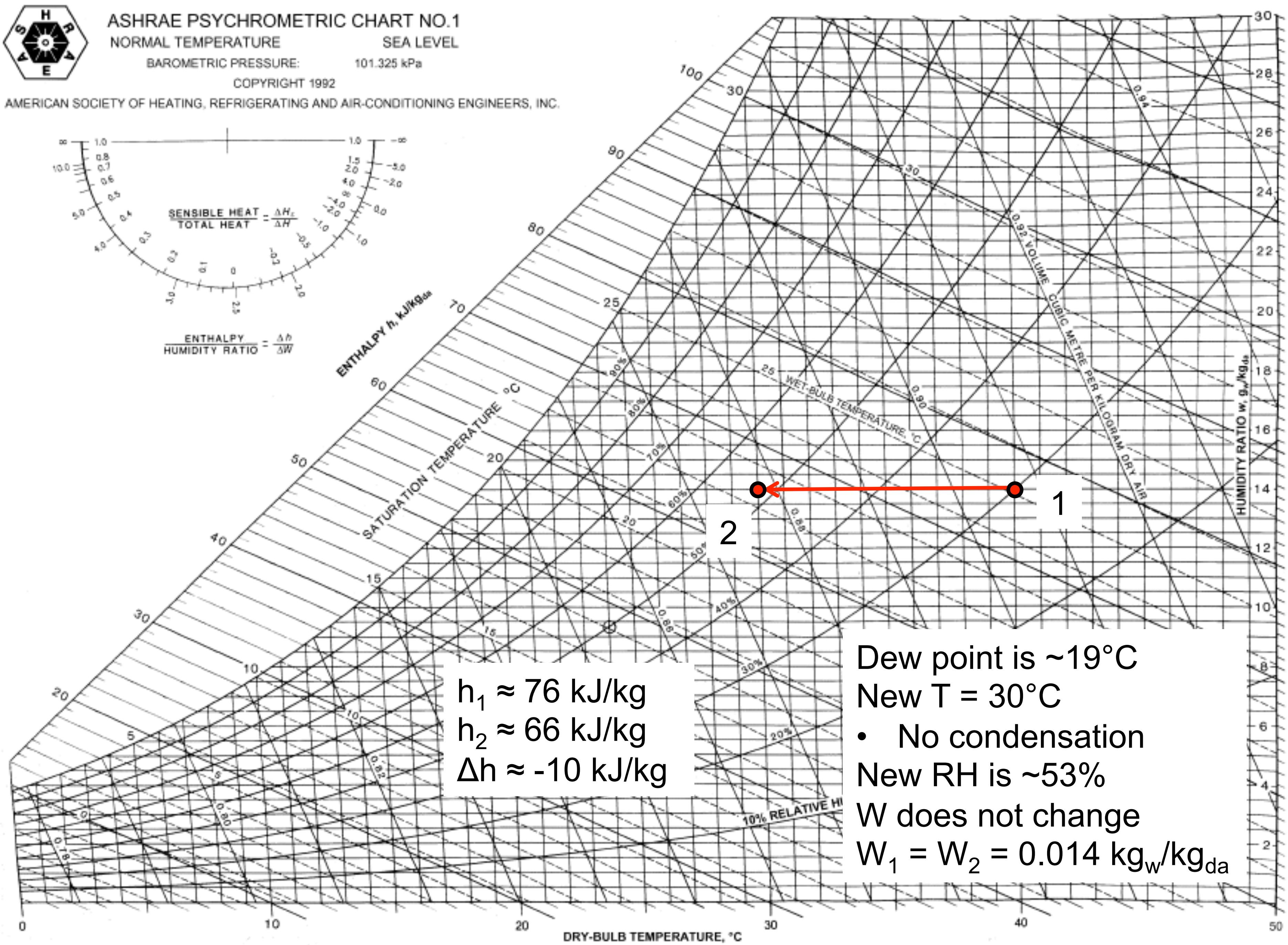
New T = 30°C

- No condensation

New RH is ~53%

W does not change

$W_1 = W_2 = 0.014\ kg_w/kg_{da}$


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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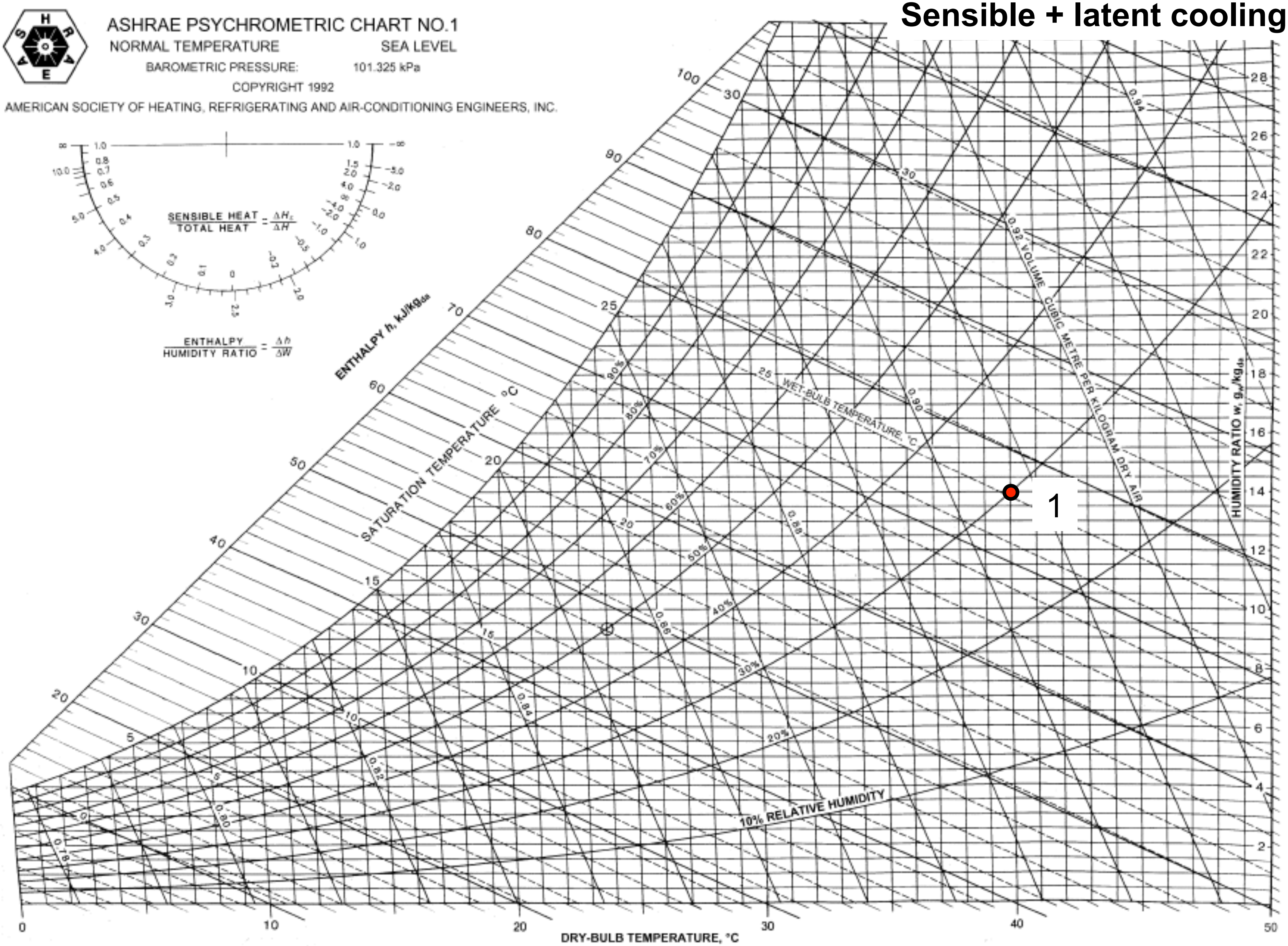
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
10% RELATIVE HU
1
2
h1 ≈ 76 kJ/kg
h2 ≈ 66 kJ/kg
Δh ≈ -10 kJ/kg
Dew point is ~19°C
New T = 30°C
• No condensation
New RH is ~53%
W does not change
W1 = W2 = 0.014 kgw/kgda

Example: Sensible + latent cooling

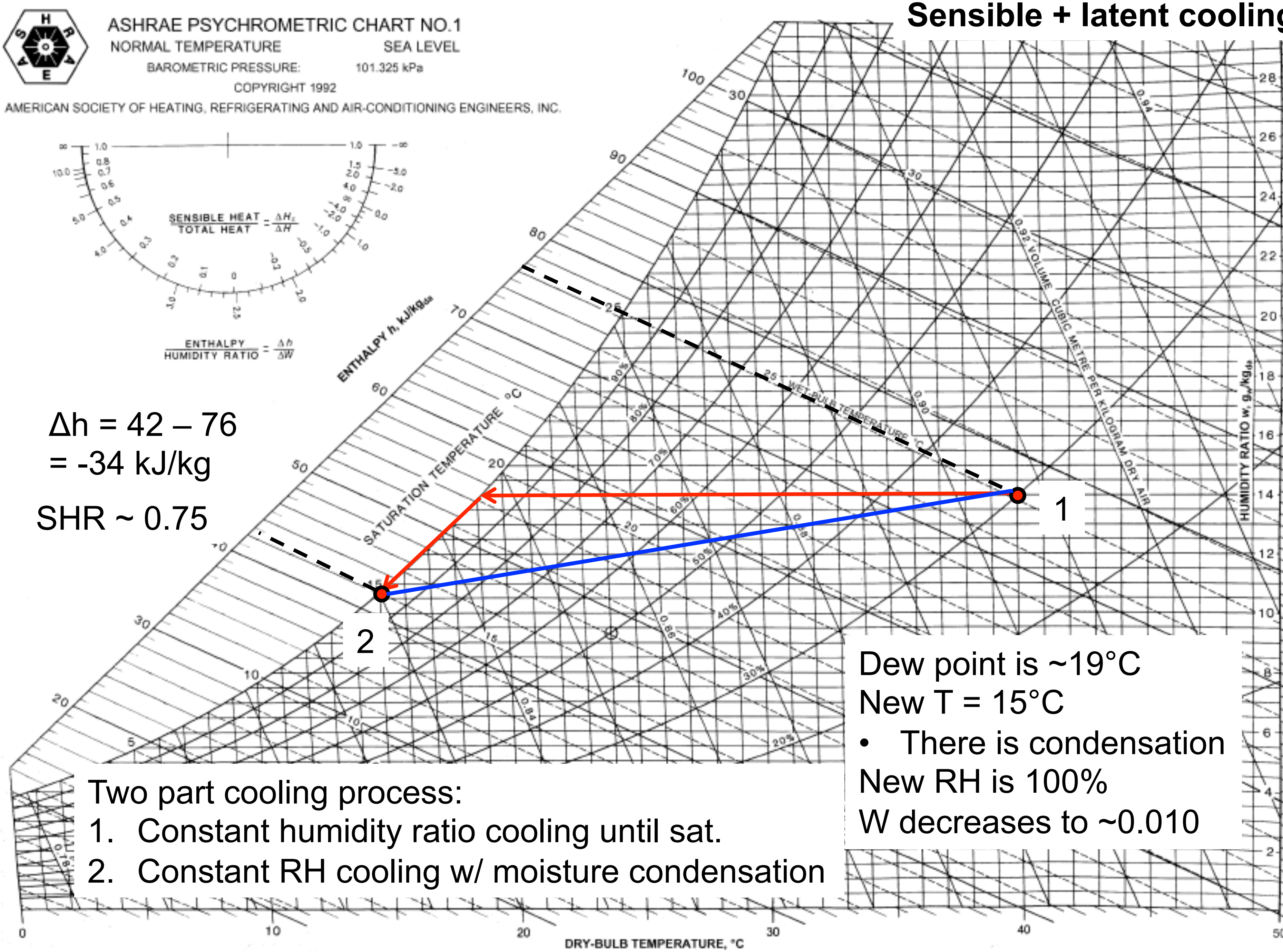
- Moist air is cooled from 40°C and 30% RH to 15°C
- Does the moisture condense?
- What are values of RH at W at the process end point?

- What is the rate of heat transfer if the airflow rate is 1000 ft^3/min?

Sensible + latent cooling



Sensible + latent cooling



Δh = 42 – 76
= -34 kJ/kg

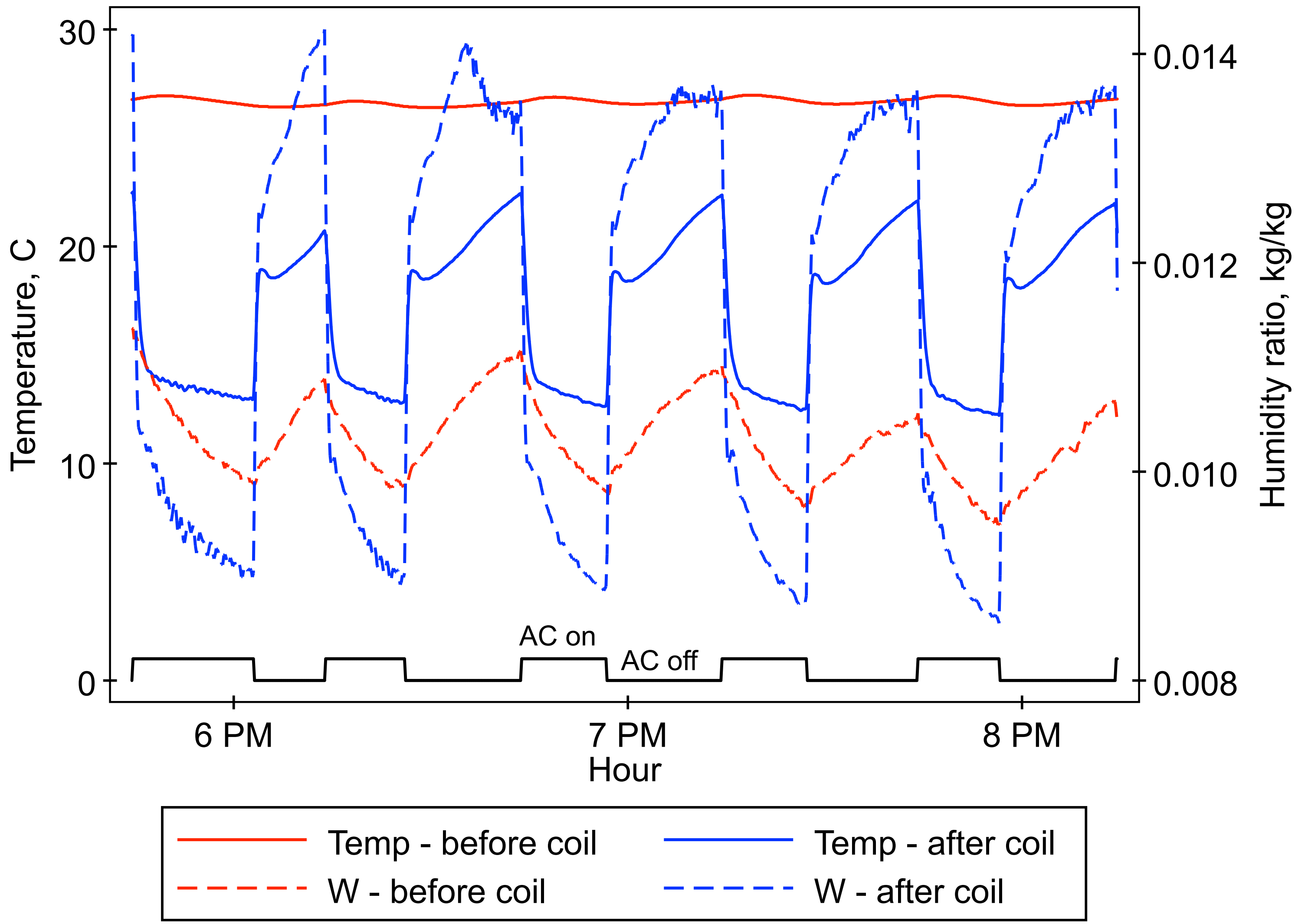
SHR ~ 0.75

Dew point is ~19°C
New T = 15°C
- There is condensation

New RH is 100%
W decreases to ~0.010

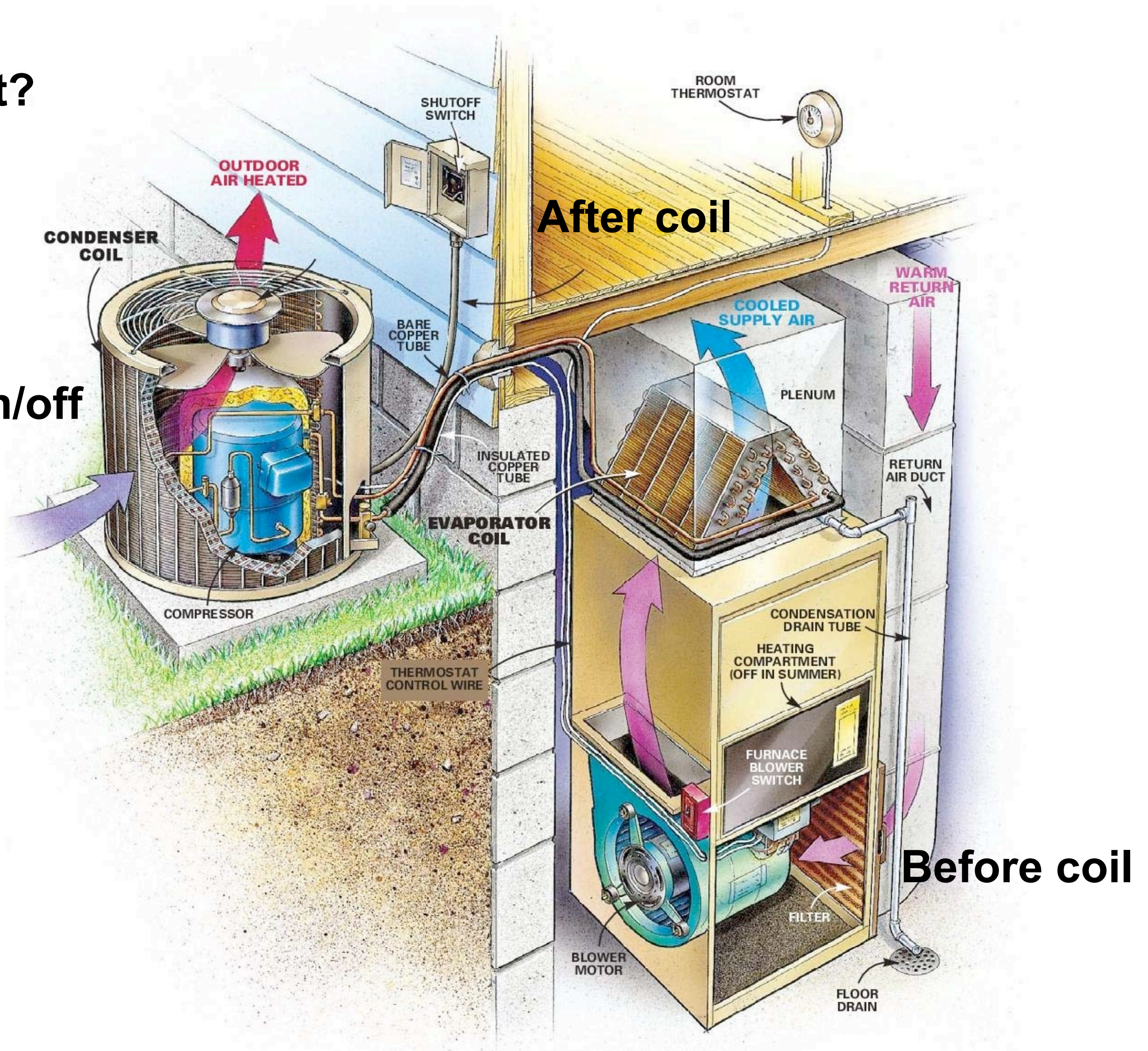
Two part cooling process:
1. Constant humidity ratio cooling until sat.
2. Constant RH cooling w/ moisture condensation

Real data: ASHRAE RP-1299
Energy implications of filters

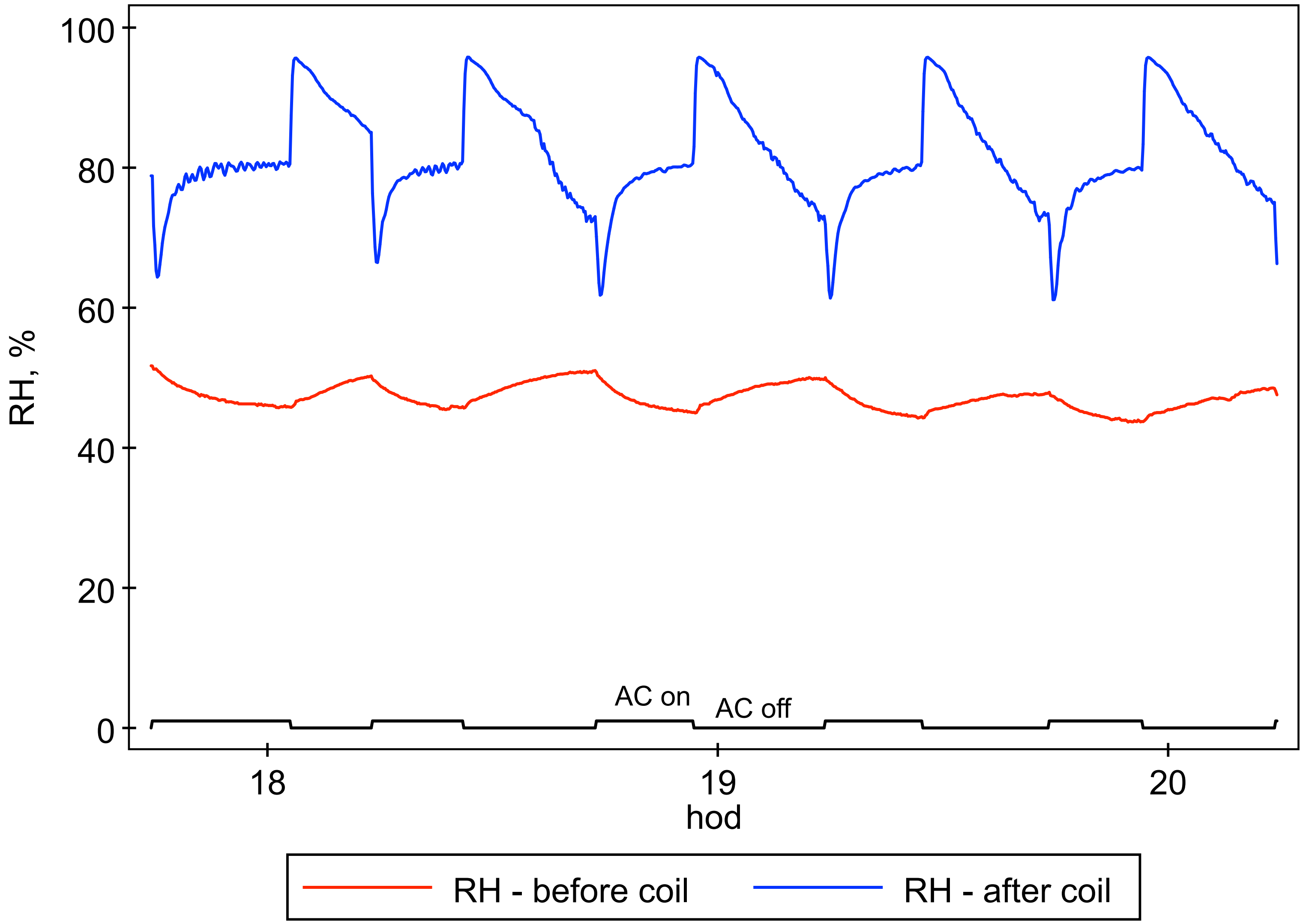


Real data: ASHRAE RP-1299
Energy implications of filters

What are we looking at?



Real data: ASHRAE RP-1299
Energy implications of filters

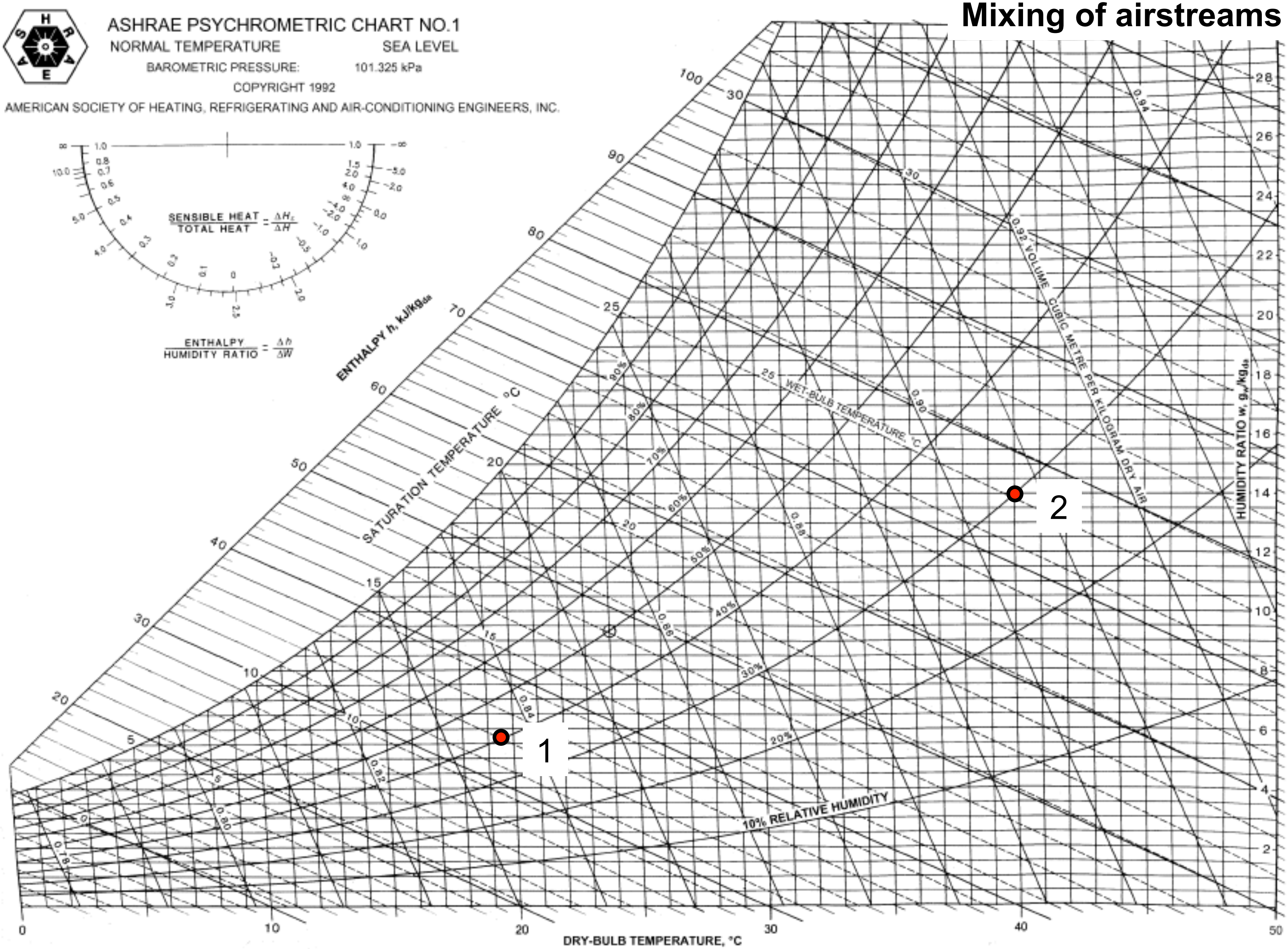


Mixing of air streams

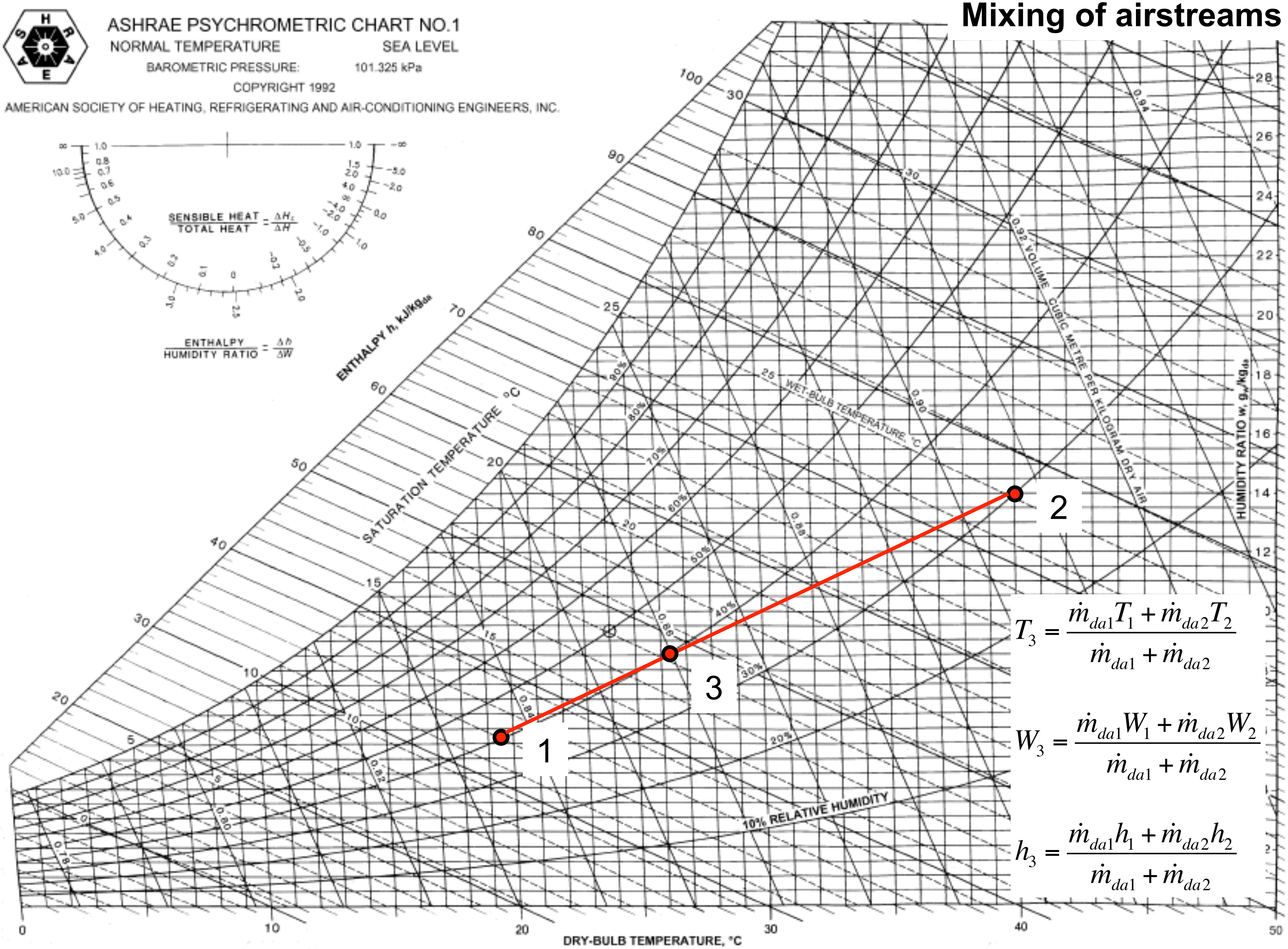
- Often in HVAC systems we mix airstreams adiabatically
  - Without the addition or extraction of heat
  - e.g. outdoor air mixed with a portion of return/recirculated air

- For most parameters, the outlet conditions end up being the weighted-averages of the input conditions
  - Dry bulb temperature
  - Humidity ratio
  - Enthalpy
  - (not wet-bulb temperature though)

Mixing of airstreams



Mixing of airstreams



$$T_3 = \frac{\dot{m}_{da1} T_1 + \dot{m}_{da2} T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

$$W_3 = \frac{\dot{m}_{da1} W_1 + \dot{m}_{da2} W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

$$h_3 = \frac{\dot{m}_{da1} h_1 + \dot{m}_{da2} h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

HUMAN THERMAL COMFORT

Human thermal comfort

- Our ultimate desire in designing a building and its HVAC system is to provide a suitably comfortable environment for the occupants

- One important consideration is thermal comfort

- In general, thermal comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized

- Something else we want to be able to do is quantify the amount of discomfort that a space might present to people and what fraction of occupants are dissatisfied with a space

Thermal balance of body and effective temperature

- The heat produced by the body's metabolism dissipates to the environment
  - Otherwise we would overheat

- Roughly, if the rate of heat transfer is higher than the rate of heat production, the body cools down and we feel cold
  - If heat transfer is lower than production, we feel hot

- This is a complex problem in transient heat transfer, involving radiation, convection, conduction, and evaporation, and many variables including skin wetness and clothing composition
  - We can simplify a lot of this

Assessing thermal comfort

- To develop equations and guidelines for thermal comfort, we have to have some idea of what people perceive to be comfortable
- Comfort analysis is usually done through surveys of users in real spaces and through controlled human experiments and a questionnaire that rates comfort on a seven point scale
- The result of the questionnaire is the Mean Vote (MV)
  - If we predict the results of a questionnaire through equations we generate a predicted mean vote (PMV)

Predicted Mean Vote (PMV)

- The PMV is an estimate of the mean value that would be obtained if a large number of people were asked to vote on thermal comfort using a 7 point scale:

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

The environment is considered acceptable when: $-0.5 < PMV < 0.5$

Percent People Dissatisfied (PPD)

- Once we have the PMV (which are average results) we need to estimate how many people are satisfied with the thermal conditions for that PMV
  - We quantify that as the percent of people dissatisfied (PPD)
- Our design goal usually is to achieve a PPD<10%
- After lots of testing, researchers have found that PPD is a fairly nonlinear function of PMV

Percent People Dissatisfied (PPD)

A plot of the PPD Function is shown below:

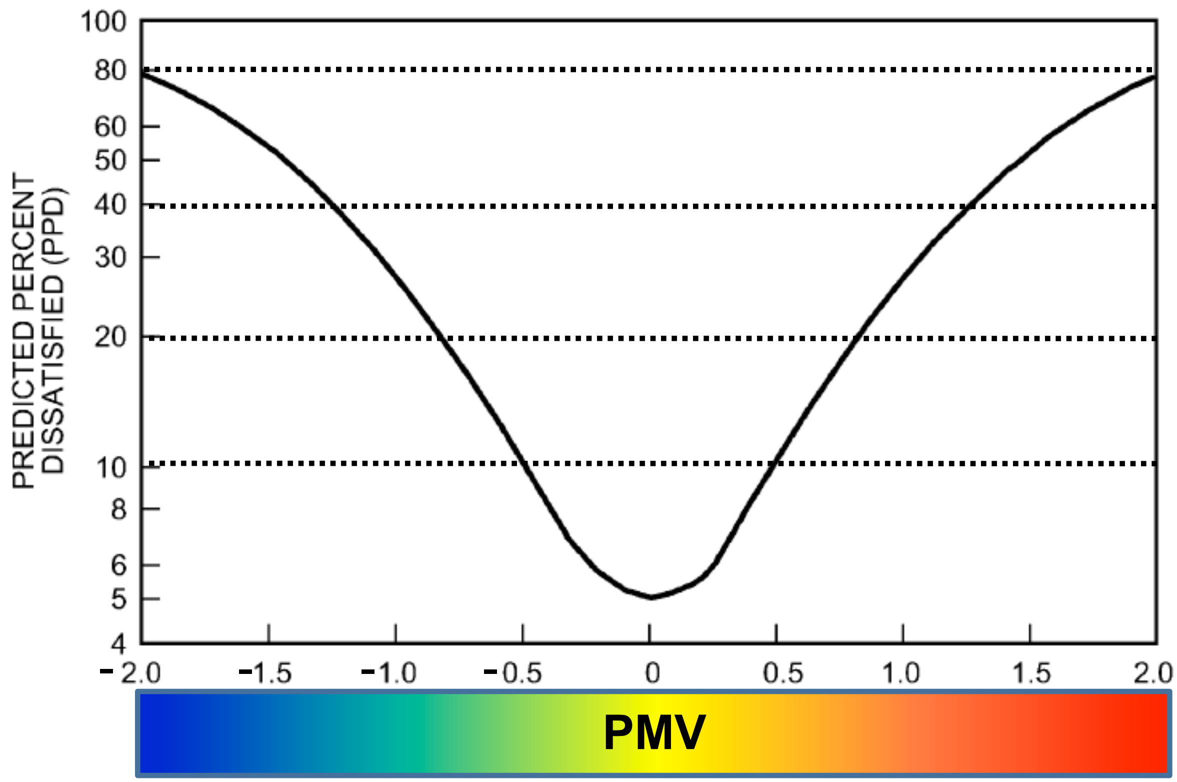
Since we want

PPD<10%

we can see that

-0.5<PMV<0.5

Notice that the minimum PPD is 5% showing that you cannot satisfy everyone at the same time



Variables affecting thermal comfort

- ASHRAE Standard 55 considers 6 parameters important for thermal comfort

Some are familiar:

Ambient Air Temp (T)

Humidity (W or RH)

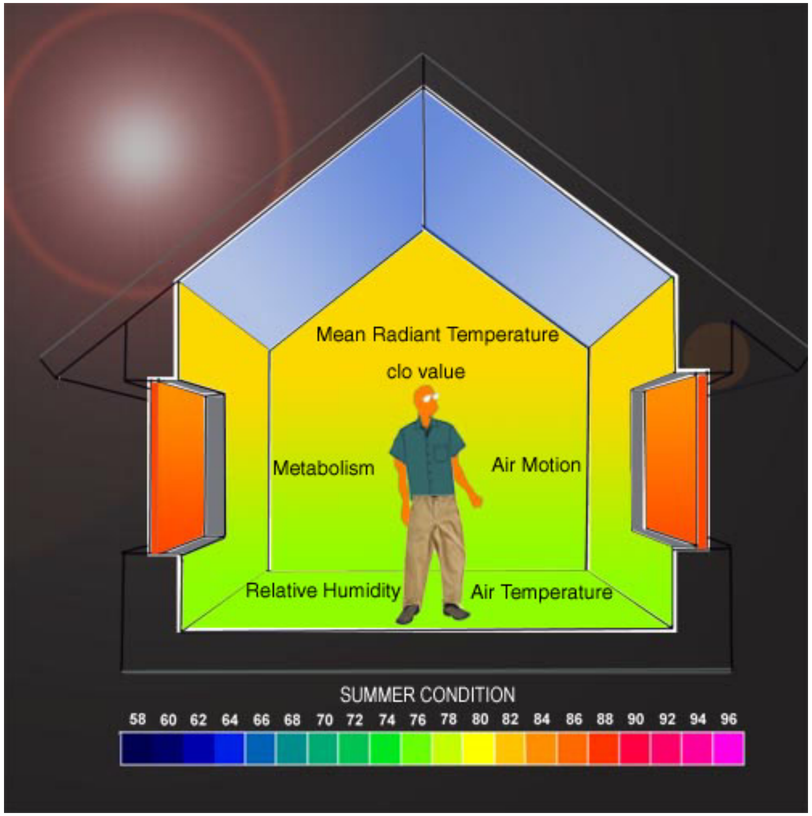
Local Air Speed (v)

Some are probably not:

Metabolic Rate (M)

Clothing Insulation (I_{cl})

Mean Radiant Temp. (T_r)



Metabolic energy production

- The total energy production rate of the human body is the sum of the production rates of heat (Q) and work (W):

$$\dot{Q} + \dot{W} = MA_{skin}$$

where
M = rate of metabolic energy production per surface area of skin (W/m^2)
A_{skin} = total surface area of skin (m^2)
(work, W, is typically neglected)

$$1 \text{ met} = 18.4 \frac{\text{Btu}}{\text{h} \cdot \text{ft}^2} = 58 \frac{\text{W}}{\text{m}^2}$$

Metabolic Rates for Typical Tasks

Activity	Met Units	Metabolic Rate W/m^2	(Btu/h·ft^2)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)

Metabolic rates (continued)

Activity	Met Units	Metabolic Rate W/m^2	(Btu/h·ft^2)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0-2.4	115-140	(37-44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

What about A_{skin}?

- For an adult, the area of our skin is typically on the order of 16-22 ft^2 (1.5 to 2 m^2)

- So for a typical adult doing typical indoor activities, their heat production rate will be:

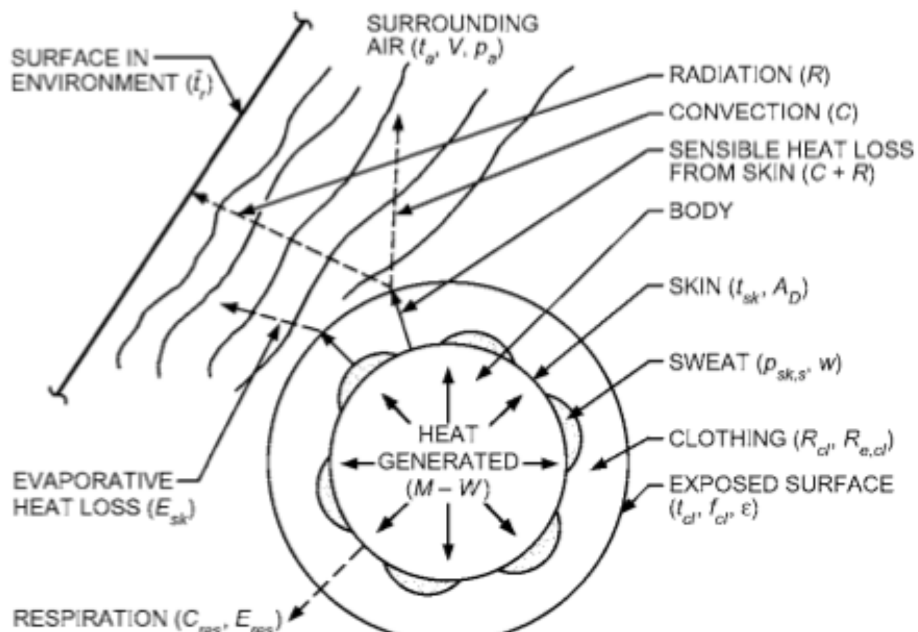
$$\dot{Q} + \dot{W} = MA_{skin} \approx (1\ \text{met})(1.5 - 2\ \text{m}^2)$$

$$\approx (58.2\ \frac{\text{W}}{\text{m}^2})(1.5 - 2\ \text{m}^2) \approx 100\ \text{W}$$

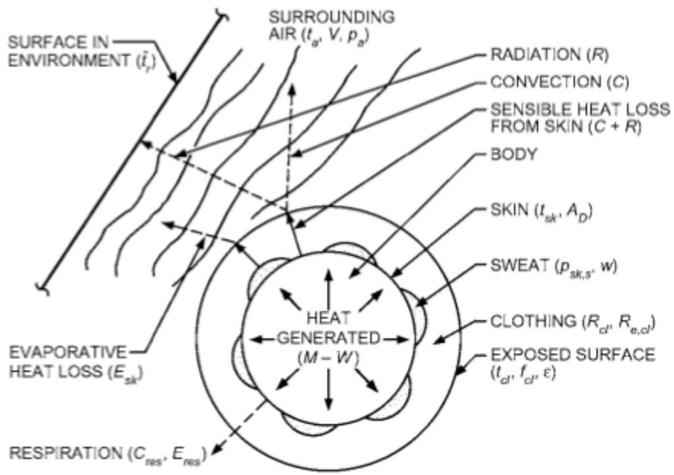
Body energy balance in a space

- Our internal body temperatures are consistent around 36-37°C
- We can set our heat production rate equal to the instantaneous heat flow to the environment (no storage):

$$\dot{Q} = MA_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{resp,sens} + \dot{Q}_{resp,latent}$$
$$q = M = q_{conv} + q_{rad} + q_{evap} + q_{resp,sens} + q_{resp,latent}$$



Body energy balance in a space



$$M - W = q_{sk} + q_{res} + S$$
$$= (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr})$$

where

M = rate of metabolic heat production, W/m^2
W = rate of mechanical work accomplished, W/m^2
q_{sk} = total rate of heat loss from skin, W/m^2
q_{res} = total rate of heat loss through respiration, W/m^2
$C + R$ = sensible heat loss from skin, W/m^2
E_{sk} = total rate of evaporative heat loss from skin, W/m^2
C_{res} = rate of convective heat loss from respiration, W/m^2
E_{res} = rate of evaporative heat loss from respiration, W/m^2
S_{sk} = rate of heat storage in skin compartment, W/m^2
S_{cr} = rate of heat storage in core compartment, W/m^2

Sensible heat loss from skin

$$C = f_{cl} h_c (t_{cl} - t_a) \quad (5)$$

$$R = f_{cl} h_r (t_{cl} - \bar{t}_r) \quad (6)$$

where

h_c = convective heat transfer coefficient, W/(m$^2\cdot$K)
h_r = linear radiative heat transfer coefficient, W/(m$^2\cdot$K)
f_{cl} = clothing area factor A_{cl}/A_D, dimensionless

The coefficients h_c and h_r are both evaluated at the clothing surface.

Evaporative heat loss from skin

$$E_{sk} = \frac{w(p_{sk,s} - p_a)}{R_{e,cl} + 1/(f_{cl} h_e)} \quad (12)$$

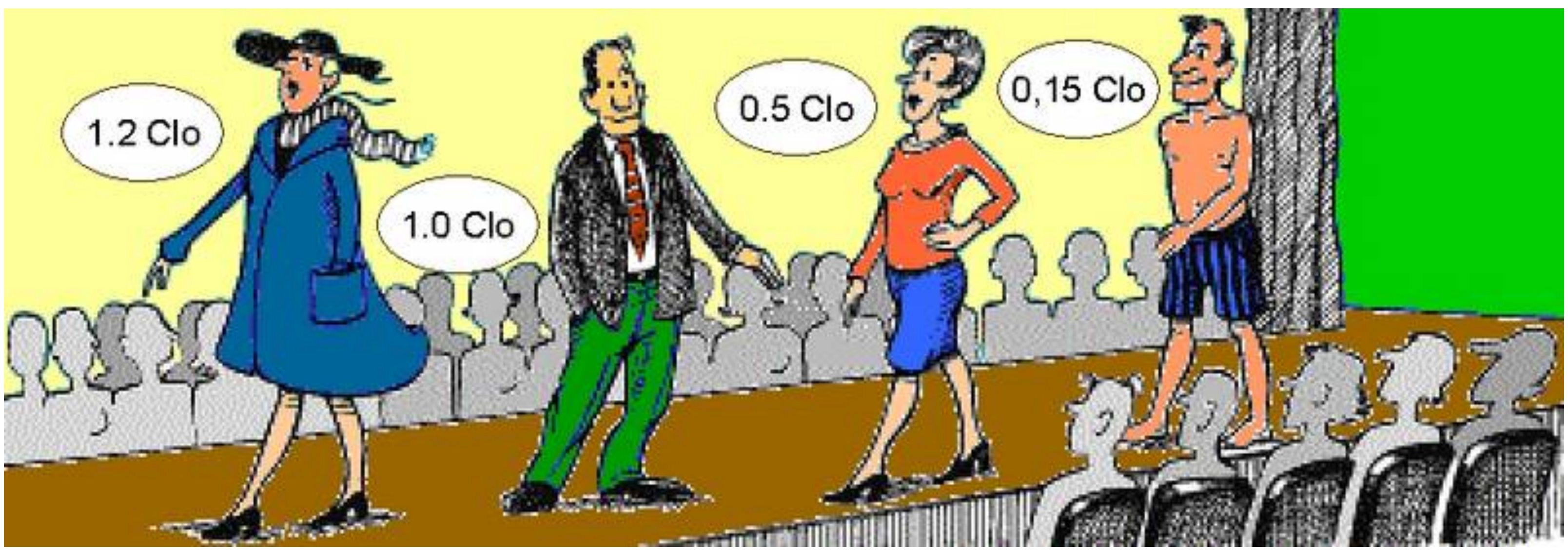
where

w = skin wettedness, dimensionless
$p_{sk,s}$ = water vapor pressure at skin, normally assumed to be that of saturated water vapor at t_{sk}, kPa
p_a = water vapor pressure in ambient air, kPa
$R_{e,cl}$ = evaporative heat transfer resistance of clothing layer (analogous to R_{cl}), (m$^2\cdot$kPa)/W
h_e = evaporative heat transfer coefficient (analogous to h_c), W/(m$^2\cdot$kPa)

These equations get complex quickly…

Thermal insulation, R_{cl}

- The thermal insulating effects of clothes are measured in **clos** (1 clo = 0.88 h·ft^2·˚F/Btu)
- Insulating values for various garments are found in ASHRAE Fundamentals and Appendix B of Std 55



Mean radiant temperature, T_r

- Radiation to/from occupants is a primary form of energy exchange
  - We can estimate its effects using the **mean radiant temperature**

- The mean radiant temperature is the temperature of an imaginary uniform black box that results in the same radiation heat loss to the occupant as the current room

- This is particularly important for environments with drastically different surface temperatures
  - e.g. a poorly insulated window on a winter day has a surface temperature much lower than most other surfaces around it
  - e.g. a concrete slab warmed by the sun may have a higher temperature than its surroundings

$$\bar{T}_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots + T_N^4 F_{p-N}$$

where

$\bar{T}_r$ = mean radiant temperature, K
T_N = surface temperature of surface N, K
F_{p-N} = angle factor between a person and surface N

Finding T_r from globe temperature

- We can measure the temperature of the interior of a black globe as well as the ambient air temperature to estimate T_r
  - The black globe acts as a perfectly round black body radiator

$$T_r = \left[(T_{globe} + 273)^4 + \frac{1.1 \times 10^8 v_{air}^{0.6}}{\varepsilon D^{0.4}} (T_{globe} - T_{air}) \right]^{1/4} - 273$$

T_{globe} = temperature inside globe (°C)
T_{air} = air temperature (°C)
T_r = mean radiant temperature (°C)

v_{air} = air velocity (m/s)
D = globe diameter (m)
ε = emissivity of globe (-)

ASHRAE comfort zone

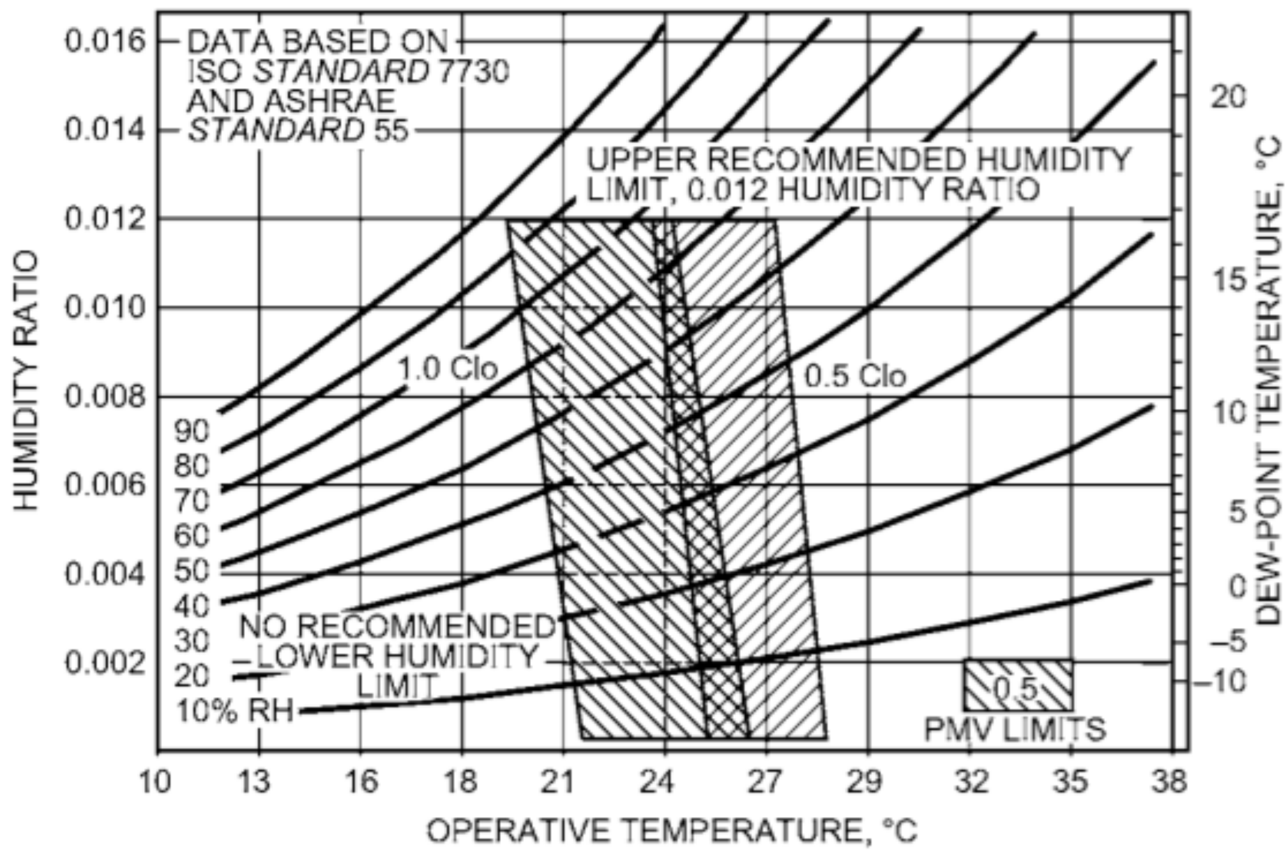


Fig. 5 ASHRAE Summer and Winter Comfort Zones
[Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met)].

Operative temperature?

- The operative temp is basically the average value between the air temperature and the mean radiant temperature, adjusted for air velocity effects:

$$T_{operative} = AT_a + (1 - A)T_r$$

T_a = ambient temp, T_r =mean radiant temp

$$A = \begin{cases} 0.5 \text{ for } v < 0.2 \text{ m/s} \\ 0.6 \text{ for } 0.2 < v < 0.6 \text{ m/s} \\ 0.7 \text{ for } 0.6 < v < 1.0 \text{ m/s} \end{cases}$$

where v is the air velocity

- **Is this room within the ASHRAE comfort zone?**

Next time

- No class next Monday
- Turn in your HW to our TA Liz (place in her box)