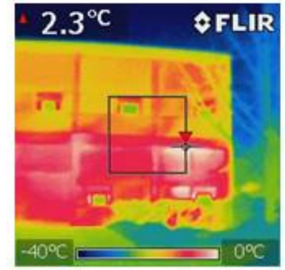
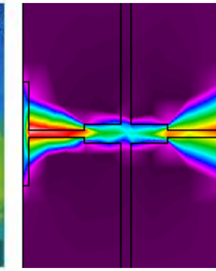
CAE 331/513
Building Science
Fall 2019





September 26, 2019
Psychrometrics (chart and definitions)

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Illinois Institute of Technology
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PSYCHROMETRICS

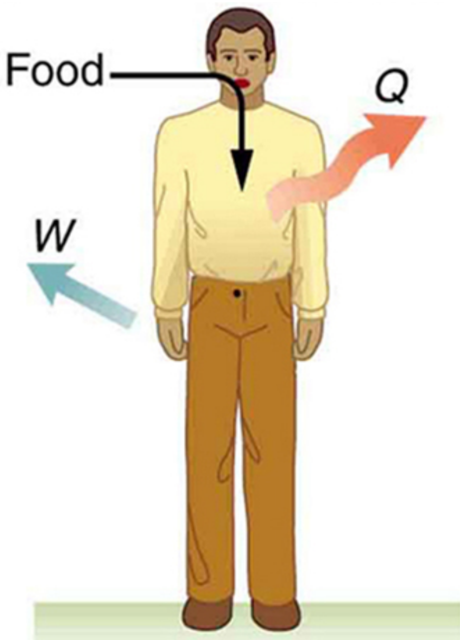
Last time

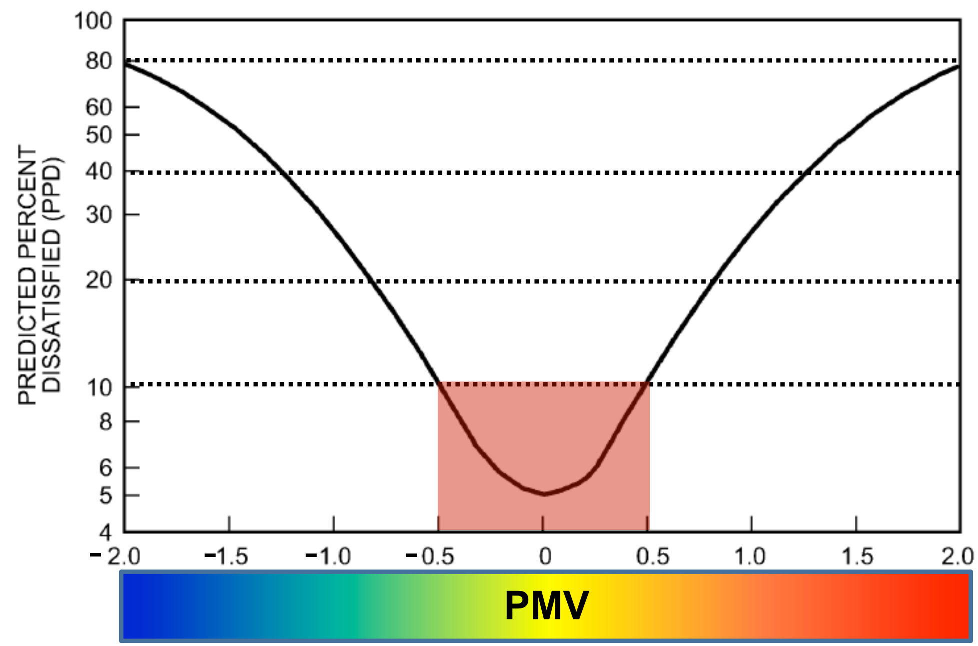
- Human thermal comfort

$$A_D = 0.202 m^{0.425} l^{0.725}$$

A_D = DuBois surface area, m^2
m = mass, kg
l = height, m

$$\dot{Q} = M A_{skin}$$

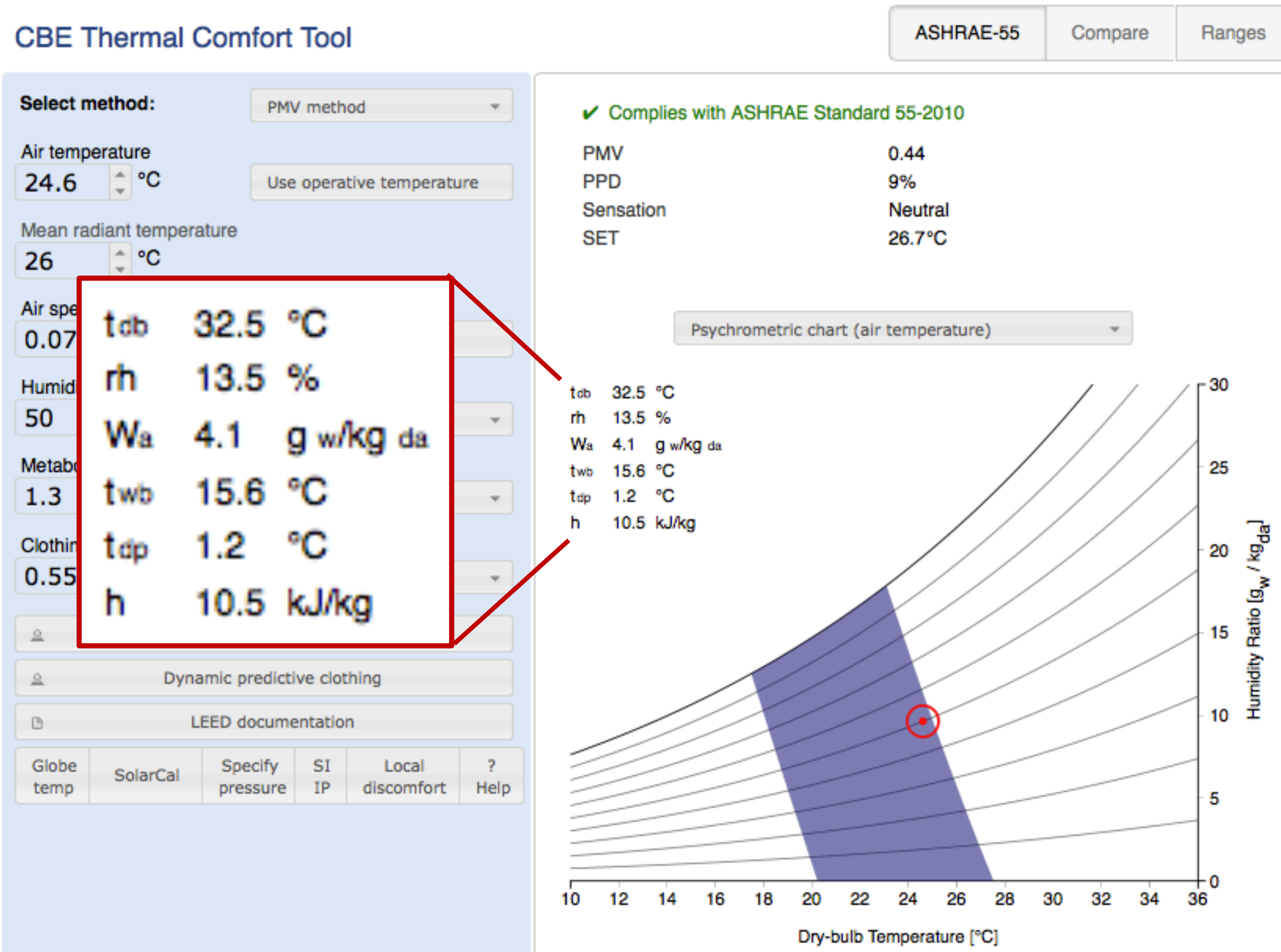




$$1 \text{ met} = 18.4 \frac{\text{Btu}}{\text{h} \cdot \text{ft}^2} = 58 \frac{\text{W}}{\text{m}^2}$$

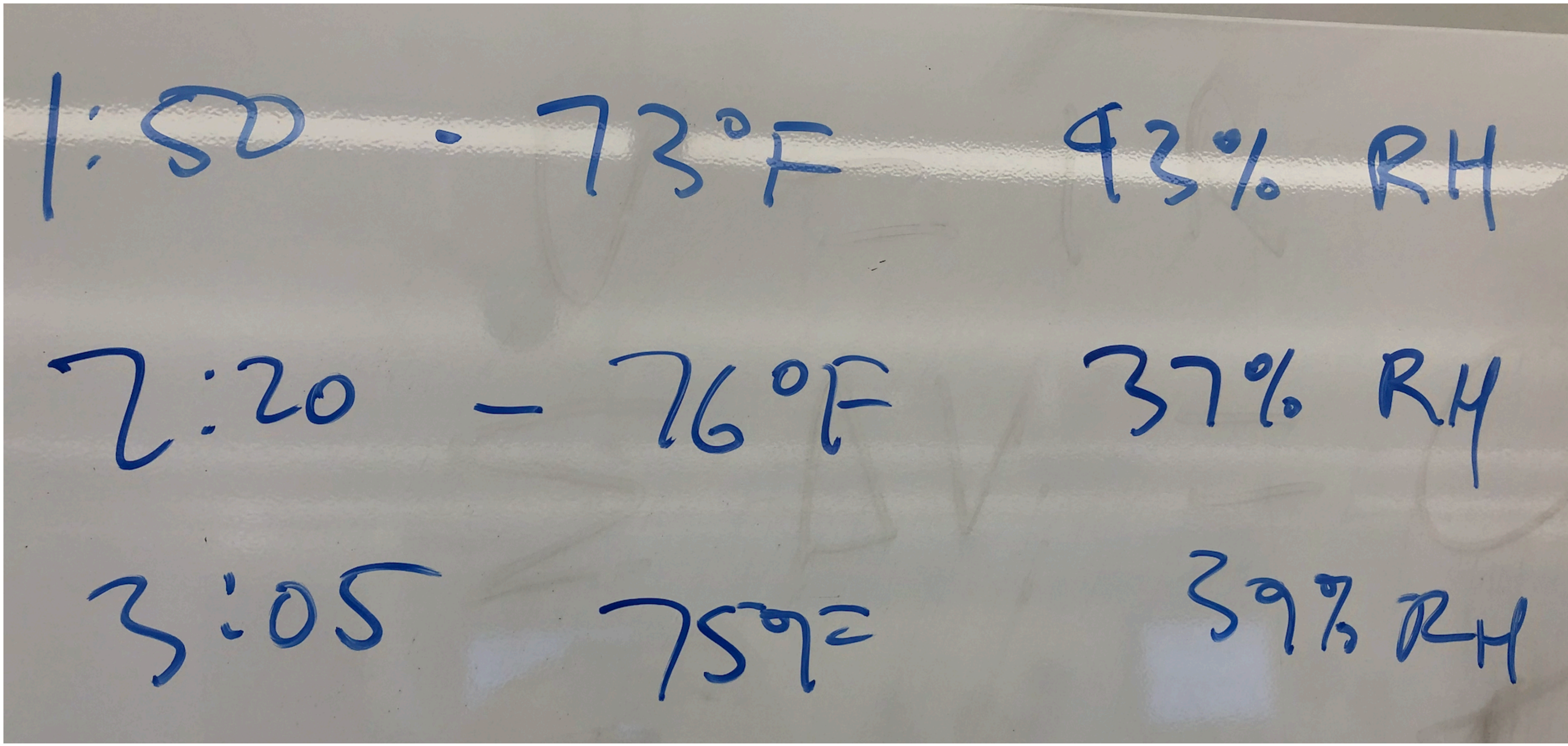
-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

ASHRAE comfort zone: CBE Thermal Comfort Tool

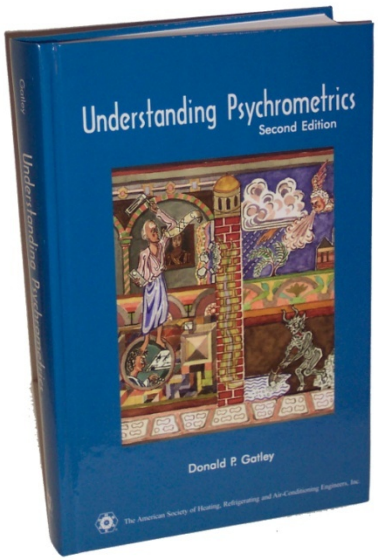


http://comfort.cbe.berkeley.edu/

Classroom conditions



Psychrometrics



Psychrometrics is the science and engineering of air/vapor mixtures

– For architectural engineers and building scientists, the vapor is **water vapor**

– We use psychrometrics to relate the thermodynamic and physical properties of moist air

Applying psychrometrics

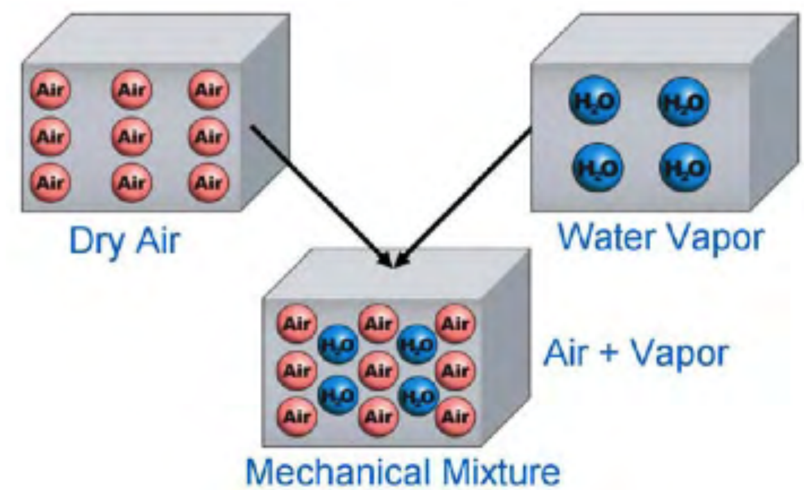
- We need to understand air temperature and moisture content to understand **human thermal comfort**
  - In hot, humid weather we design HVAC systems to remove moisture by dehumidification/cooling
  - In dry, cold weather, we add moisture by humidifiers

- We are also concerned about moisture for energy use, structural, aesthetic, and indoor air quality reasons

- Psychrometrics also involves learning how to use and combine a variety of moist air parameters

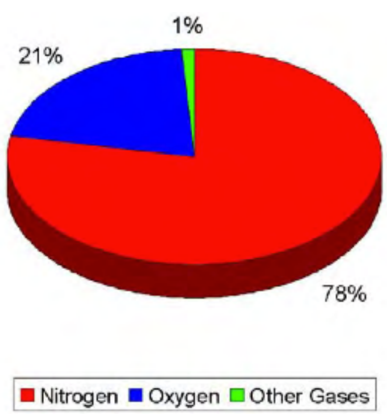
Some definitions for psychrometrics

- **Atmospheric air** contains:
  - Many gaseous components
  - Water vapor
  - Contaminants (particulate matter and gaseous pollutants)
- **Dry air** is atmospheric air with all of the water vapor removed
- **Moist air** is a two-component mixture of dry air and water vapor



Standard composition of dry air

Gas	Molecular weight (g/mol)	Volume %
Nitrogen (N_2)	32.000	78.084
Oxygen (O_2)	28.016	20.946
Argon (Ar)	39.444	0.9340
Carbon Dioxide (CO_2)	44.010	0.03697
Neon (Ne)	20.179	0.00182
Helium (He)	4.002	0.00052
Methane (CH_4)	16.042	0.00014
Krypton	83.800	0.00010



Where does water fit in?

Standard composition of **moist** air

Gas	Molecular weight (g/mol)	Volume %
Nitrogen (N_2)	32.000	78.084%
Oxygen (O_2)	28.016	20.946%
Water (H_2O)	**18.015**	**0 to 4%**
Argon (Ar)	39.444	0.9340%
Carbon Dioxide (CO_2)	44.010	0.03697%
Neon (Ne)	20.179	0.00182%
Helium (He)	4.002	0.00052%
Methane (CH_4)	16.042	0.00014%
Krypton	83.800	0.00010%

Key terms for describing moist air

- To describe and deal with moist air, we need to be able to describe the relative portions of dry air and water vapor

- There are several different measures…

- Which one you use depends on what data you have to start with and what quantity you are trying to find

- If you know **two psychrometric properties**, you can usually get all the others

Key terms for describing moist air

Key terms to learn today:

1. Dry bulb temperature
2. Vapor pressure
3. Saturation
4. Relative humidity
5. Absolute humidity (or humidity ratio)
6. Dew point temperature
7. Wet bulb temperature
8. Enthalpy
9. Density
10. Specific volume

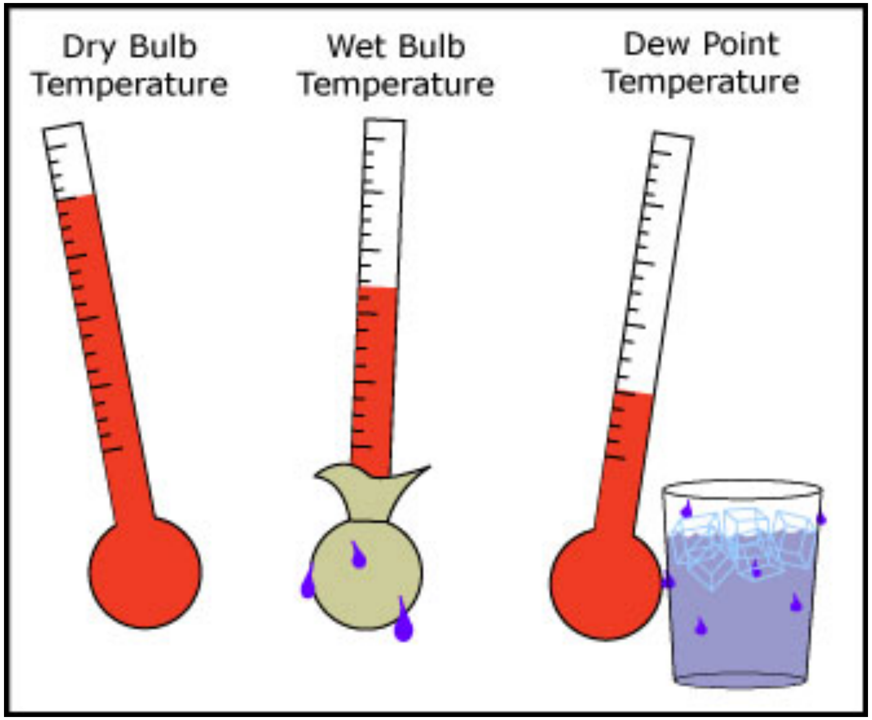
Three different temperatures: T, T_{dew}, and T_{wb}

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



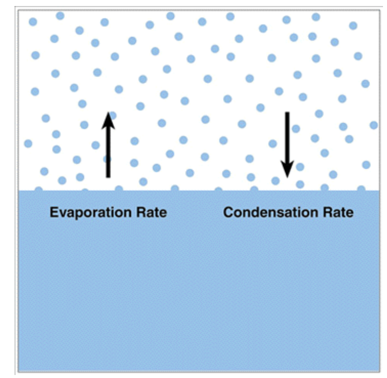
*Units of Celsius, Fahrenheit, or Kelvin

✓ The energy needed to evaporate liquid water (heat of vaporization) is taken from the air in the form of sensible heat and converted to latent heat, which lowers the temperature at constant enthalpy

Key concepts: Vapor pressure and Saturation

- Air can hold moisture (i.e., **water vapor**)
- **Vapor pressure** is the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases

p_w *Units of pressure, psia (Pa or kPa)
(aka "partial pressure")



- 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, psia (Pa or kPa)
(aka "saturation vapor pressure")

Key concept: Relative humidity, ϕ

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

- Relative humidity ≠ absolute humidity!

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

Key concept: Saturation vapor pressure, p_{ws}

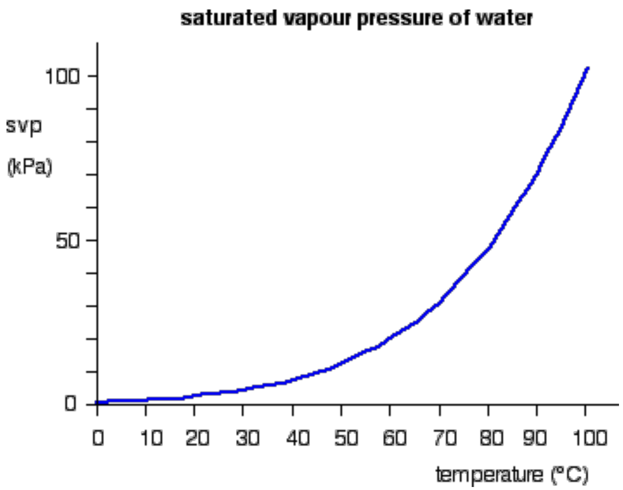
- The **saturation vapor pressure** is the partial pressure of water vapor at saturation (p_{ws}) *Units of pressure, **Pa** (or **kPa**) and **psia**
  - Cannot absorb any more moisture at that temperature
- We can look up p_{ws} in tables (as a function of T)
  - Table 3 in Chapter 1 of the ASHRAE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

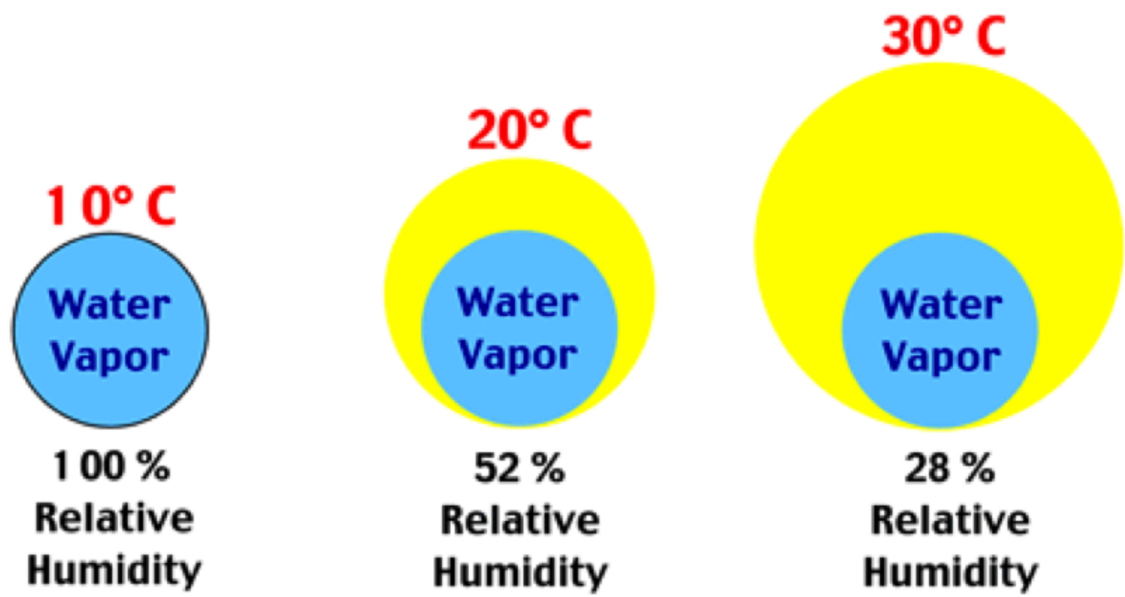
Temp., °F	Absolute Pressure	Specific Volume, ft^3/lb_w			Specific Enthalpy, Btu/lb_w			Specific Entropy, $Btu/lb_w \cdot °F$			Temp., °F
		Sat. Solid	Evap.	Sat. Vapor	Sat. Solid	Evap.	Sat. Vapor	Sat. Solid	Evap.	Sat. Vapor	
t	p_{ws}, psia	v_i/v_f	v_{ig}/v_{fg}	v_g	h_i/h_f	h_{ig}/h_{fg}	h_g	s_i/s_f	s_{ig}/s_{fg}	s_g	t
–13	0.009177	0.01741	28990	28990	–164.91	1220.33	1055.42	–0.3375	2.7321	2.3946	–13
–12	0.009700	0.01741	27490	27490	–164.46	1220.32	1055.86	–0.3365	2.7259	2.3895	–12
–11	0.010249	0.01741	26073	26073	–164.00	1220.30	1056.30	–0.3355	2.7198	2.3844	–11
–10	0.010827	0.01741	24736	24736	–163.54	1220.28	1056.74	–0.3344	2.7137	2.3793	–10
–9	0.011435	0.01741	23473	23473	–163.08	1220.26	1057.18	–0.3334	2.7077	2.3743	–9
–8	0.012075	0.01741	22279	22279	–162.62	1220.24	1057.63	–0.3324	2.7016	2.3692	–8
–7	0.012747	0.01742	21151	21152	–162.15	1220.22	1058.07	–0.3314	2.6956	2.3642	–7
–6	0.013453	0.01742	20086	20086	–161.69	1220.20	1058.51	–0.3303	2.6896	2.3593	–6
–5	0.014194	0.01742	19078	19078	–161.23	1220.17	1058.95	–0.3293	2.6837	2.3543	–5
–4	0.014974	0.01742	18125	18125	–160.76	1220.15	1059.39	–0.3283	2.6777	2.3494	–4
–3	0.015792	0.01742	17223	17223	–160.29	1220.12	1059.83	–0.3273	2.6718	2.3445	–3
–2	0.016651	0.01742	16370	16370	–159.83	1220.10	1060.27	–0.3263	2.6659	2.3396	–2
–1	0.017553	0.01742	15563	15563	–159.36	1220.07	1060.71	–0.3252	2.6600	2.3348	–1
0	0.018499	0.01743	14799	14799	–158.89	1220.04	1061.15	–0.3242	2.6542	2.3300	0
1	0.019492	0.01743	14076	14076	–158.42	1220.01	1061.59	–0.3232	2.6483	2.3251	1
2	0.020533	0.01743	13391	13391	–157.95	1219.98	1062.03	–0.3222	2.6425	2.3204	2
3	0.021625	0.01743	12742	12742	–157.48	1219.95	1062.47	–0.3212	2.6368	2.3156	3

Relative humidity and temperature

- **Relative humidity** (RH, or ϕ) is a <u>function of temperature</u>

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





Key concept: Humidity ratio, W

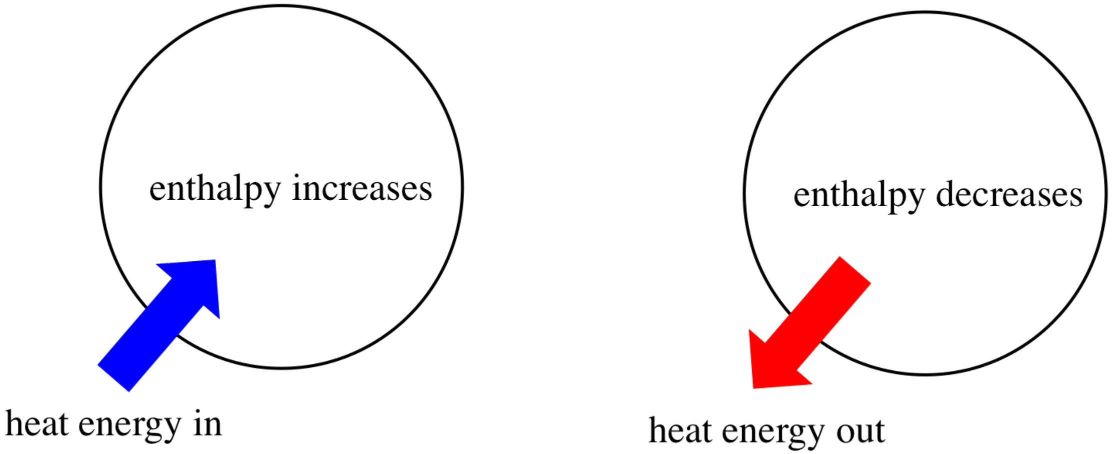
- The **humidity ratio** is a measure of the mass of water vapor present in a parcel of air (a measure of *absolute humidity*)

- The humidity ratio is simply the mass of water vapor that exists in a parcel of mass of *dry air*
  - Units of mass of water vapor per mass of dry air
    - kg/kg (kg_w/kg_{da})
    - g/kg (g_w/kg_{da})
    - lb/lb (lb_w/lb_{da})

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

Key concept: Enthalpy

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



Key concept: Density and specific volume

Air density

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

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

Specific volume

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

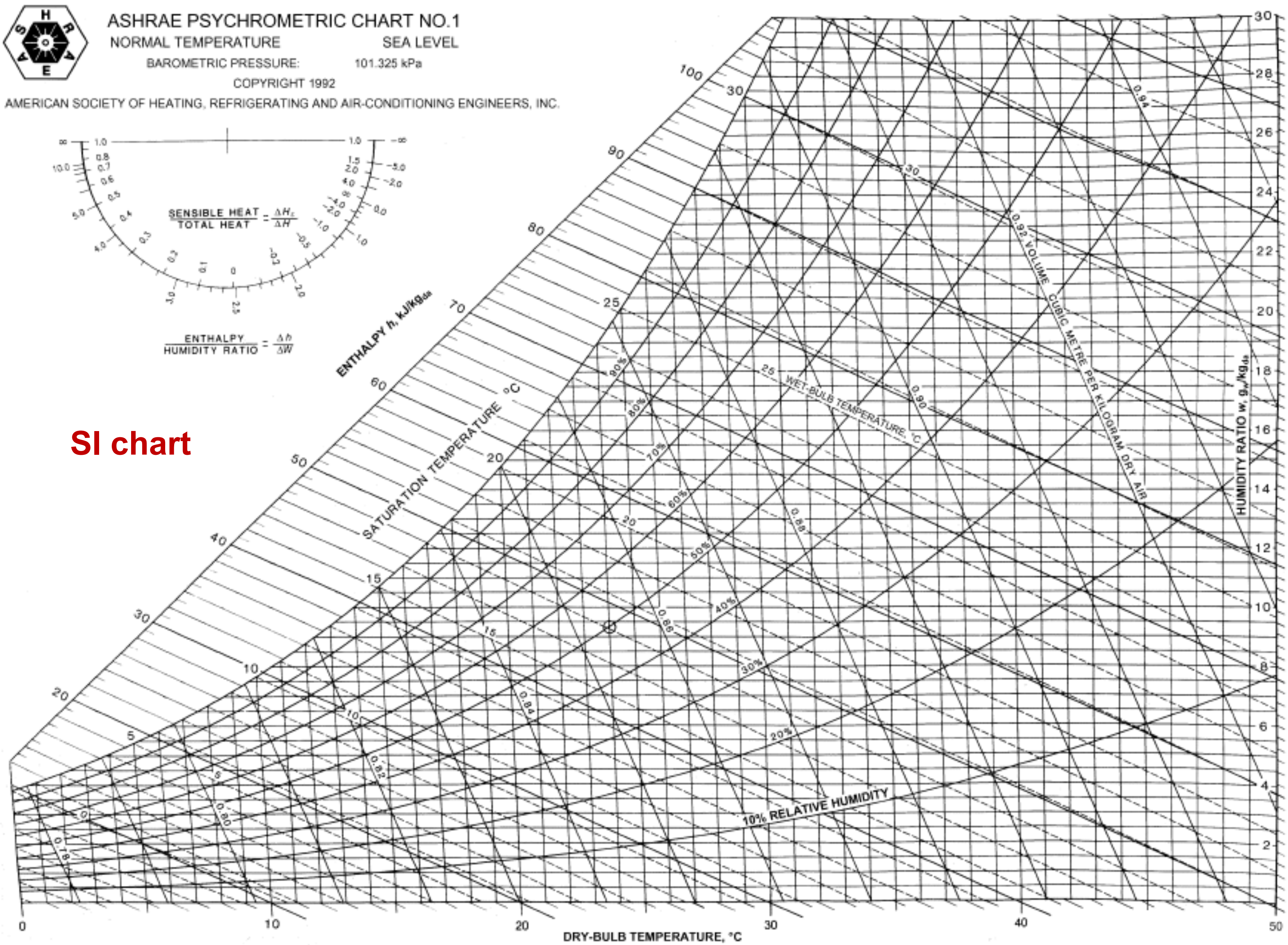
$$\upsilon = \frac{\text{volume of dry air}}{\text{mass of dry air}} \quad [\frac{\text{m}^3}{\text{kg}_{da}}][\frac{\text{ft}^3}{\text{lb}_{da}}]$$

The Psychrometric Chart

- There are both simple and complex ways to estimate these properties
  - Equations and tables (more complex, save for next lecture)
  - Graphically using …

- **The Psychrometric Chart**
  - Plots dry bulb temperature (T) on the x-axis and humidity ratio (W) on the y-axis
    - Shows relationships between T and W and relative humidity, wet-bulb temperature, vapor pressure, specific volume, and enthalpy
  - Charts are unique at each value of atmospheric pressure (p)

- Both SI and IP versions are on BB in the ASHRAE materials folder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SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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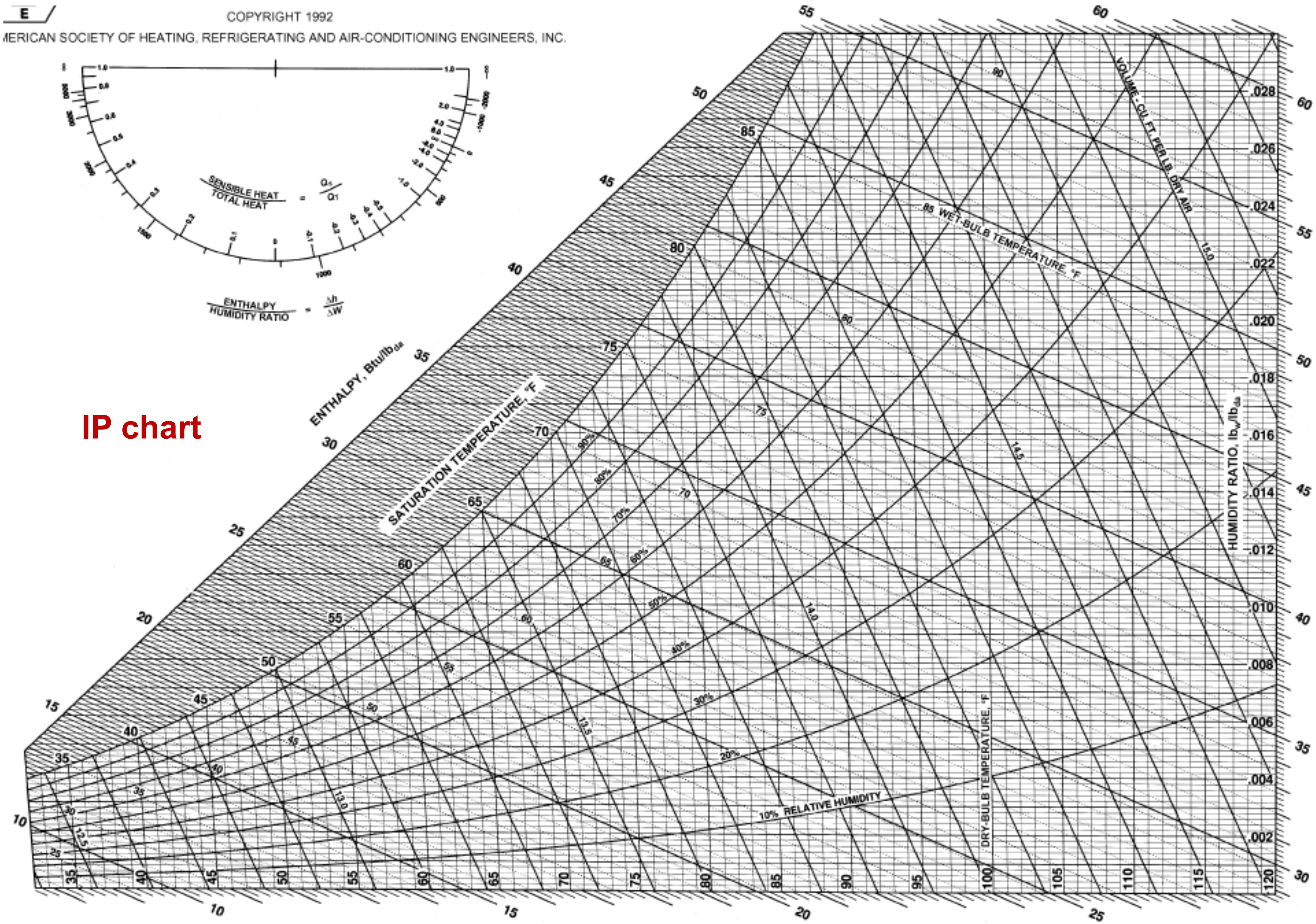
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g w/kg da
DRY-BULB TEMPERATURE, °C

SI chart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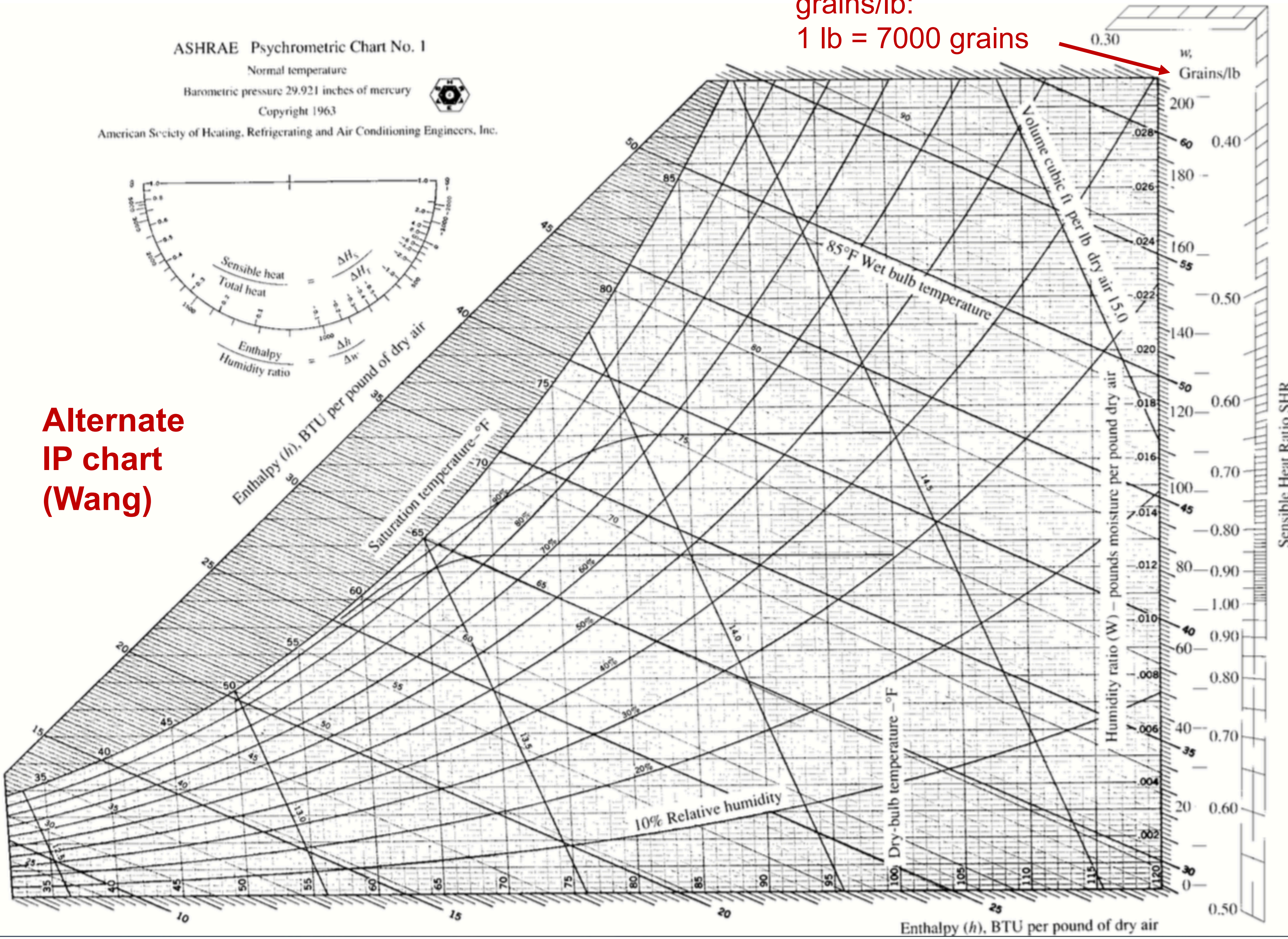
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU. FT. PER LB. DRY AIR
HUMIDITY RATIO, lb w/lb da
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY

IP chart

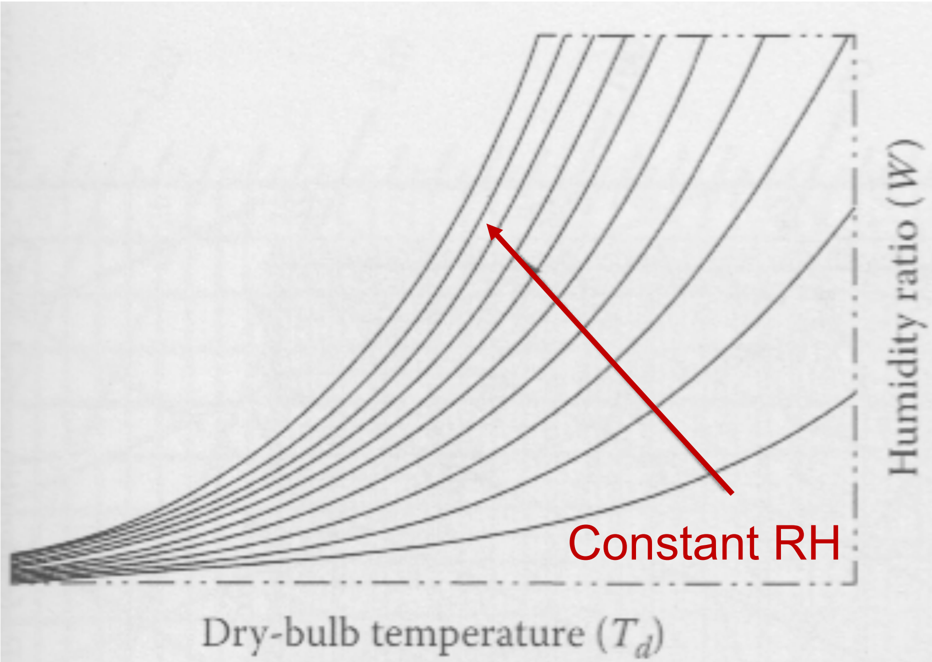
grains/lb:
1 lb = 7000 grains



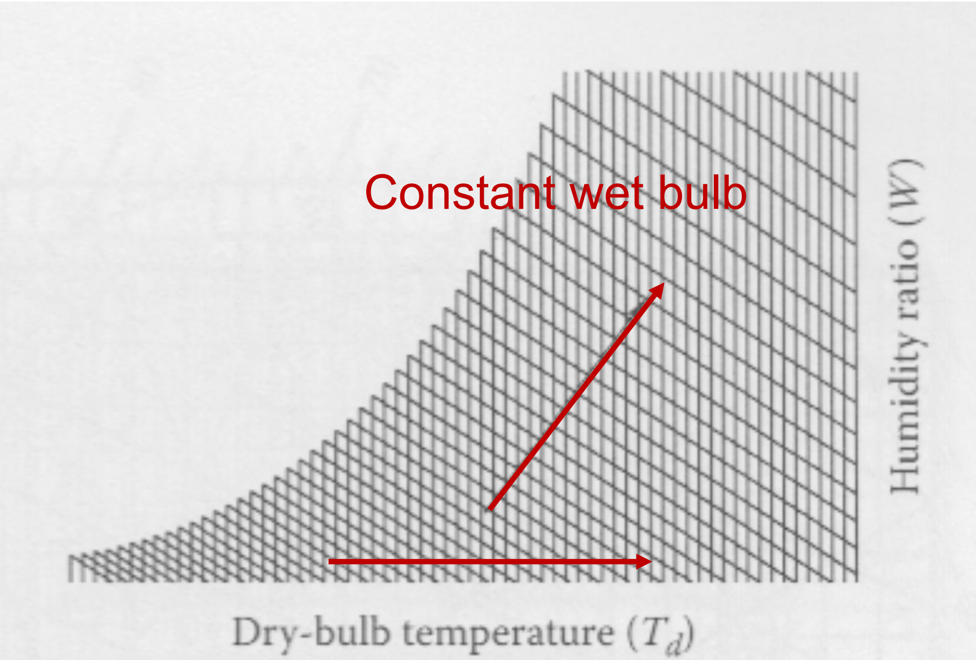
Alternate IP chart (Wang)

Deciphering the psychrometric chart

Lines of constant RH



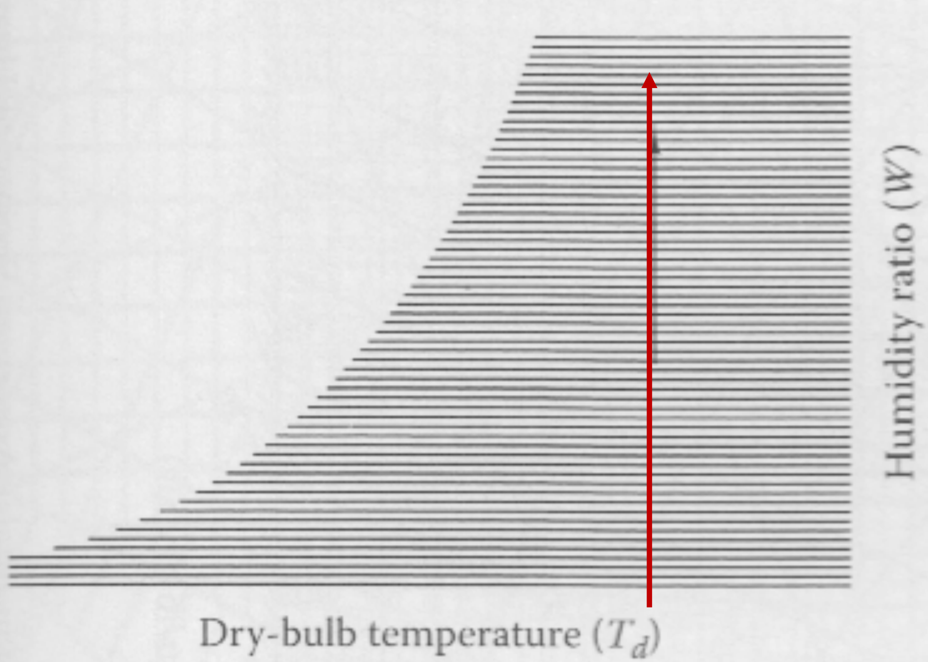
Lines of constant wet-bulb and dry-bulb



Constant dry bulb temperature

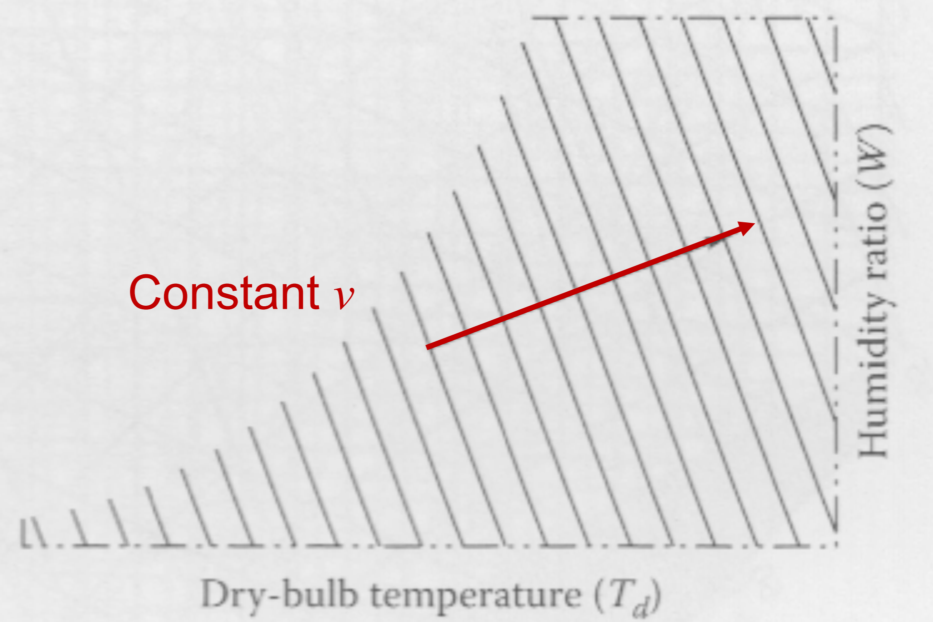
Deciphering the psychrometric chart

Lines of constant humidity ratio



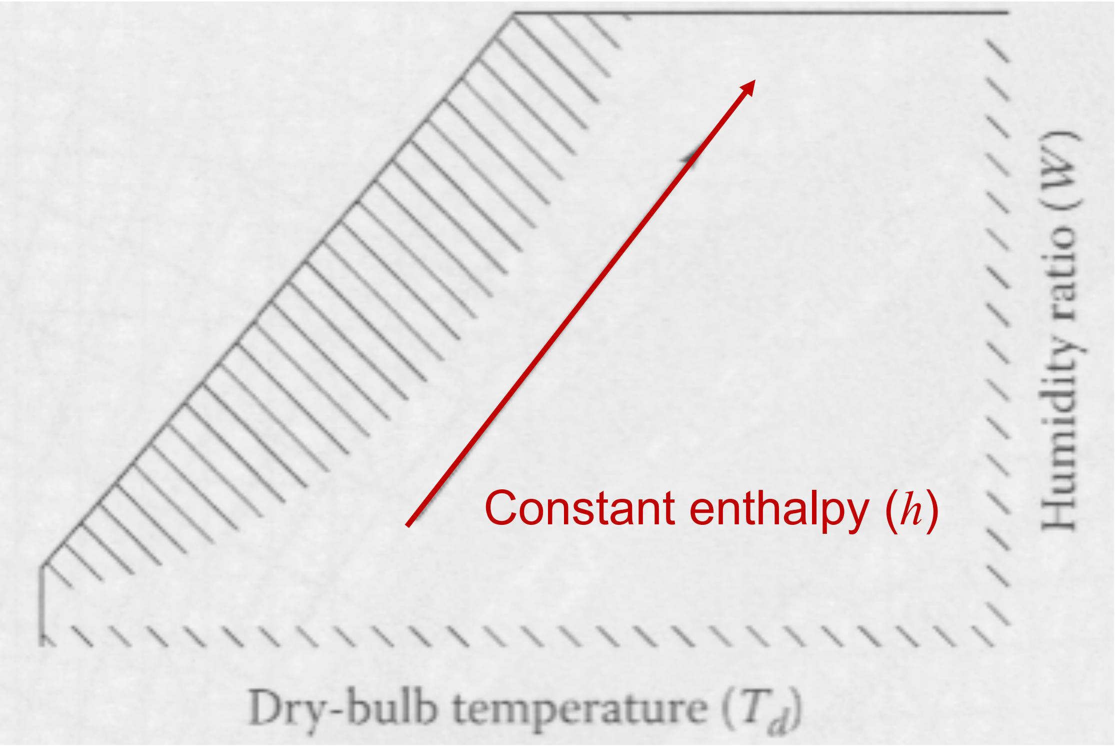
Constant *W*

Lines of constant specific volume



Deciphering the psychrometric chart

Lines of constant enthalpy



Some psychrometric examples

Moist air exists at 22°C dry-bulb temperature with 50% RH

Find the following:

(a) the humidity ratio, W

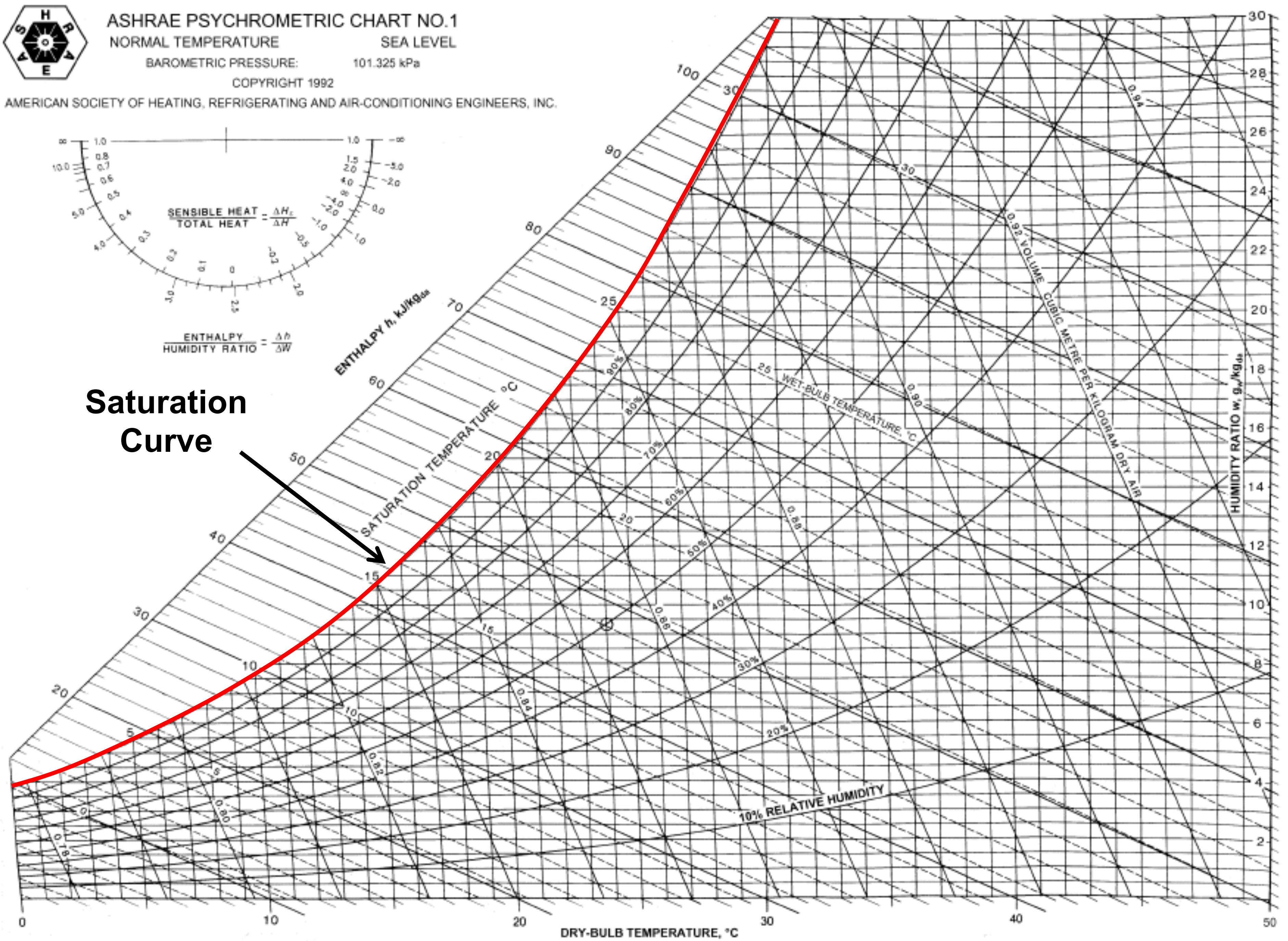
(b) dew point temperature, T_{dew}

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

(d) enthalpy, h

(e) specific volume, v

(f) dry air density, ρ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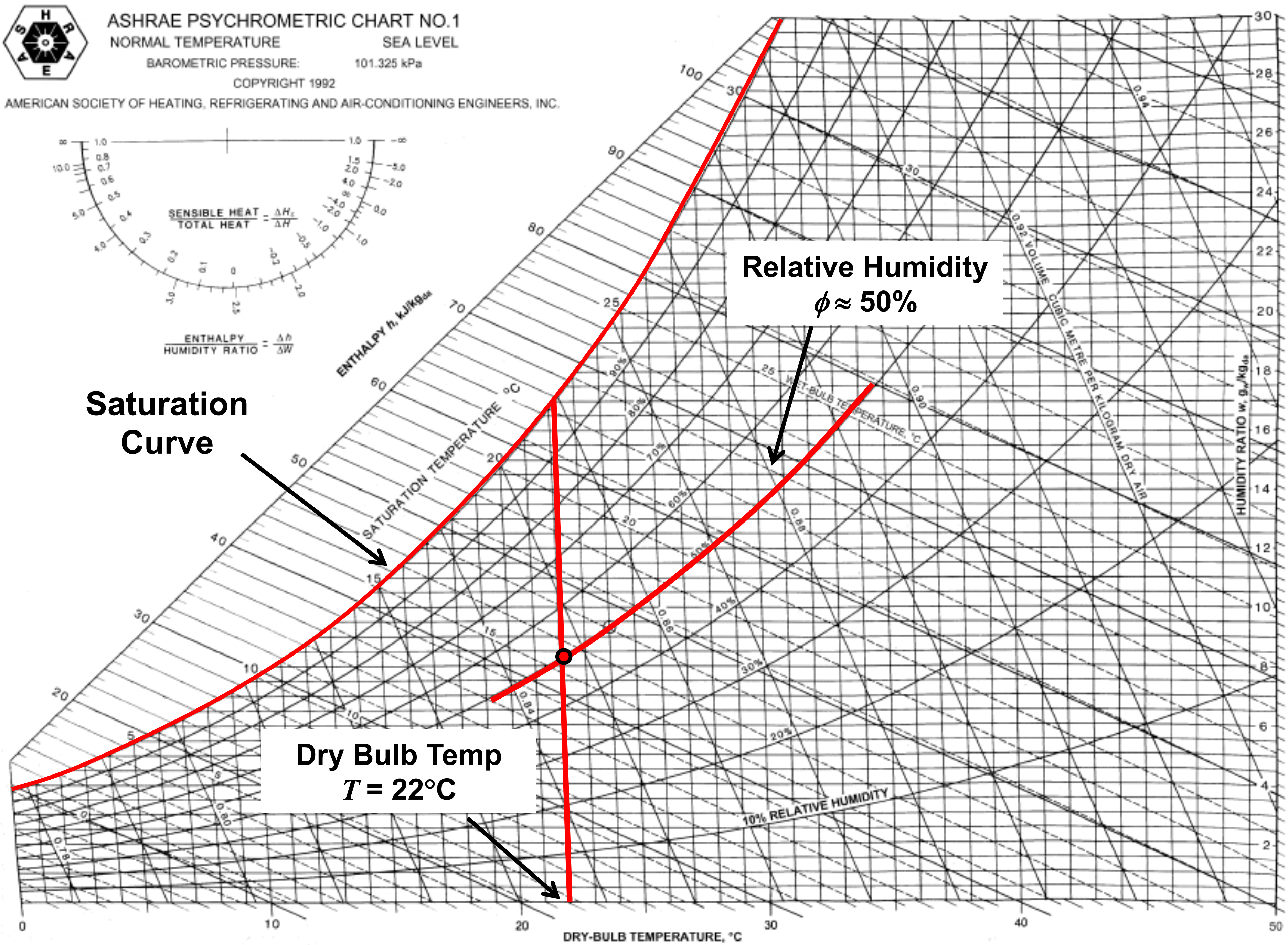
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Saturation Curve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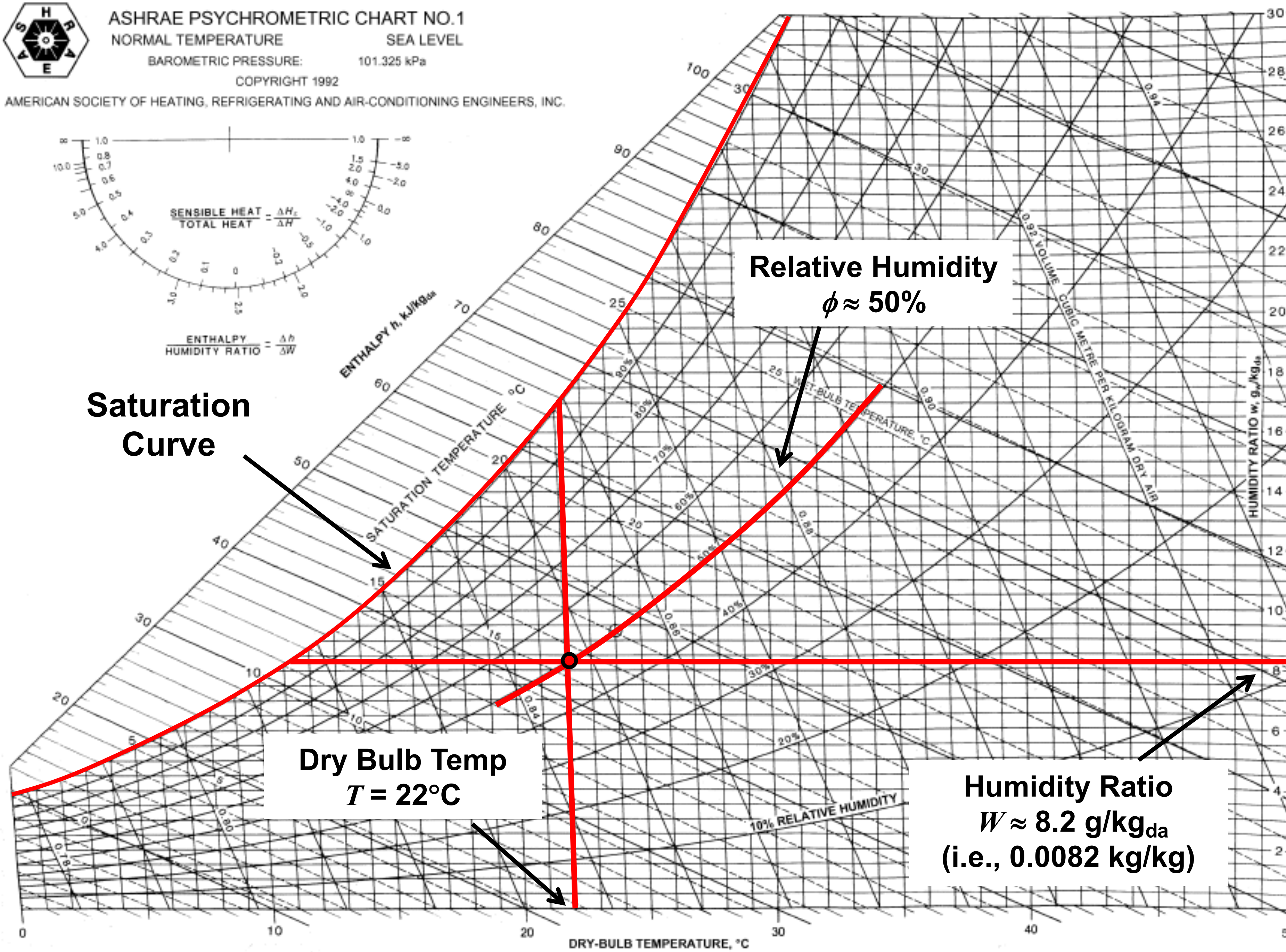
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g_w/kg_da
DRY-BULB TEMPERATURE, °C
Saturation Curve
Relative Humidity
φ ≈ 50%
Dry Bulb Temp
T = 22°C



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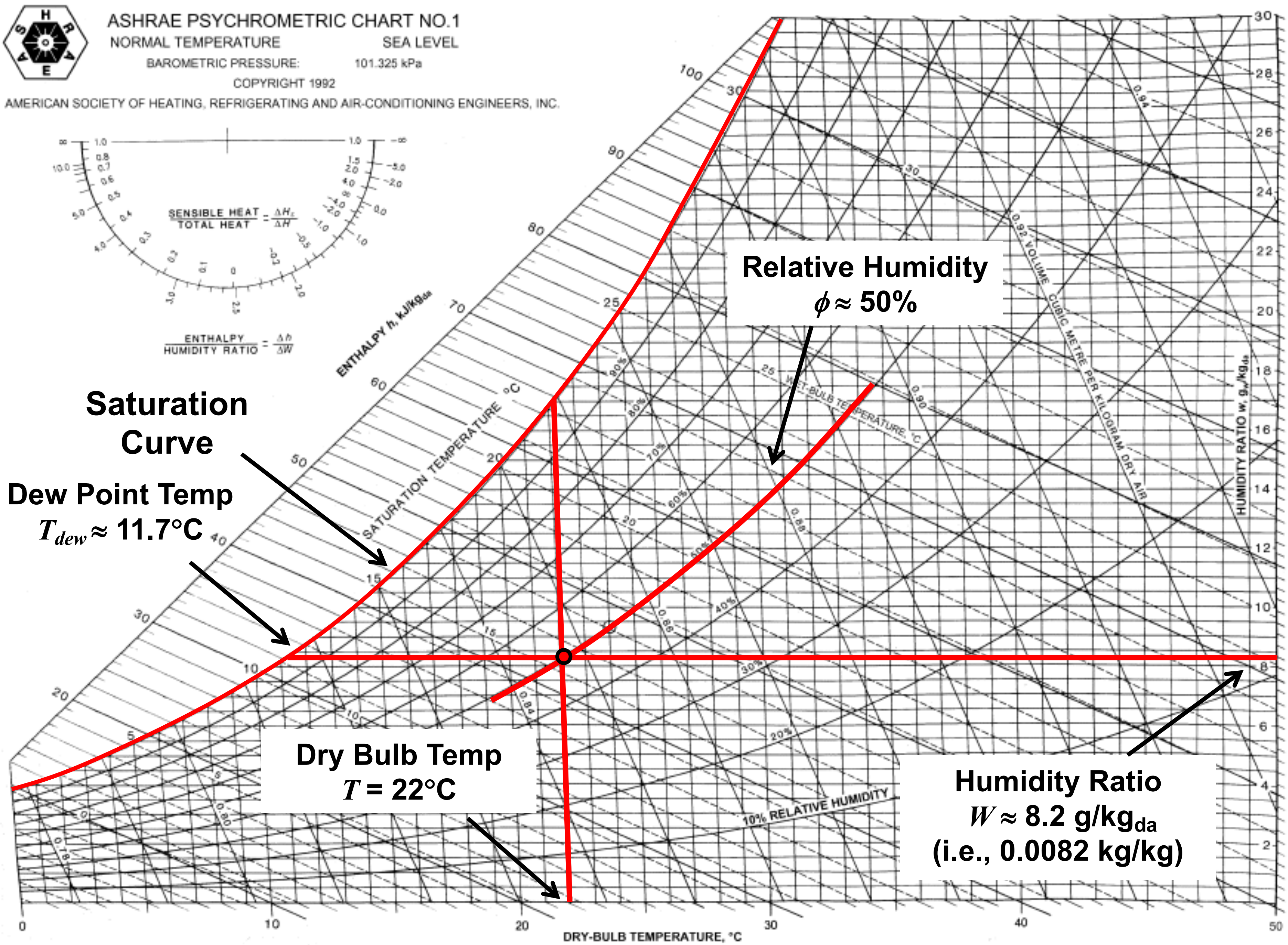
WET-BULB TEMPERATURE °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C
Saturation Curve
Relative Humidity
$\phi \approx$ 50%
Dry Bulb Temp
T = 22°C
Humidity Ratio
$W \approx$ 8.2 g/kg$_{da}$
(i.e., 0.0082 kg/kg)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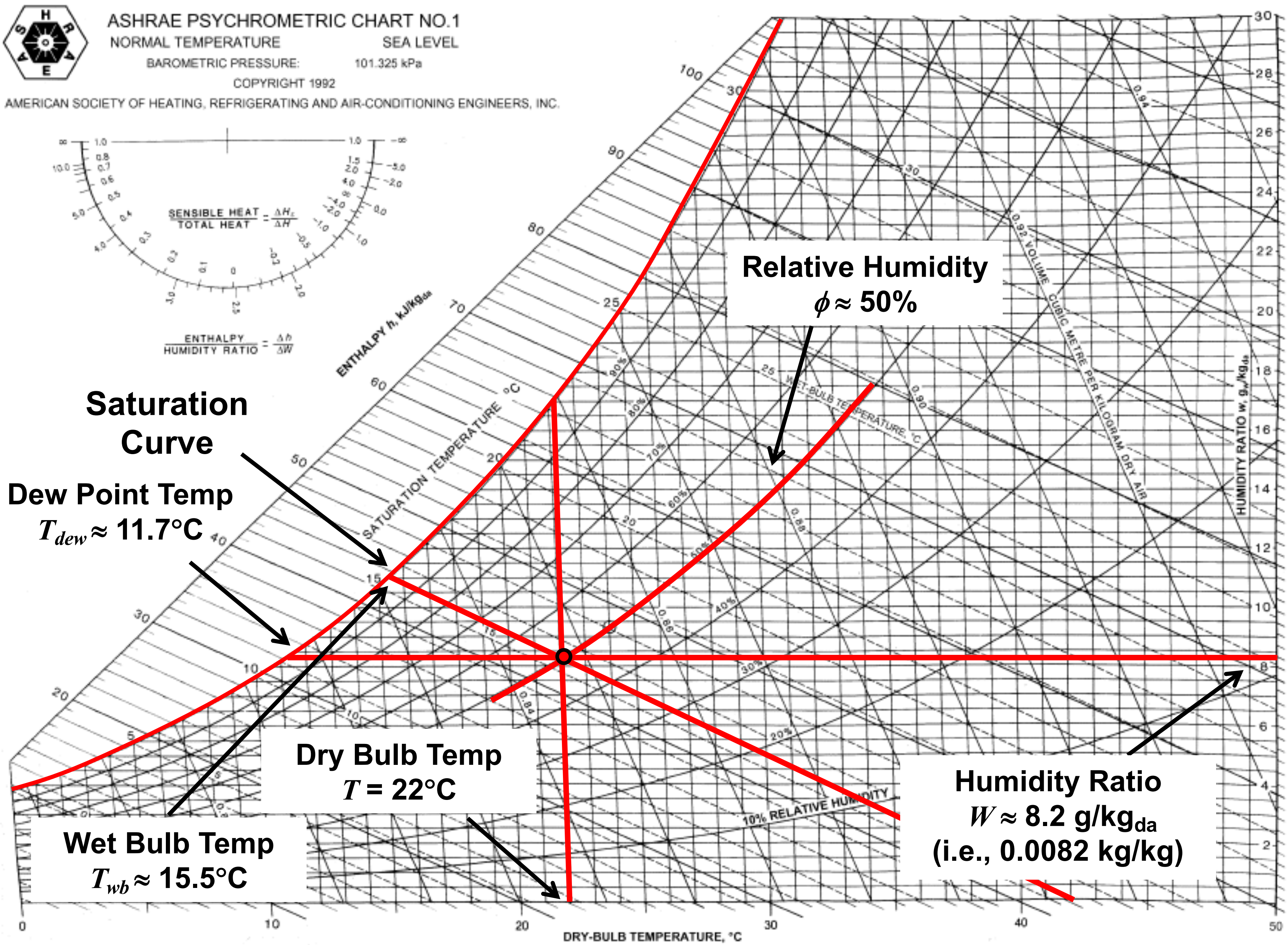
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Saturation Curve
Dew Point Temp
$T_{dew} \approx$ 11.7°C
Relative Humidity
$\phi \approx$ 50%
Dry Bulb Temp
T = 22°C
Humidity Ratio
$W \approx$ 8.2 g/kg_{da}
(i.e., 0.0082 kg/kg)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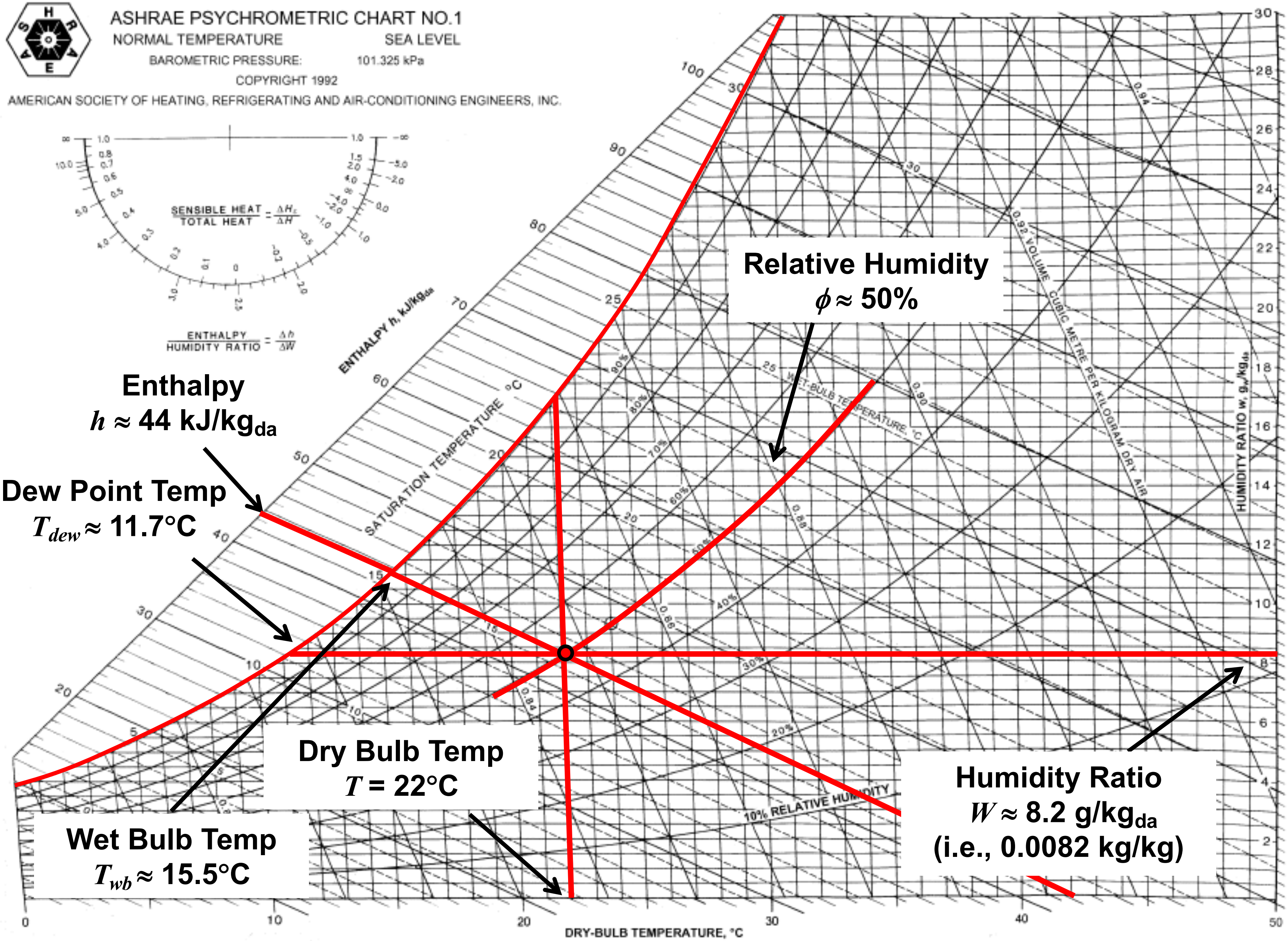
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
Saturation Curve
Dew Point Temp
$T_{dew} \approx$ 11.7°C
Relative Humidity
$\phi \approx$ 50%
Dry Bulb Temp
T = 22°C
Wet Bulb Temp
$T_{wb} \approx$ 15.5°C
Humidity Ratio
$W \approx$ 8.2 g/kg$_{da}$
(i.e., 0.0082 kg/kg)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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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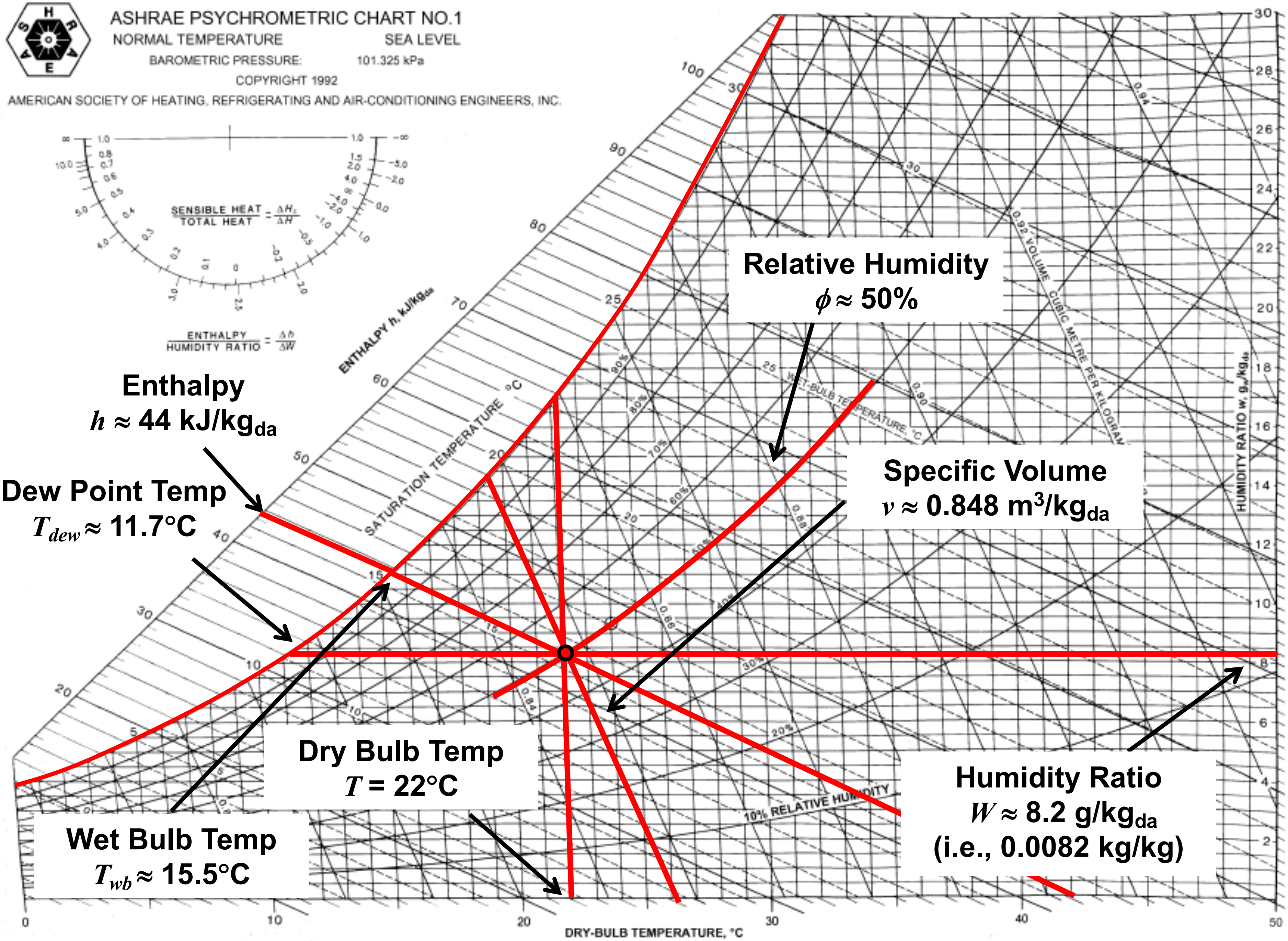
SENSIBLE HEAT / TOTAL HEAT = $\Delta H_s / \Delta H$
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C
Relative Humidity
$\phi \approx 50\%$
Enthalpy
$h \approx 44$ kJ/kg$_{da}$
Dew Point Temp
$T_{dew} \approx 11.7$°C
Dry Bulb Temp
$T = 22$°C
Wet Bulb Temp
$T_{wb} \approx 15.5$°C
Humidity Ratio
$W \approx 8.2$ g/kg$_{da}$
(i.e., 0.0082 kg/kg)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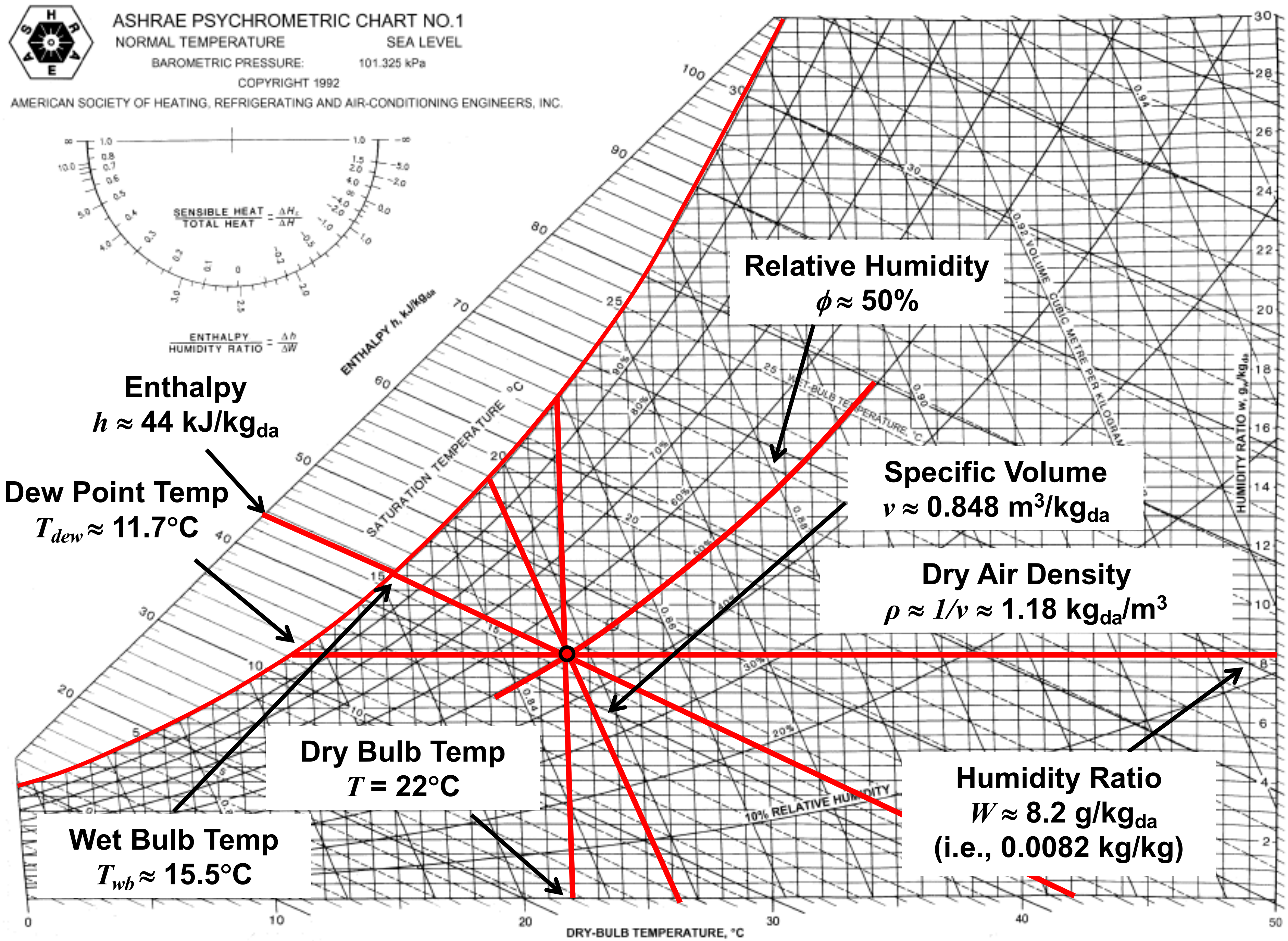
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, g/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Relative Humidity
ϕ ≈ 50%
Enthalpy
h ≈ 44 kJ/kg da
Dew Point Temp
T dew ≈ 11.7°C
Specific Volume
v ≈ 0.848 m3/kg da
Dry Bulb Temp
T = 22°C
Wet Bulb Temp
T wb ≈ 15.5°C
Humidity Ratio
W ≈ 8.2 g/kg da
(i.e., 0.0082 kg/kg)



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ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE °C
VOLUME CUBIC METRE PER KILOGRAM
HUMIDITY RATIO w, gw/kgda
10% RELATIVE HUMIDITY
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
Dry Air Density
ρ ≈ 1/v ≈ 1.18 kgda/m3
Dry Bulb Temp
T = 22°C
Humidity Ratio
W ≈ 8.2 g/kgda
(i.e., 0.0082 kg/kg)
Wet Bulb Temp
Twb ≈ 15.5°C

Some psychrometric examples

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

Find the following:

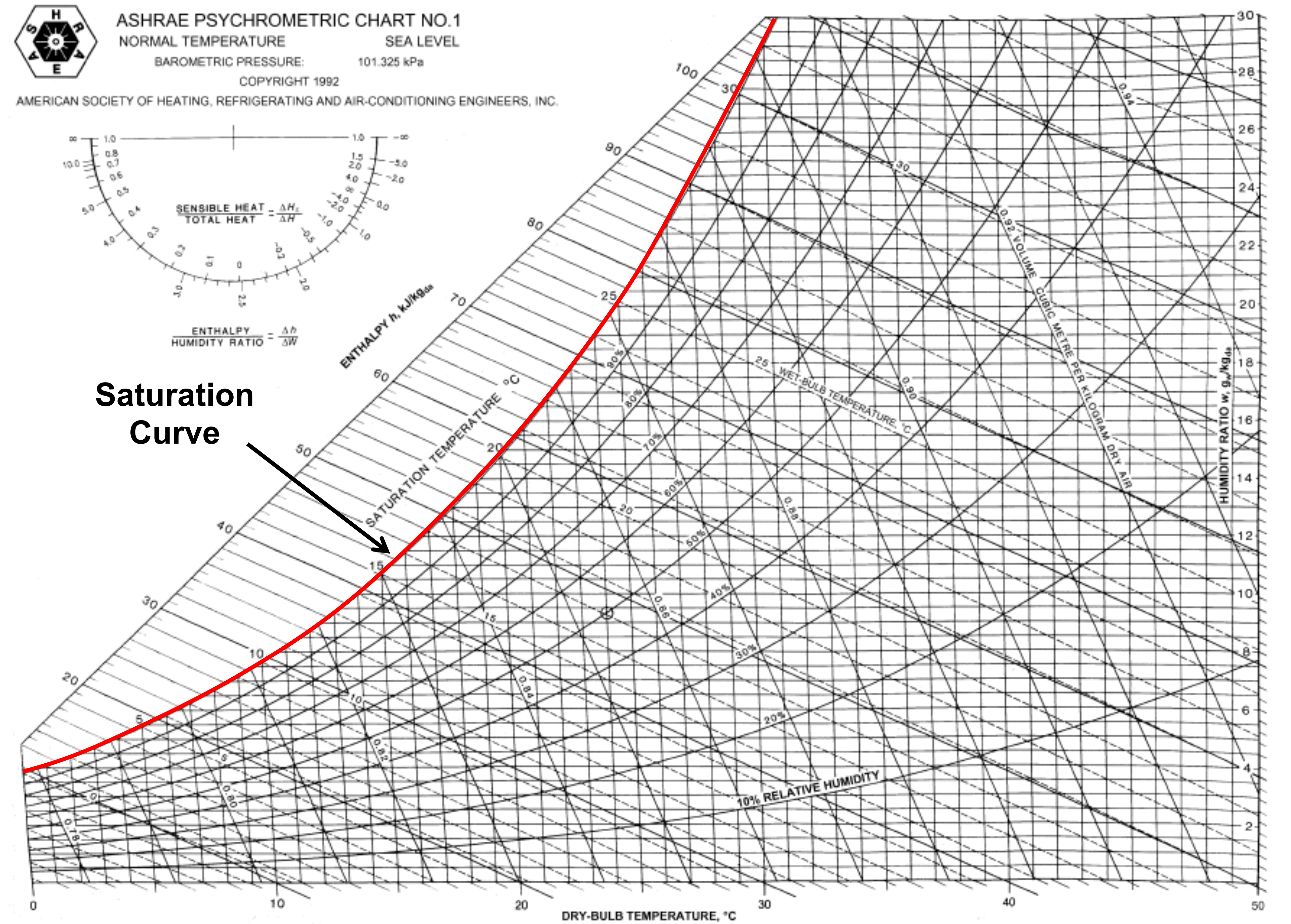
(a) the humidity ratio, W

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

(c) enthalpy, h

(d) specific volume, v

(e) relative humidity, ϕ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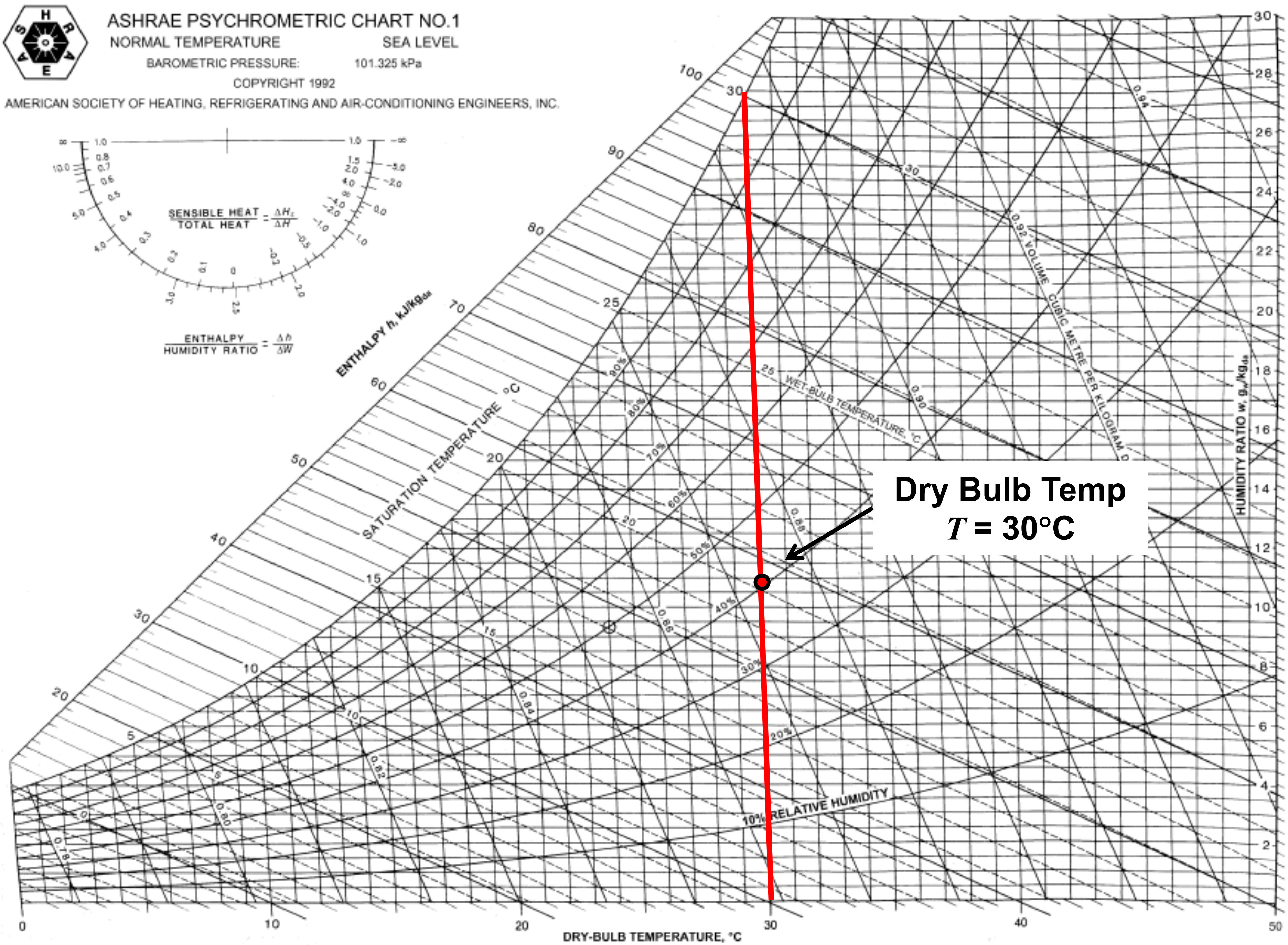
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
Saturation Curve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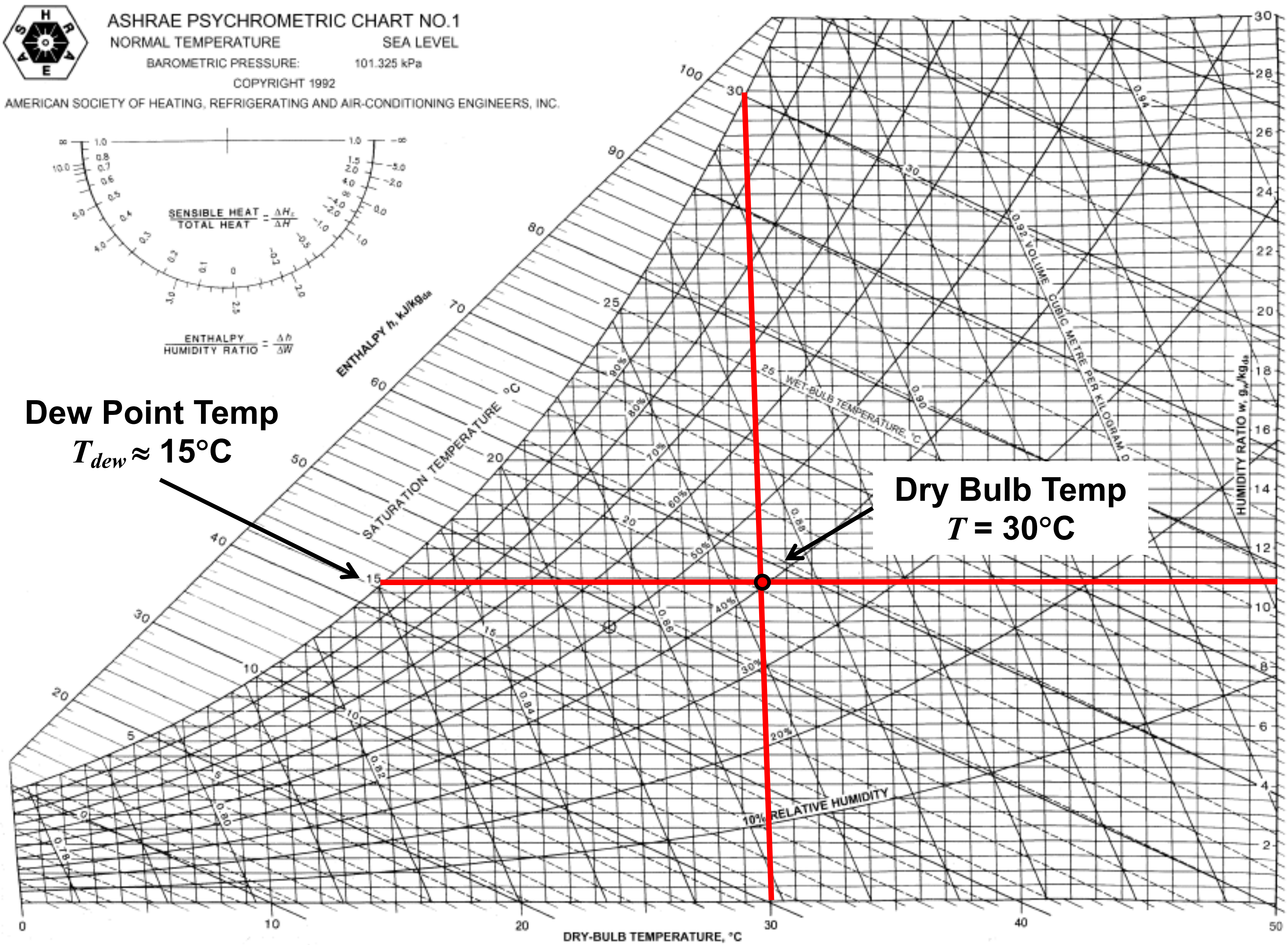
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO w, gw/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C
Dry Bulb Temp
T = 30°C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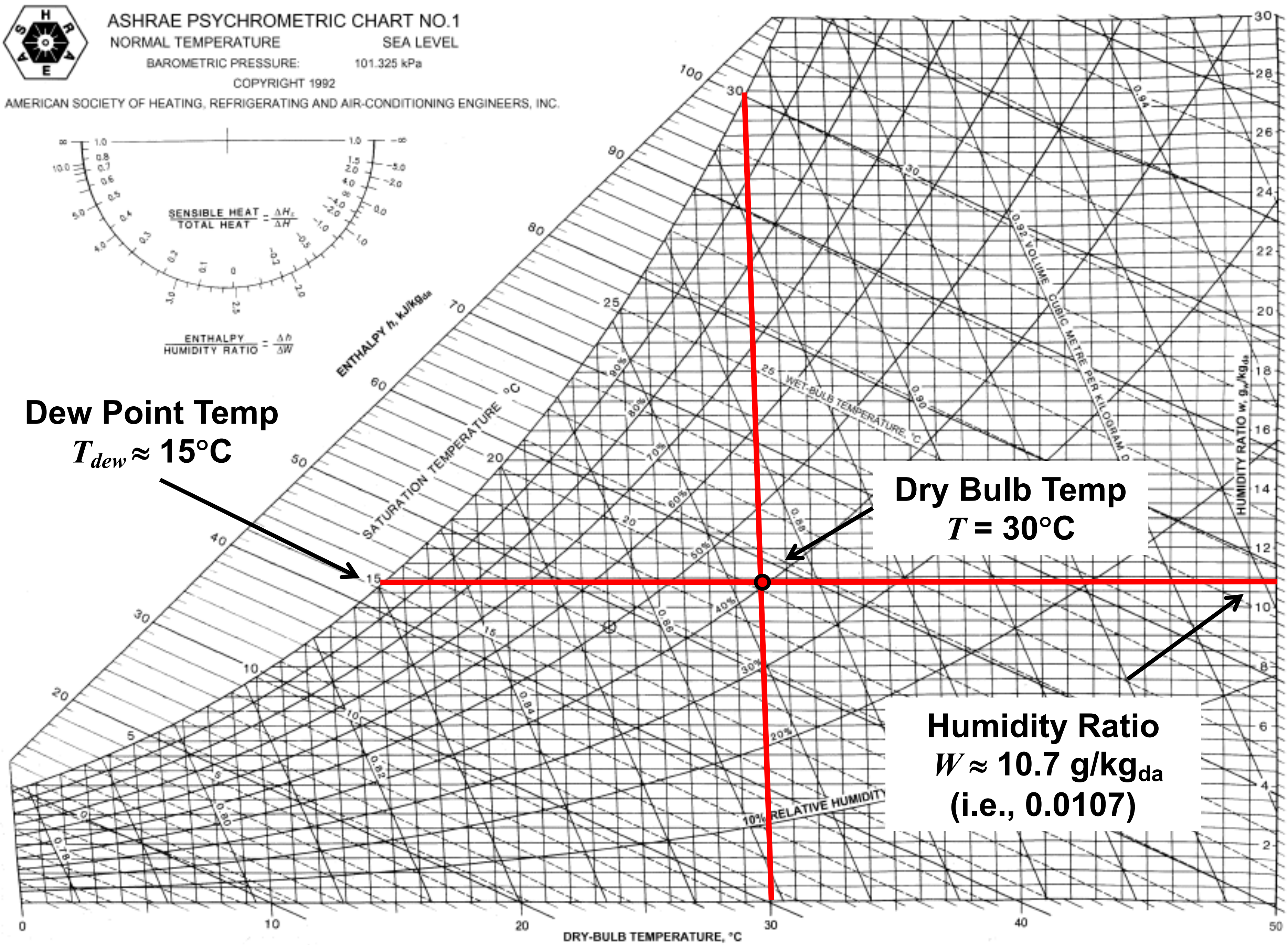
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔH
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DA
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C
Dew Point Temp
Tdew ≈ 15°C
Dry Bulb Temp
T = 30°C



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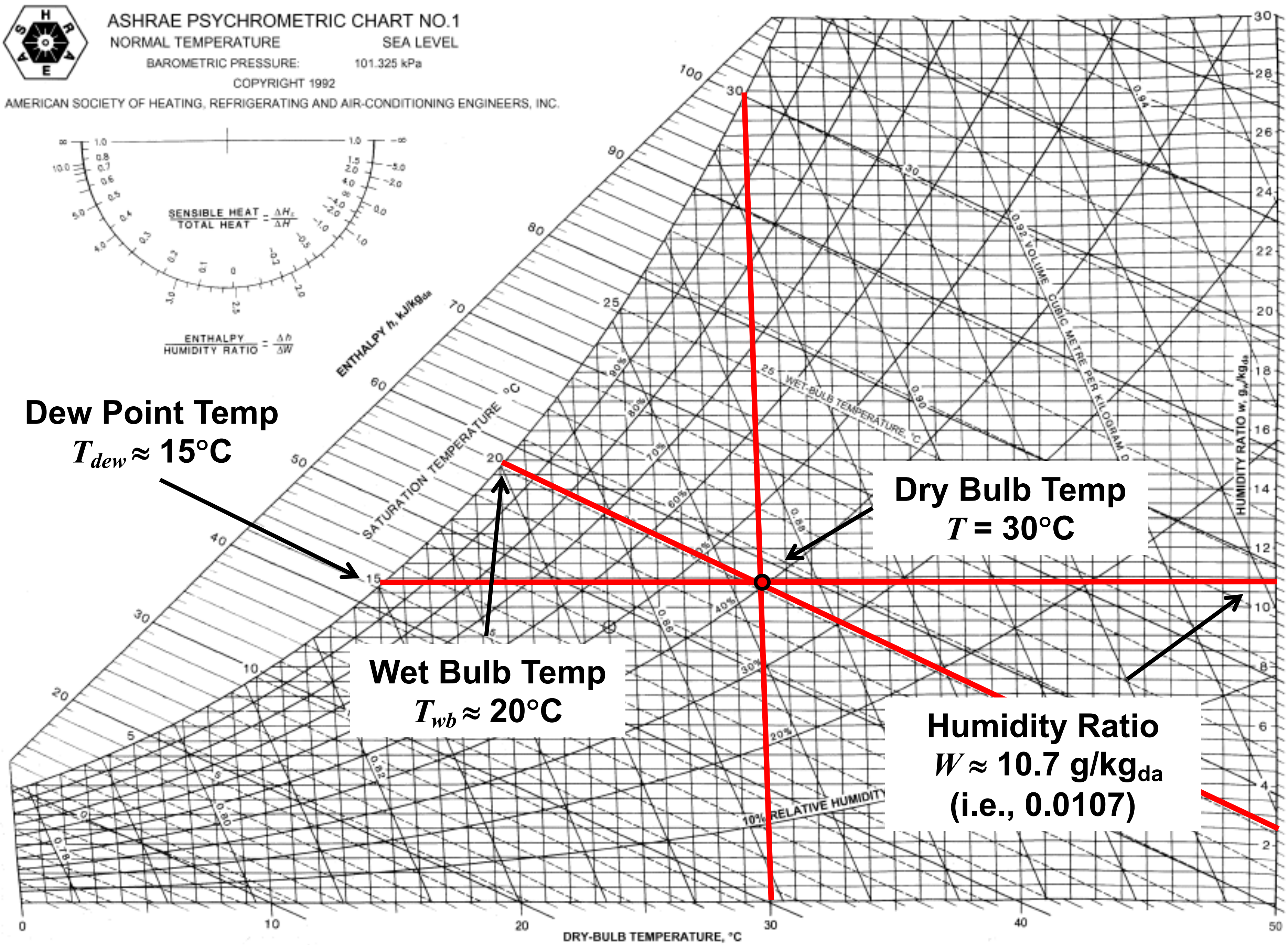
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g/kg da
DRY-BULB TEMPERATURE, °C
Dew Point Temp
$T_{dew} \approx$ 15°C
Dry Bulb Temp
T = 30°C
Humidity Ratio
$W \approx$ 10.7 g/kg$_{da}$
(i.e., 0.0107)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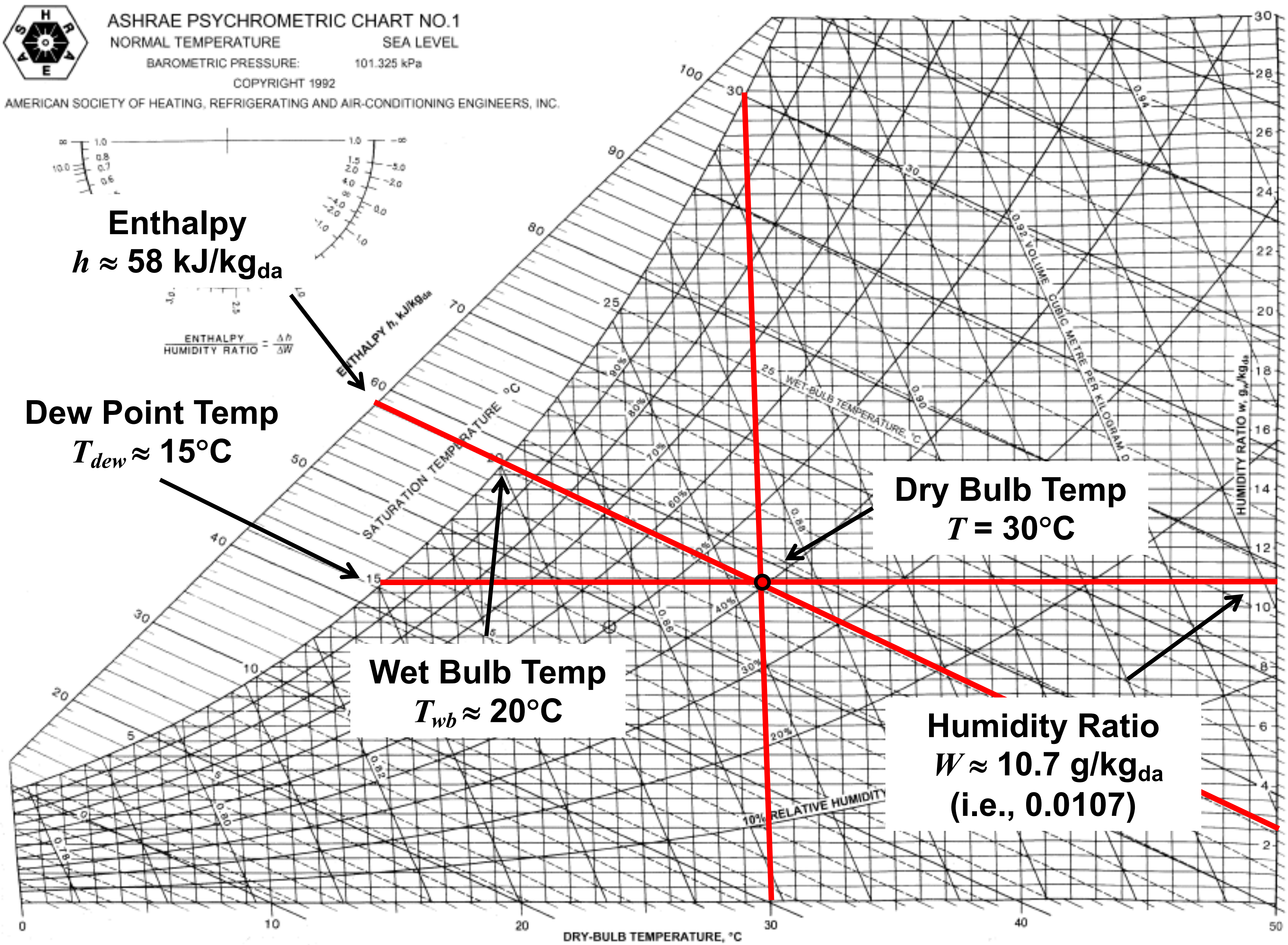
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM DA
10% RELATIVE HUMIDITY
HUMIDITY RATIO W, gw/kgda
DRY-BULB TEMPERATURE, °C
Dew Point Temp
$T_{dew} \approx$ 15°C
Wet Bulb Temp
$T_{wb} \approx$ 20°C
Dry Bulb Temp
T = 30°C
Humidity Ratio
$W \approx$ 10.7 g/kg_{da}
(i.e.,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



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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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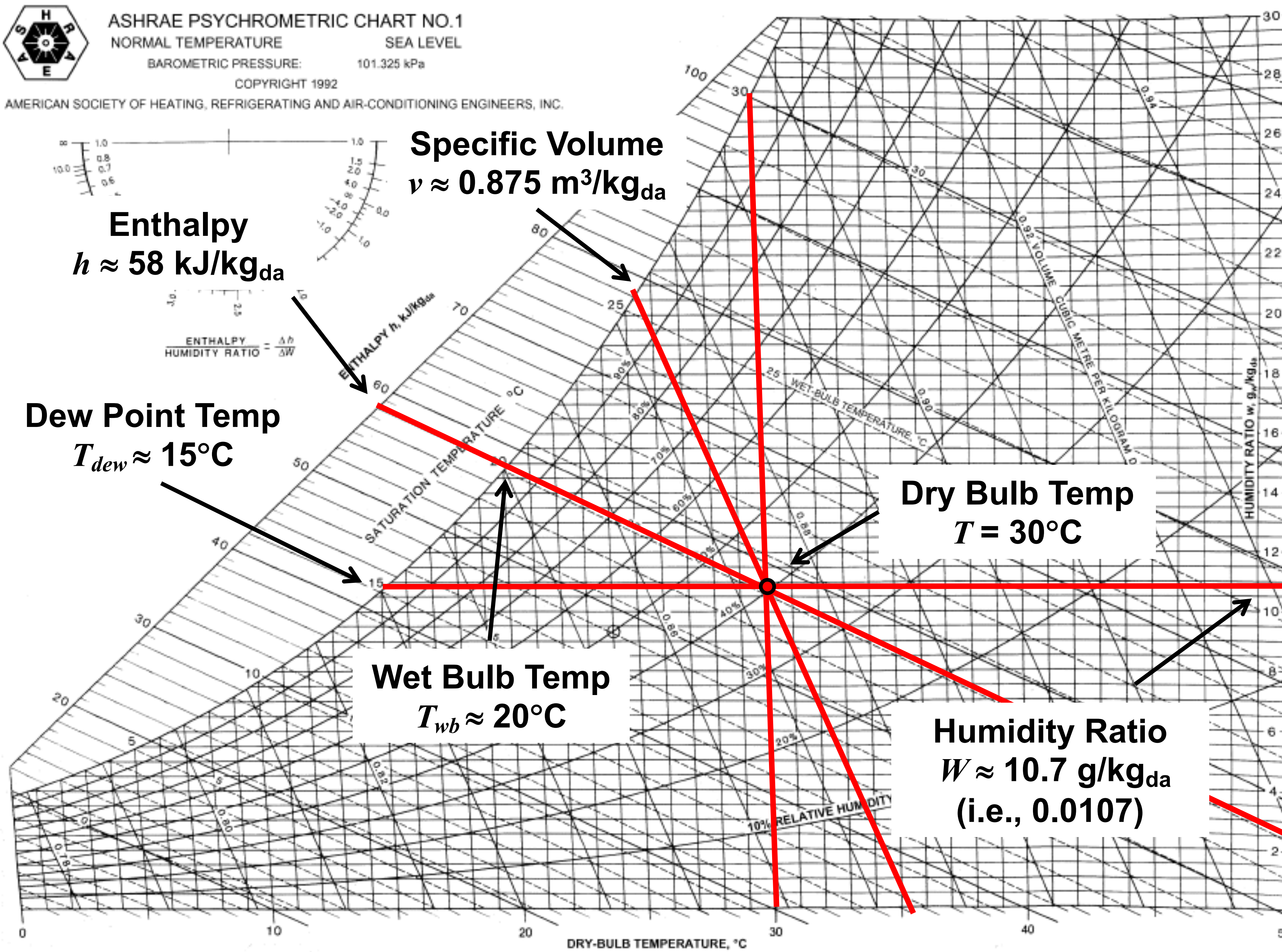
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Enthalpy
h ≈ 58 kJ/kgda
Dew Point Temp
Tdew ≈ 15°C
Wet Bulb Temp
Twb ≈ 20°C
Dry Bulb Temp
T = 30°C
Humidity Ratio
W ≈ 10.7 g/kgda
(i.e., 0.0107)
ENTHALPY h, kJ/kgda
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, gw/kgda
DRY-BULB TEMPERATURE, °C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NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
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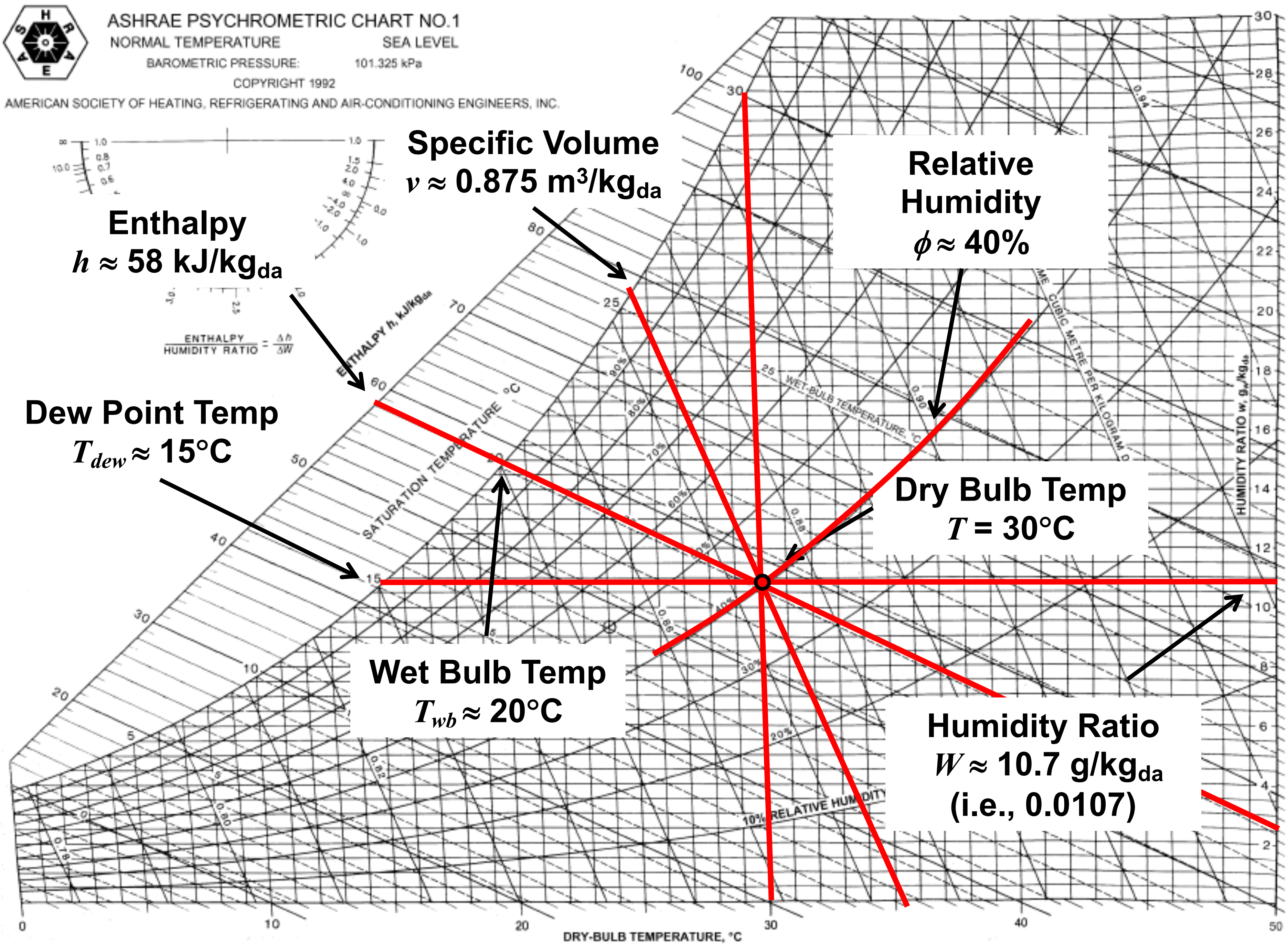
Specific Volume
ν ≈ 0.875 m³/kg_da
Enthalpy
h ≈ 58 kJ/kg_da
Dew Point Temp
T_dew ≈ 15°C
Dry Bulb Temp
T = 30°C
Wet Bulb Temp
T_wb ≈ 20°C
Humidity Ratio
W ≈ 10.7 g/kg_da
(i.e., 0.0107)
ENTHALPY h, kJ/kg_da
SATURATION TEMPERATURE °C
WET BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO w, g_w/kg_da
DRY-BULB TEMPERATURE, °C



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SEA LEVEL
BAROMETRIC PRESSURE:
101.325 kPa
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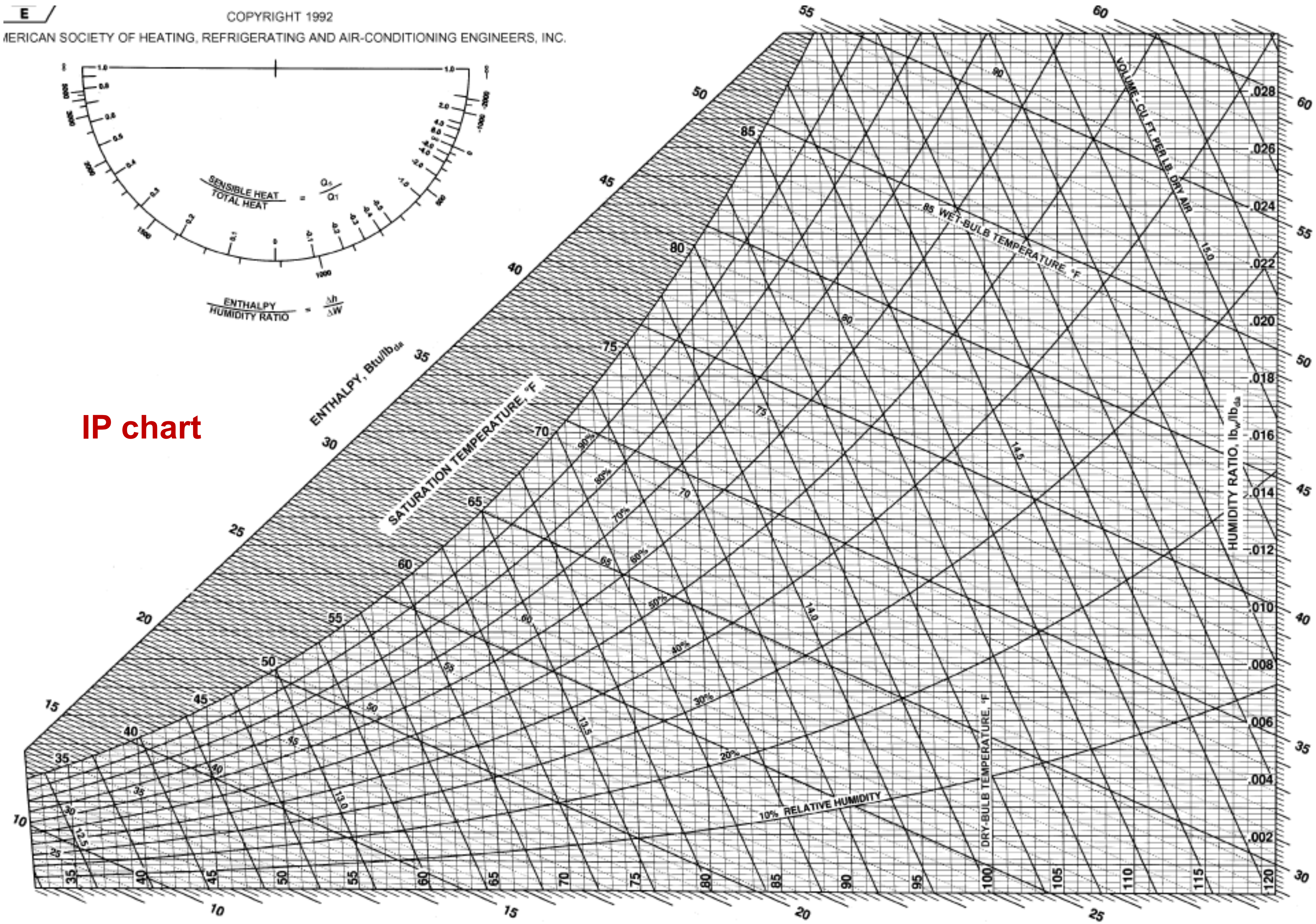
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Specific Volume
v ≈ 0.875 m³/kg_da
Relative Humidity
φ ≈ 40%
Enthalpy
h ≈ 58 kJ/kg_da
Dew Point Temp
T_dew ≈ 15°C
Dry Bulb Temp
T = 30°C
Wet Bulb Temp
T_wb ≈ 20°C
Humidity Ratio
W ≈ 10.7 g/kg_da
(i.e., 0.0107)
ENTHALPY h, kJ/kg_da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE °C
CUBIC METRE PER KILOGRAM
10% RELATIVE HUMIDITY
HUMIDITY RATIO W, g_w/kg_da
DRY-BULB TEMPERATURE, °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



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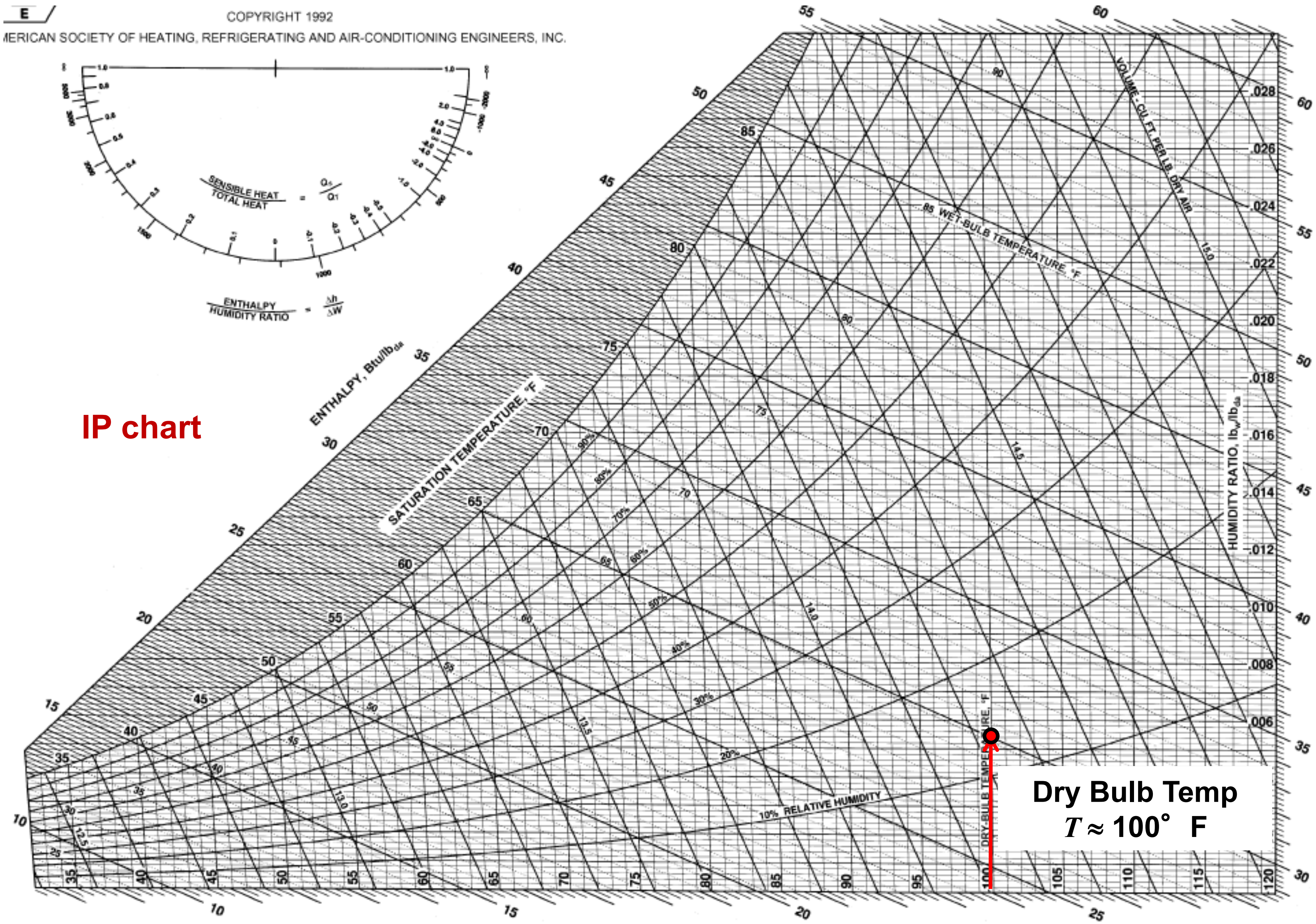
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU. FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY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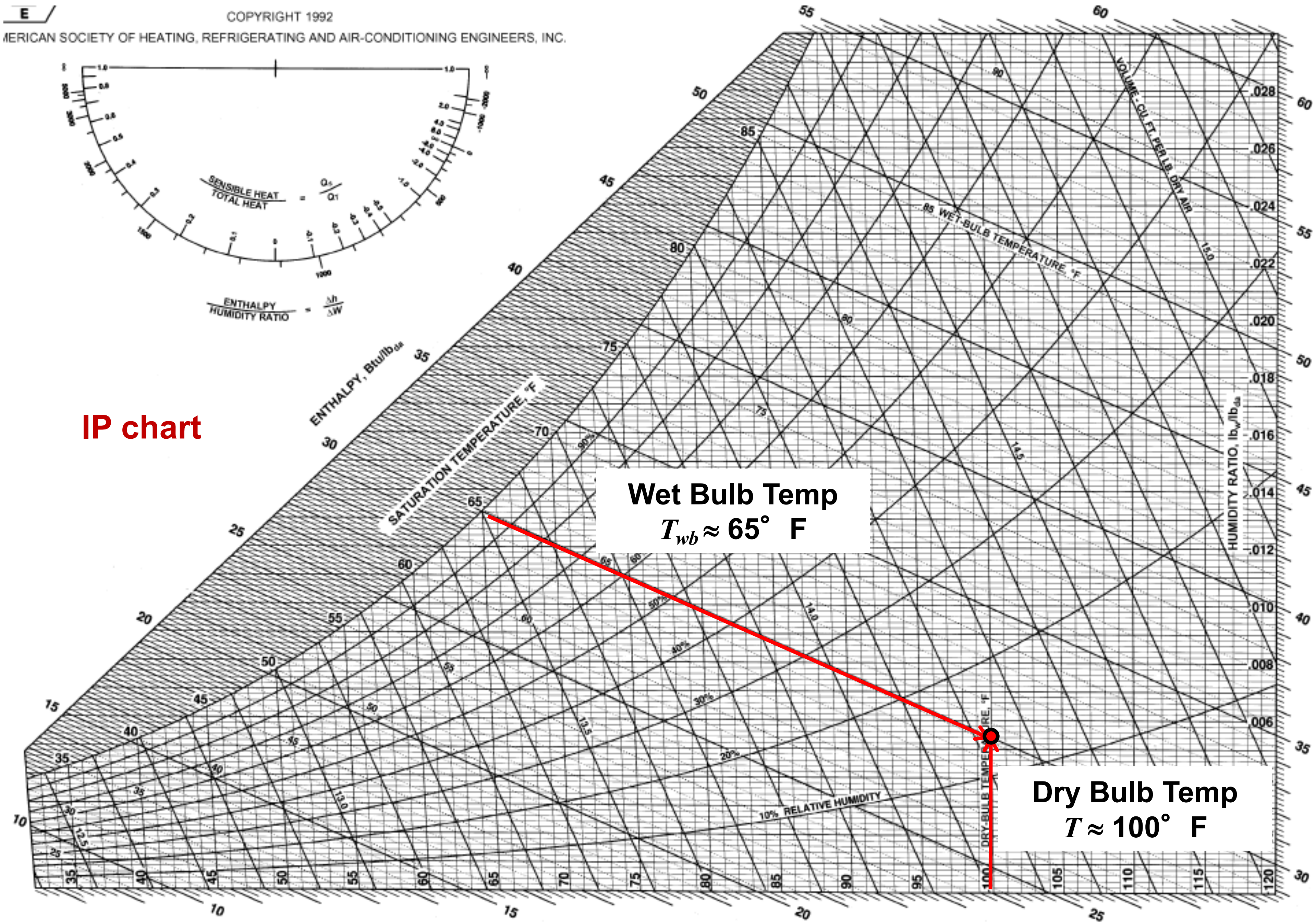
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
IP chart
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb_w/lb_da
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Dry Bulb Temp
T ≈ 100° F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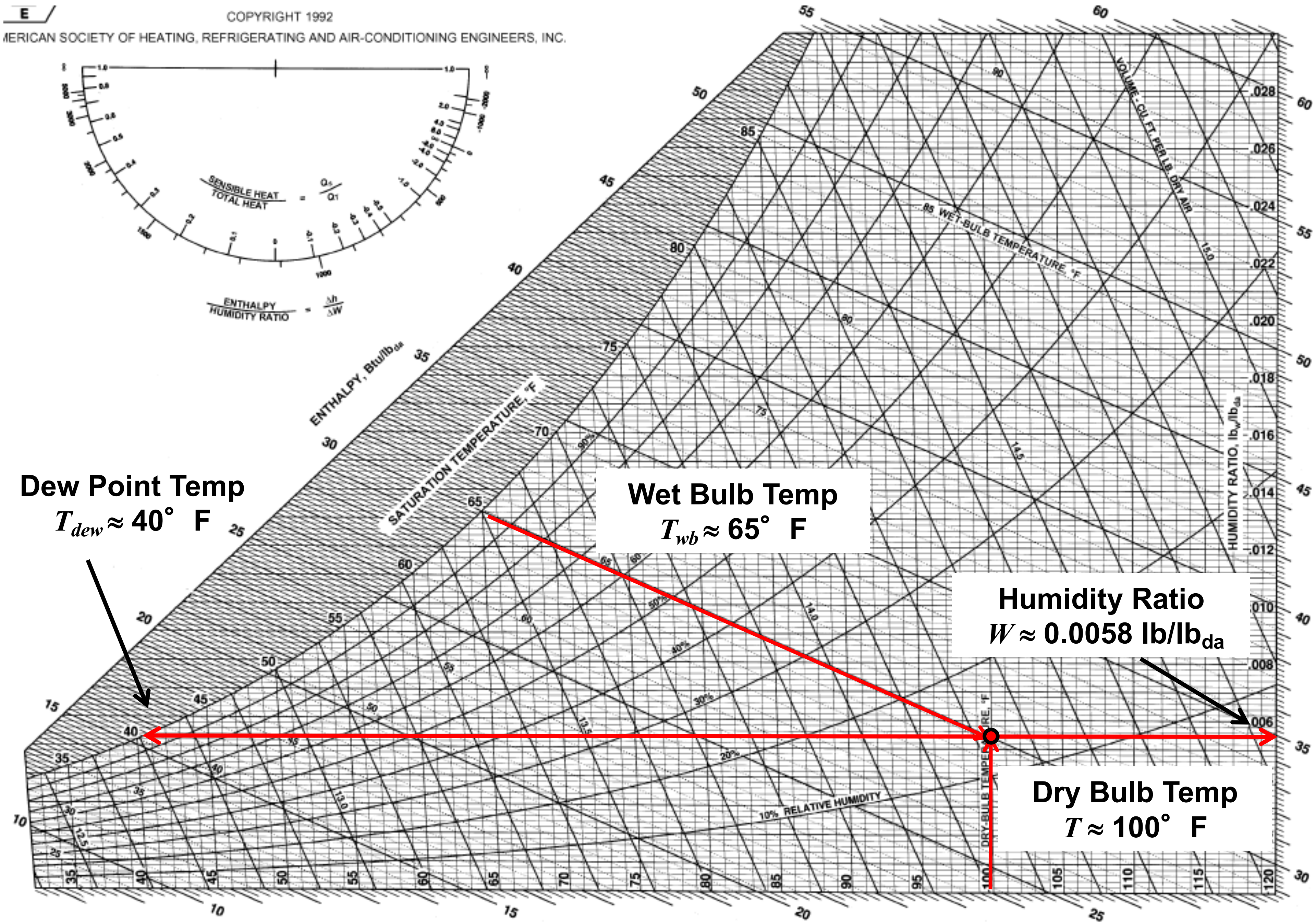
IP chart
ENTHALPY, Btu/lb$_{da}$
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lb$_w$/lb$_{da}$
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Wet Bulb Temp
$T_{wb} \approx 65^\circ$ F
Dry Bulb Temp
$T \approx 100^\circ$ F



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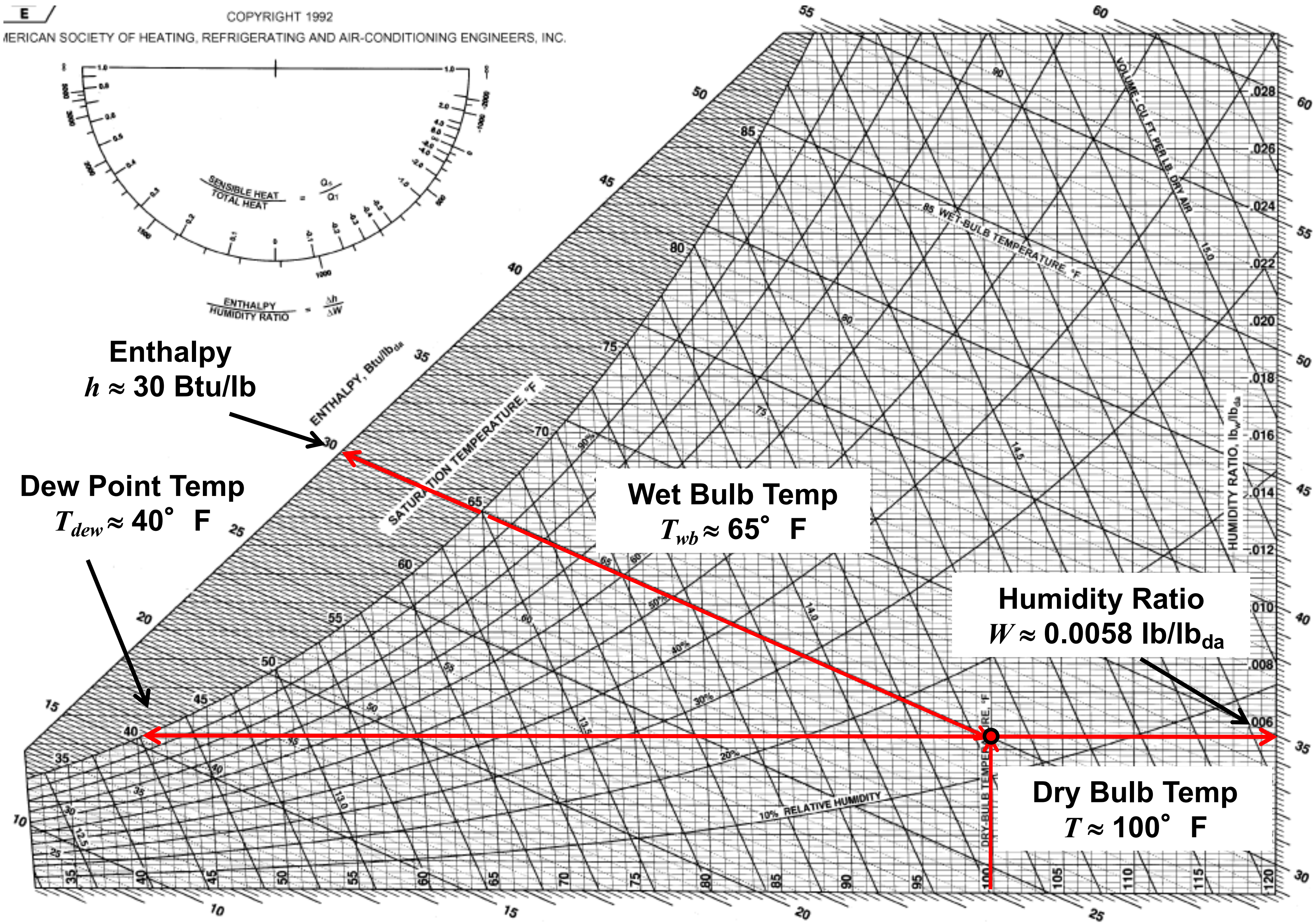
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME, CU FT PER LB DRY AIR
HUMIDITY RATIO, lb_w/lb_da
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Dew Point Temp
$T_{dew} \approx$ 40° F
Wet Bulb Temp
$T_{wb} \approx$ 65° F
Humidity Ratio
$W \approx$ 0.0058 lb/lb_da
Dry Bulb Temp
$T \approx$ 100° F



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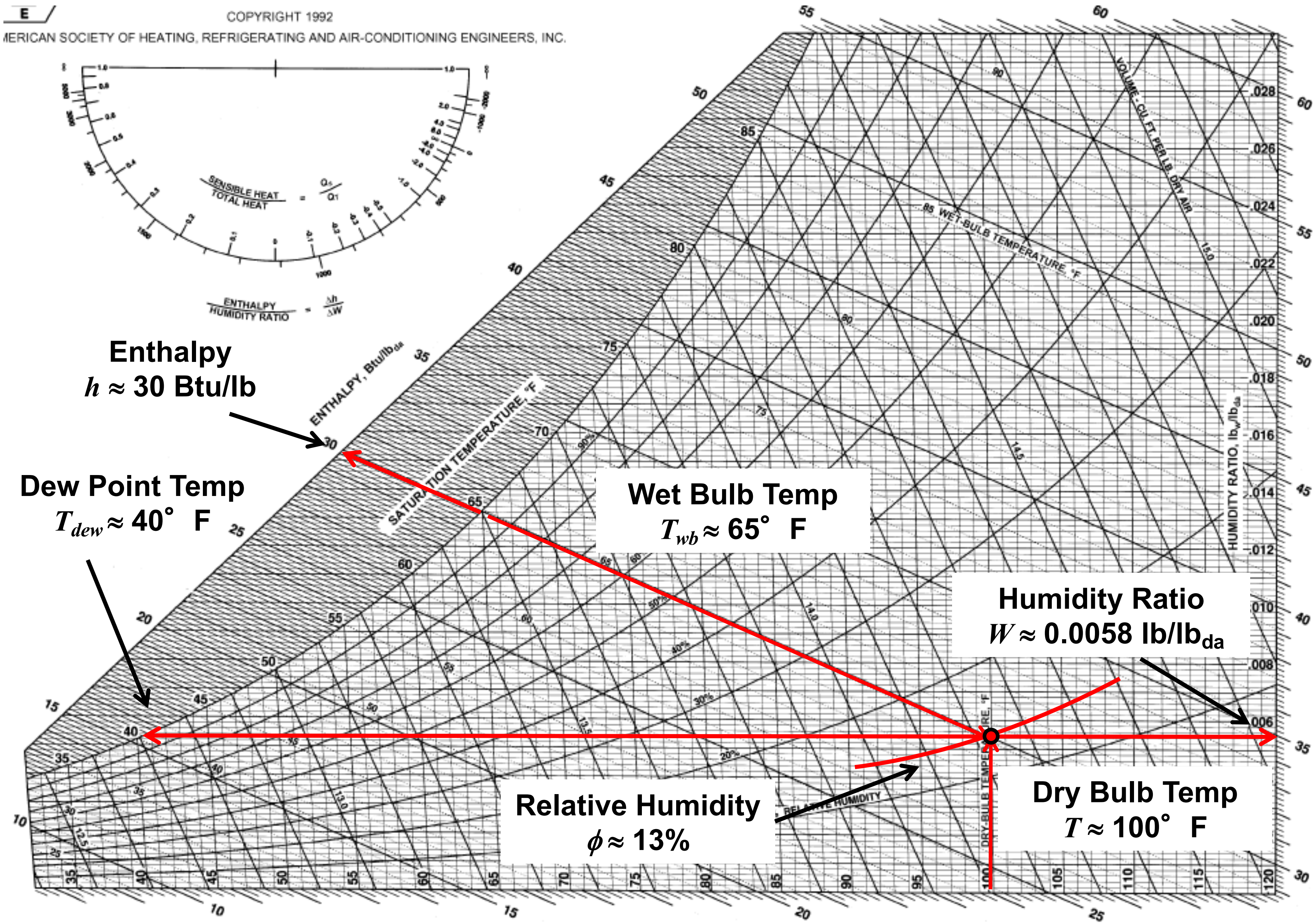
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
Enthalpy
h ≈ 30 Btu/lb
Dew Point Temp
T_dew ≈ 40° F
Wet Bulb Temp
T_wb ≈ 65° F
Humidity Ratio
W ≈ 0.0058 lb/lb_da
Dry Bulb Temp
T ≈ 100° F
ENTHALPY, Btu/lb_da
SATURATION TEMPERATURE, °F
85 WET-BULB TEMPERATURE, °F
VOLUME, CU FT PER LB DRY AIR
HUMIDITY RATIO, lb_w/lb_da
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F



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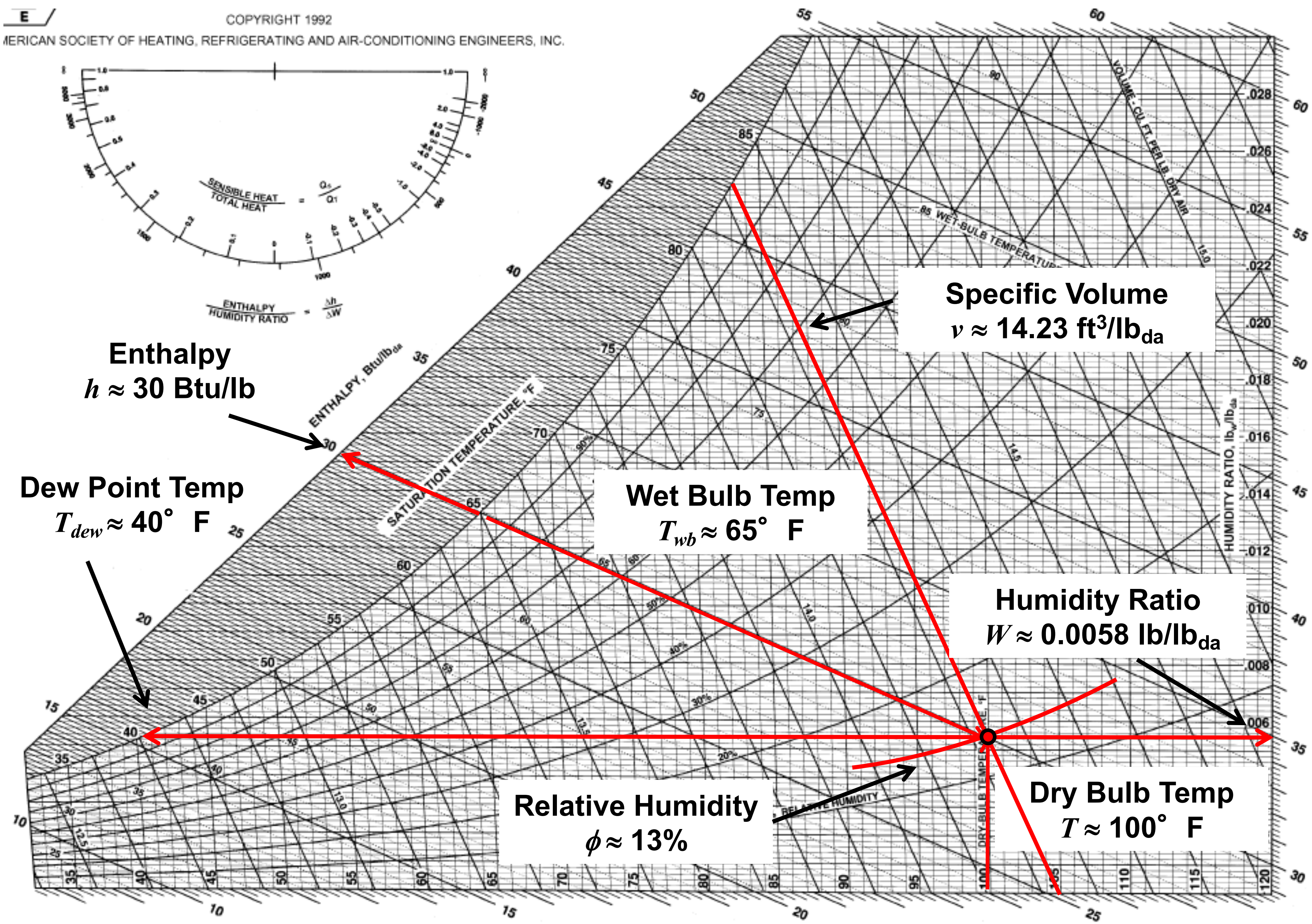
ENTHALPY, Btu/lbda
SATURATION TEMPERATURE, °F
WET-BULB TEMPERATURE, °F
VOLUME - CU.FT. PER LB. DRY AIR
HUMIDITY RATIO, lbw/lbda
RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Enthalpy
$h \approx 30$ Btu/lb
Dew Point Temp
$T_{dew} \approx 40^\circ$ F
Wet Bulb Temp
$T_{wb} \approx 65^\circ$ F
Humidity Ratio
$W \approx 0.0058$ lb/lb$_{da}$
Relative Humidity
$\phi \approx 13\%$
Dry Bulb Temp
$T \approx 100^\circ$ F



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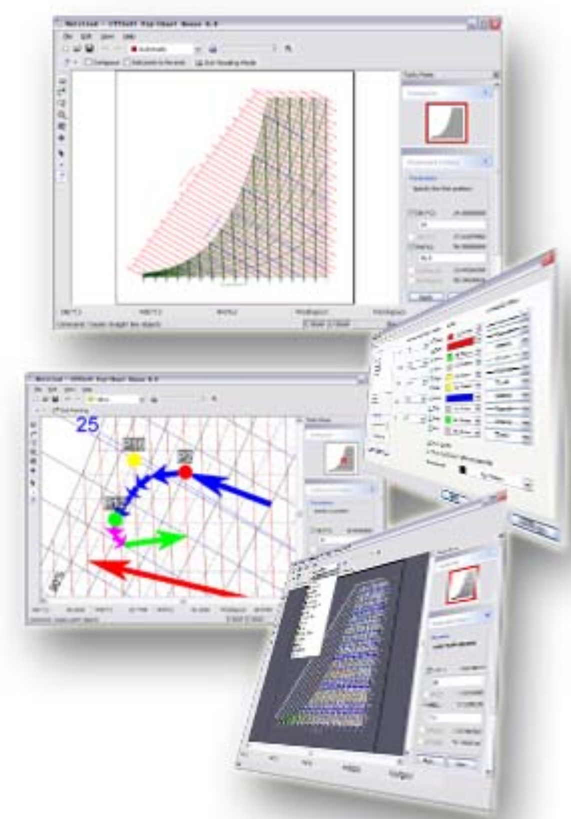
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY, Btu/lb da
SATURATION TEMPERATURE, °F
VOLUME, CU.FT. PER LB. DRY AIR
85 WET-BULB TEMPERATURE
HUMIDITY RATIO, lbw/lbda
RELATIVE HUMIDITY
DRY BULB TEMPERATURE, °F
Specific Volume
$v \approx 14.23$ ft^3/lb$_{da}$
Enthalpy
$h \approx 30$ Btu/lb
Dew Point Temp
$T_{dew} \approx 40°$ F
Wet Bulb Temp
$T_{wb} \approx 65°$ F
Humidity Ratio
$W \approx 0.0058$ lb/lb$_{da}$
Relative Humidity
$\phi \approx 13\%$
Dry Bulb Temp
$T \approx 100°$ F

Applying psychrometrics



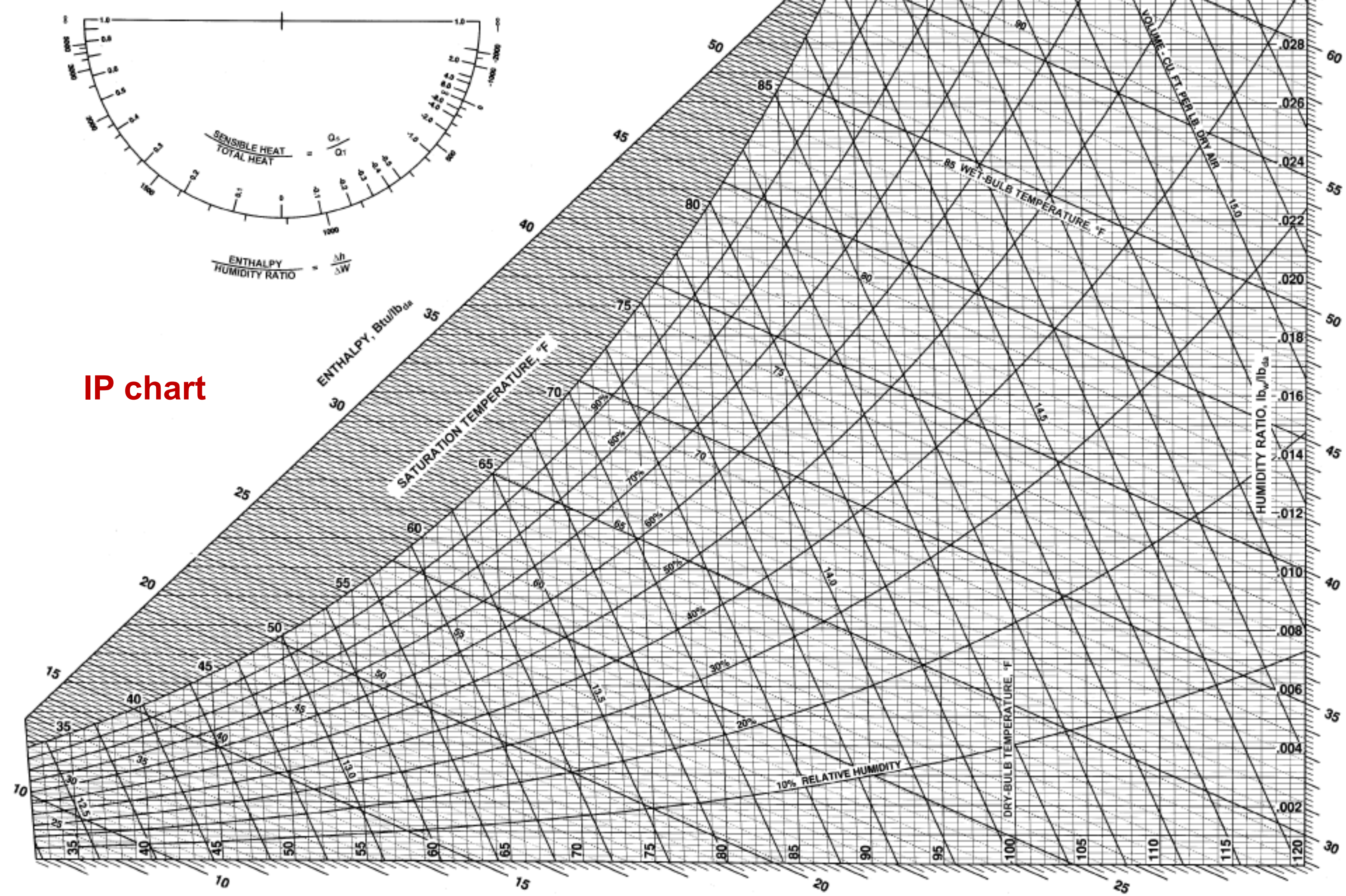
- We can also use psychrometric charts or software
  - Psych and Psychpro
    - Very popular psych chart and analysis software
    - I think at least one of these is in the AM 218 lab
- There are a bunch of online calculators as well
  - http://www.psychrometric-calculator.com
  - http://www.sugartech.co.za/psychro/
  - http://www.wolframalpha.com/examples/Psychrometrics.html
- 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

Psychrometrics also involves learning how to use and combine those quantities to determine things like sensible and latent heating and cooling loads (i.e., ***processes***) (covered in a future lecture)

Using these parameters

- Question:
  - What is the mass of water vapor in this classroom right now?

E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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
DRY-BULB TEMPERATURE, °F
10% RELATIVE HUMIDITY
IP chart

PSYCHROMETRIC EQUATIONS

Psychrometric equations

- When we need more precise answers, or when we need to automate engineering calculations, we must:
  - Use the underlying **equations** that govern moist air properties and processes and make up the psychrometric chart

- This begins by treating air as an **ideal gas**

Treating air as an ideal gas

- At typical temperatures and pressures within buildings, air and its constituents act approximately as ideal gases
- Each gas i in the mixture, as well as the entire mixture, will follow the ideal gas law:

Ideal Gas Law (Boyle's law + Charles's law)

$$pV = nRT$$

p = pressure (lb/ft^2)
V = volume (ft^3)
n = number of moles (#)
R = gas constant ($lb_f \cdot ft/(lb_{mol}\ R)$)*
T = absolute temperature (R)

*Units on R vary with units of pressure

Air as an ideal gas

- We can treat air as a composition of ideal gases
  - A bunch of ideal gases acting as an ideal gas
- For individual gases (e.g., N_2, O_2, H_2O, CO_2, constituent i):

$$P_i V = n_i R T$$

P_i = partial pressure exerted by gas i
n_i = # of moles of gas i
R, V, T = gas constant, volume, temperature

$$P_i = \frac{n_i}{V} R T$$

Rearrange so that n_i/V is the molar concentration

$$P_i = y_i P_{tot}$$

P_{tot} = total pressure of air (atm, Pa, psia, etc.)
y_i = mole fraction of gas i in air (moles i / moles air)

Air as an ideal gas

- Air as a composite mixture

$$P_i = y_i P_{tot}$$

$$P_{tot} = \sum P_i = \sum \frac{n_i}{V} RT = \frac{RT}{V} \sum n_i = \frac{RT}{V} n_{tot}$$

$$PV = nRT$$

Universal gas constant

- The universal gas constant relates energy and temperature
  - It takes many forms depending on units

Universal gas constant

$$PV = nRT$$

Value of R	**Units ($V\,P\,T^{-1}\,n^{-1}$)**
8.314	$J/(K \cdot mol)$
8.314	$m^3 \cdot Pa/(K \cdot mol)$
0.08206	$L \cdot atm/(K \cdot mol)$
8.205×10^{-5}	$m^3 \cdot atm/(K \cdot mol)$
1545.349	$ft \cdot lb_f/(R \cdot lb_{mol})$
1.986	$Btu/(lb_{mol} \cdot R)$

Dalton's law of partial pressures for psychrometrics

- In an ideal gas, the total pressure can be considered to be the sum of the partial pressures of the constituent gases

$$p = p_{N_2} + p_{O_2} + p_{H_2O} + p_{CO_2} + p_{Ar} + \dots$$

- We can consider moist air as dry air combined with water vapor and break the pressure into only two partial pressures:
  - Dry air (da)
  - Water vapor (w)

$$p = p_{da} + p_w$$

Dalton's law of partial pressures for psychrometrics

- We can analyze the dry air, the water vapor, and the mixture of each gas using the ideal gas law and assuming they are all at the same temperature

$$p_{da}v_{da} = R_{da}T \quad \& \quad p_w v_w = R_w T \quad \& \quad pv = RT$$

- For each individual gas, a mole fraction (Y_i) can be defined as the ratio of the partial pressure of gas i to the total pressure

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

Specific gas constants

- To work with air and water vapor we can also work with specific gas constants (which are functions of molecular weight)
- Dry air (no water vapor): MW_{da} = 28.966 g/mol

$$R_{da} = \frac{R}{MW_{da}} = \frac{1545.349 \frac{\text{ft}\cdot\text{lb}_\text{f}}{{}^\circ\text{R}\cdot\text{lb}_\text{mol}}}{28.965 \frac{\text{lb}_\text{m,da}}{\text{lb}_\text{mol}}} = 53.35 \frac{\text{ft}\cdot\text{lb}_\text{f}}{{}^\circ\text{R}\cdot\text{lb}_\text{da}}$$

- Water vapor alone: MW_w = 18.015 g/mol

$$R_{w} = \frac{R}{MW_{w}} = \frac{1545.349 \frac{\text{ft}\cdot\text{lb}_\text{f}}{{}^\circ\text{R}\cdot\text{lb}_\text{mol}}}{18.015 \frac{\text{lb}_\text{m,w}}{\text{lb}_\text{mol}}} = 85.78 \frac{\text{ft}\cdot\text{lb}_\text{f}}{{}^\circ\text{R}\cdot\text{lb}_\text{w}}$$

$$pv = \frac{p}{\rho} = R_i T$$

Specific gas constant:

$$R_i = \frac{R}{MW_i}$$

Note IP units:
1 g/mol = 1 lb_m/lb_{mol}

Air pressure variations

- The barometric (atmospheric) pressure and temperature of air vary with both altitude and local weather conditions
  - But there are standard values for pressure as a function of altitude that are normally used
- At sea level, the standard temperature is 59°F and the standard pressure is 14.696 psia (i.e. 101.325 kPa or 1 atm)
  - Temperature is assumed to decrease linearly with altitude
    - Pressure is more complicated

$$p = 14.696(1 - 6.8754 \times 10^{-6} Z)^{5.2559}$$

The equation for temperature as a function of altitude is

$$t = 59 - 0.00356620Z$$

where

Z = altitude, ft
p = barometric pressure, psia
t = temperature, °F

$$pv = \frac{p}{\rho} = RT$$

Air pressure variations

Table 1 Standard Atmospheric Data for Altitudes to 30,000 ft

Altitude, ft	Temperature, °F	Pressure, psia	
–1000	62.6	15.236	
–500	60.8	14.966	*Chicago, IL*
0	59.0	14.696	
500	57.2	14.430	
1,000	55.4	14.175	
2,000	51.9	13.664	*Denver, CO*
3,000	48.3	13.173	*Big Sky, MT*
4,000	44.7	12.682	
5,000	41.2	12.230	
6,000	37.6	11.778	*Breckenridge, CO*
7,000	34.0	11.341	
8,000	30.5	10.914	
9,000	26.9	10.506	
10,000	23.4	10.108	
15,000	5.5	8.296	
20,000	–12.3	6.758	
30,000	–47.8	4.371	

Source: Adapted from NASA (1976).

Specifying the state of moist air

In order to specify the state of moist air, we need total atmospheric pressure, p, the air temperature, T, and at least one other property

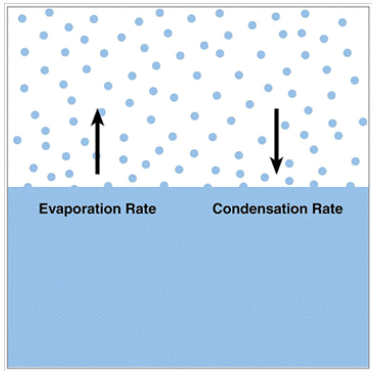
- W, ϕ, h, p_w, or T_{dew}

- We can use the psychrometric chart
- We can also use the **underlying equations** for greater accuracy and automation

Remember: Vapor pressure and Saturation

- Air can hold moisture (i.e., **water vapor**)
- **Vapor pressure** is the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases

p_w *Units of pressure, psia (Pa or kPa) (aka "partial pressure")

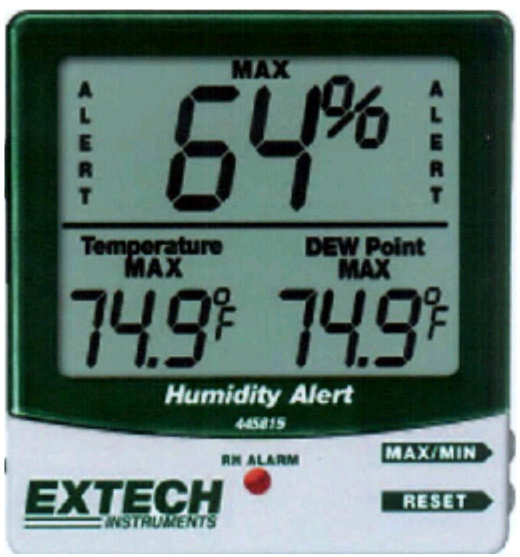


- The amount of moisture air can hold in vapor form before condensation occurs is dependent on temperature
  - We call the limit ***saturation***

p_{ws} *Units of pressure, psia (Pa or kPa) (aka "saturation vapor pressure")

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})
  - We can also describe RH by partial pressures (ideal gas)
- Relative humidity is a common measure that relates well to how we perceive moisture in air



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

p_{ws} for 32°F < T < 392°F (IP units)

For p_{ws}, the saturation pressure over **liquid water**:

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

where

C_8 = −1.044 039 7 E+04
C_9 = −1.129 465 0 E+01
C_{10} = −2.702 235 5 E−02
C_{11} = 1.289 036 0 E−05
C_{12} = −2.478 068 1 E−09
C_{13} = 6.545 967 3 E+00

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

Units:

p_{ws} = saturation pressure, psia
T = absolute temperature, °R = °F + 459.67

p_{ws} for -148°F < T < 32°F (IP units)

For p_{ws}, the saturation pressure over **ice**:

$$\ln p_{ws} = \frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \ln T$$

where

C_1 = −1.021 416 5 E+04
C_2 = −4.893 242 8 E+00
C_3 = −5.376 579 4 E−03
C_4 = 1.920 237 7 E−07
C_5 = 3.557 583 2 E−10
C_6 = −9.034 468 8 E−14
C_7 = 4.163 501 9 E+00

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

Units:

p_{ws} = saturation pressure, psia
T = absolute temperature, °R = °F + 459.67

Humidity ratio, *W* (IP units)

- 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* < 0.03 for most real building conditions)
  - Note 2: *W* is also expressed in grains/lb where 1 lb = 7000 grains

$$W = \frac{m_w}{m_{da}} = \frac{MW_w x_w}{MW_{da} x_{da}} = 0.622 \frac{x_w}{x_{da}}$$

Units:

$$[\frac{\text{lb}_\text{w}}{\text{lb}_\text{da}}]$$

$$x_{da} = \frac{p_{da}}{p_{da} + p_w} = \frac{p_{da}}{p_{tot}} \qquad x_w = \frac{p_w}{p_{da} + p_w} = \frac{p_w}{p_{tot}}$$

Humidity ratio, W (IP units)

- 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 < 0.03 for most real building conditions)
  - Note 2: W is also expressed in grains/lb where 1 lb = 7000 grains

$$W = 0.622\frac{x_w}{x_{da}} = 0.622\frac{p_w / p_{tot}}{p_{da} / p_{tot}} = 0.622\frac{p_w}{p_{da}} = 0.622\frac{p_w}{p_{tot} - p_w}$$

where: $p_{tot} = p_{da} + p_w = 14.696$ psia @ sea level