# Thermodynamics I

## *Chapter 2*

### *Properties of Pure Substances*

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# Pure Substance

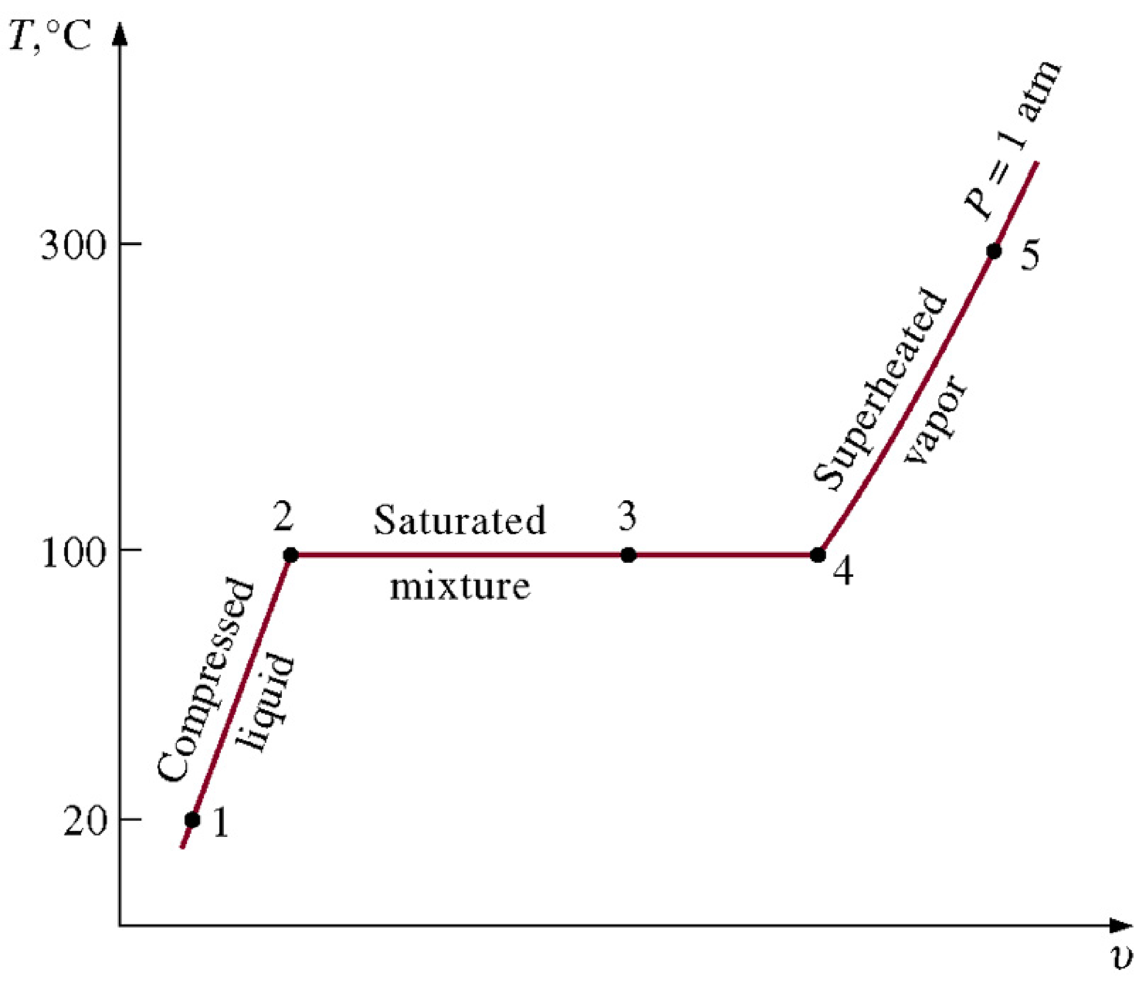
- Fixed chemical composition throughout
- There are three phases
  - Solid
  - Liquid
  - Gas
- Phase can be changed from one to another.

# Phase-Change Processes of Pure Substances

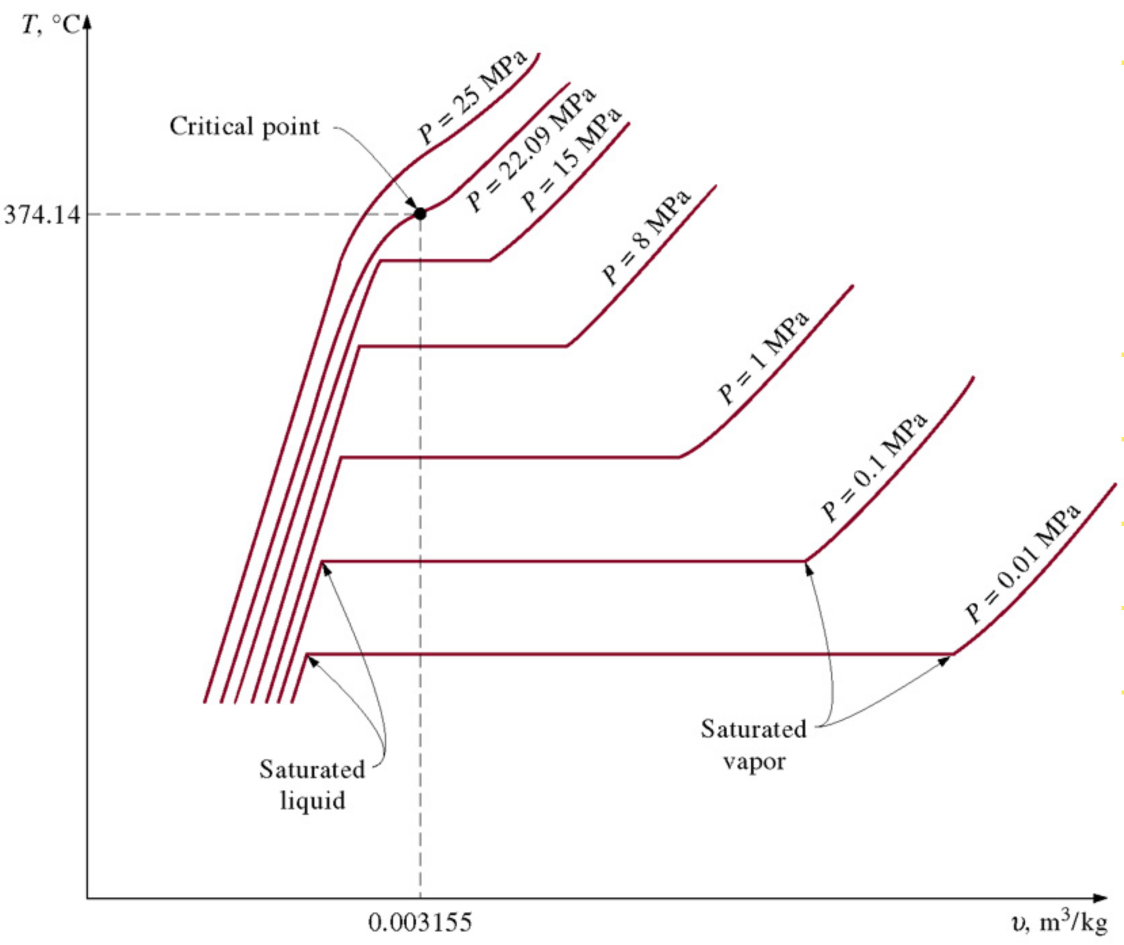
- Compressed Liquid :- not about to vaporize
- Saturated Liquid :- about to vaporize
- Saturated Vapor :- about to condense
- Saturated Liquid-Vapor Mixture :- liquid and vapor phases coexist
- Superheated vapor :- not about to condense

# Phase-Change Processes of Pure Substances

T-v diagram for the heating process of water at constant pressure.

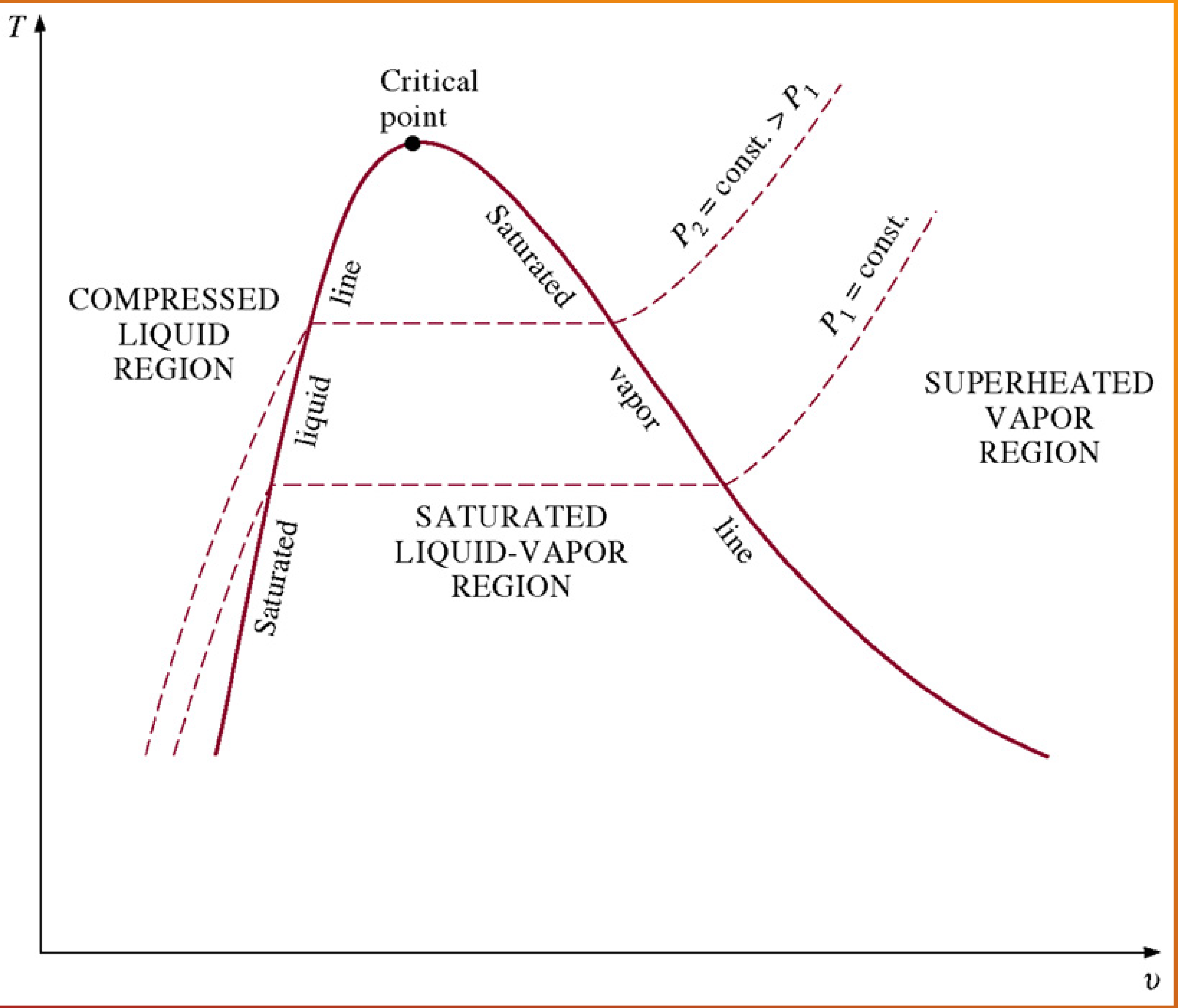


# Property Diagrams for Phase-Change Processes

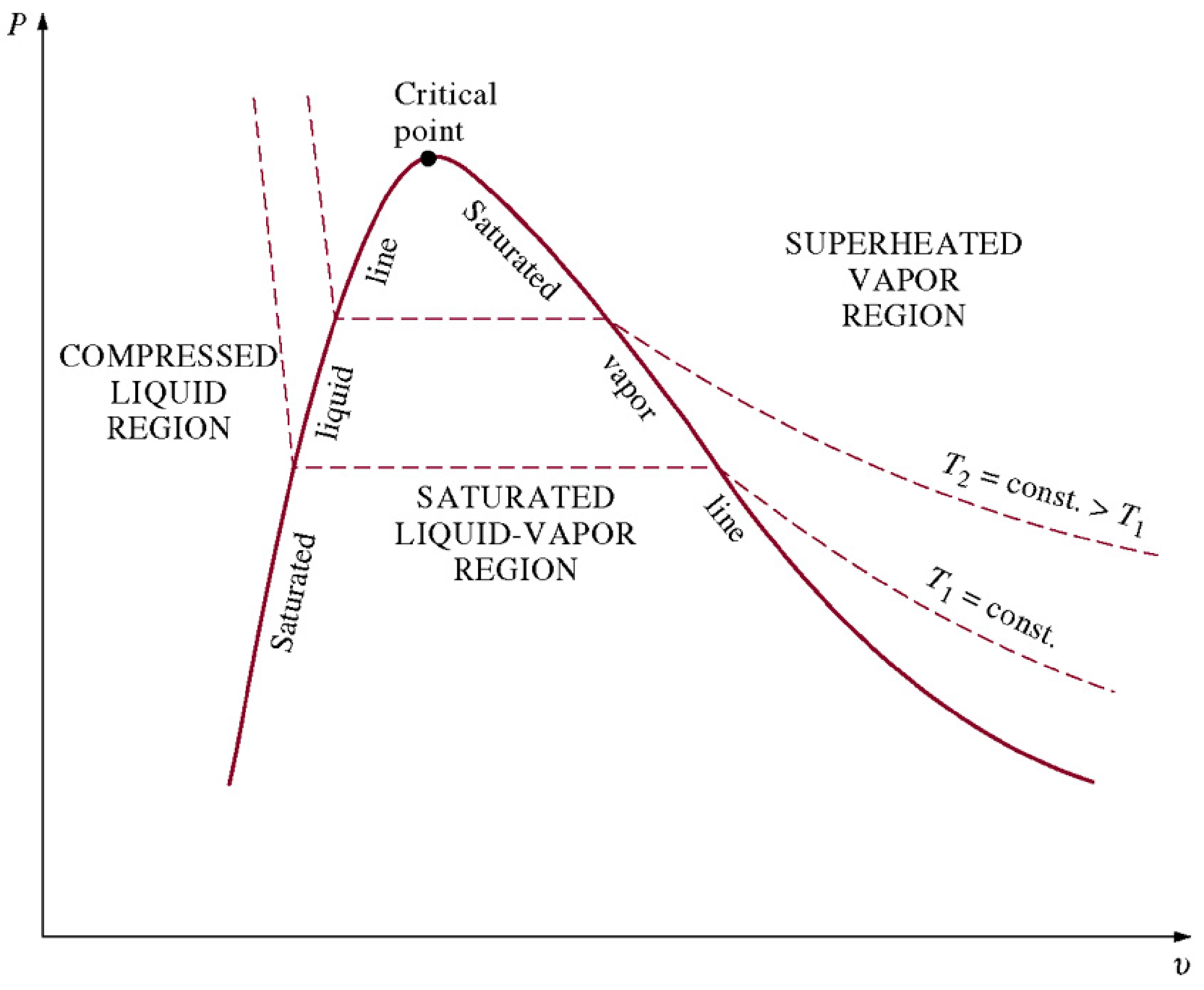



- Critical point (*the point at which the saturated liquid and saturated vapor states are identical*)
- Saturated liquid line
- Saturated vapor line
- Compressed liquid region
- Superheated vapor region
- Saturated liquid-vapor mixture region or wet region

# Property Diagrams for Phase-Change Processes :: *T-v* Diagram

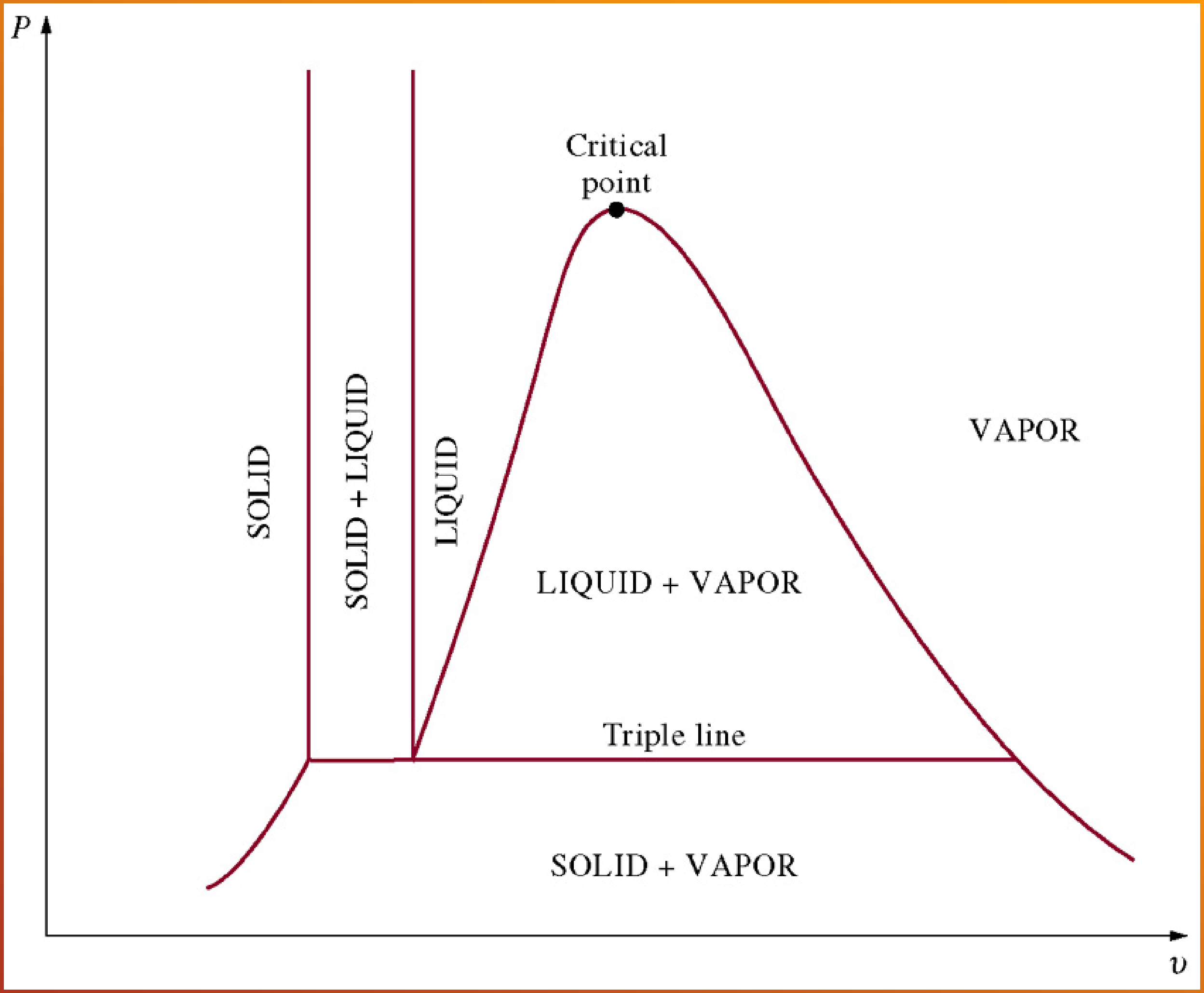


# Property Diagrams for Phase-Change Processes :: *P-v* Diagram



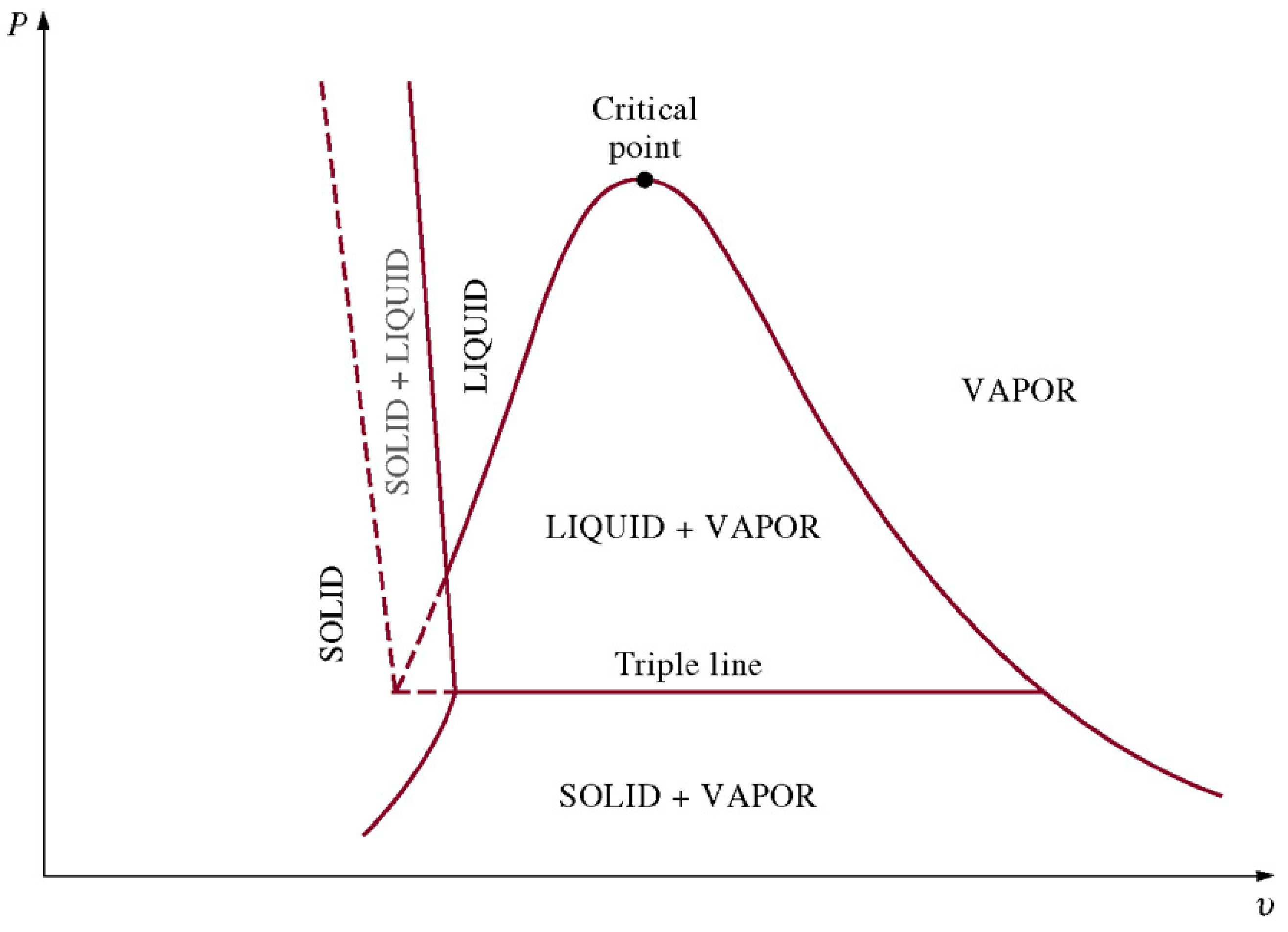
# Property Diagrams for Phase-Change Processes :: *P-v* Diagram

***P-v*** **diagram of a substance that contracts on freezing.**

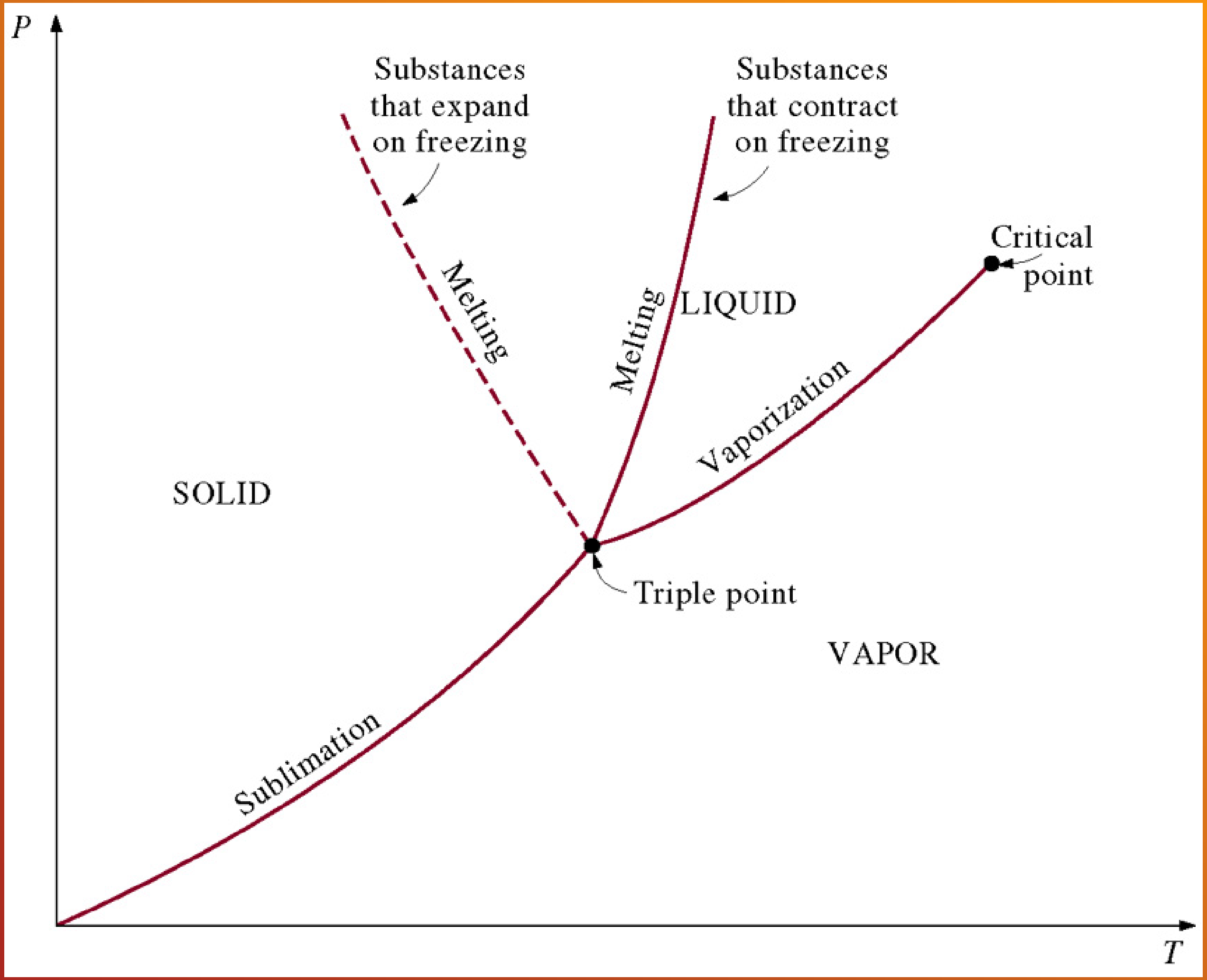


# Property Diagrams for Phase-Change Processes :: *P-v* Diagram

***P-v*** **diagram of a substance that expands on freezing (such as water).**

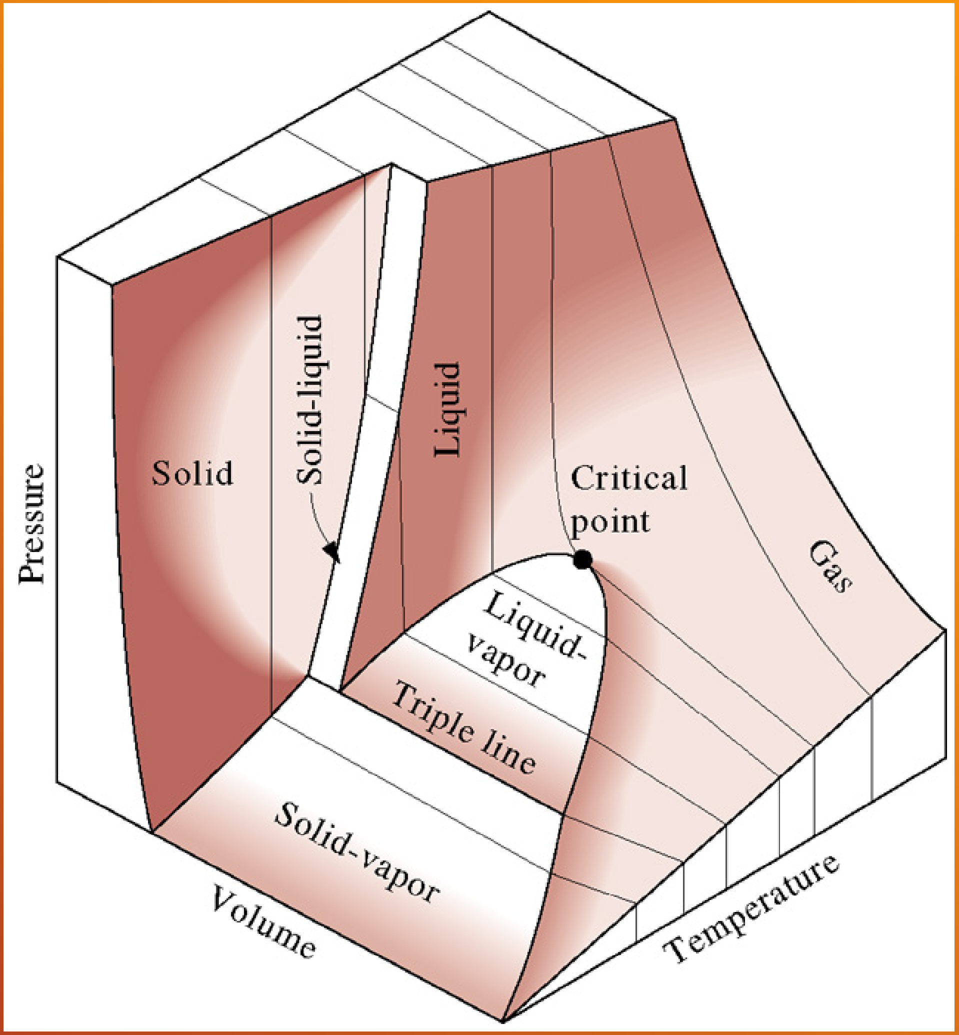


# Property Diagrams for Phase-Change Processes :: *P-T* Diagram



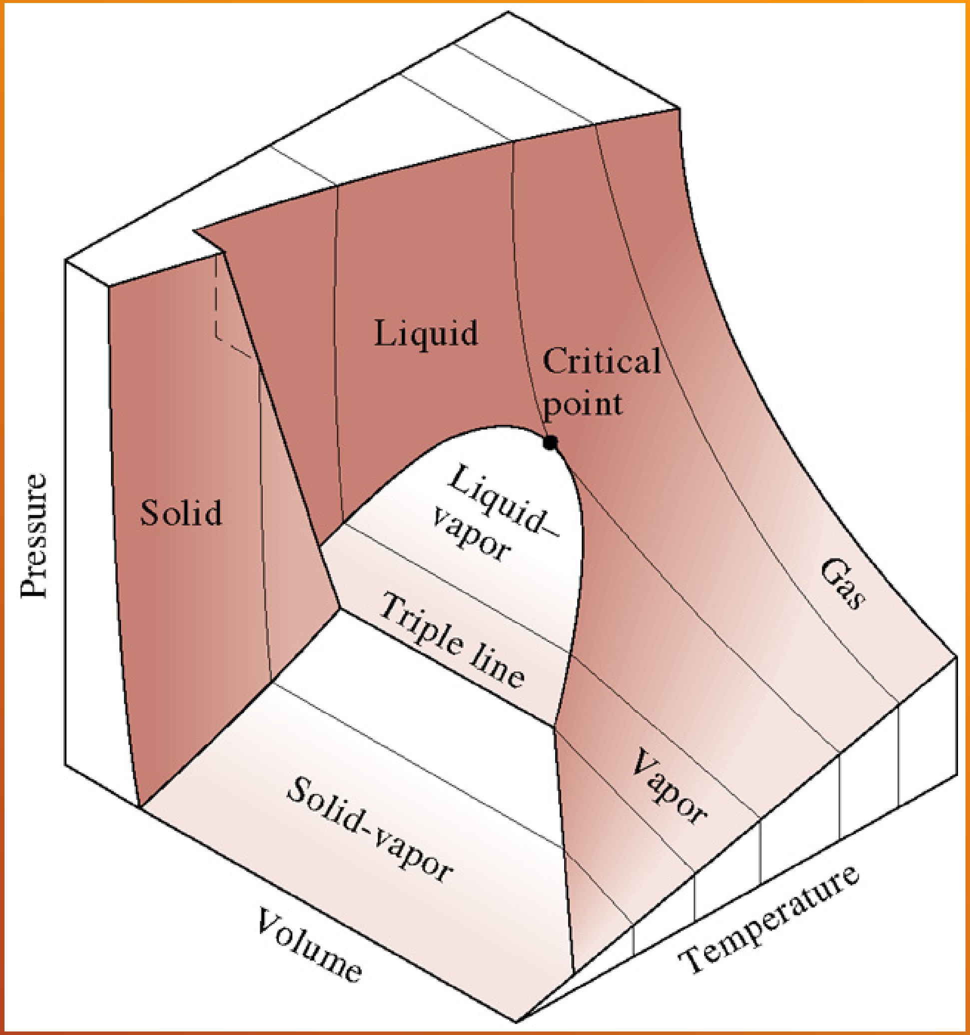
# Property Diagrams for Phase-Change Processes :: *P-v-T* Surface

***P-v-T*** **surface of a substance that** ***contracts*** **on freezing.**



# Property Diagrams for Phase-Change Processes :: *P-v-T* Surface

***P-v-T*** **surface of a substance that *expands* on freezing. (like water)**



# Enthalpy

- Enthalpy is a combination property

$$H = U + PV \qquad \text{(kJ)}$$

- Enthalpy per unit mass

$$h = u + Pv \qquad \text{(kJ/kg)}$$

# Saturated Liquid and Saturated Vapor States

**Table A-4**

| Temp. °C $T$ | Sat. press kPa $P_{sat}$ | Specific volume $m^3/kg$: Sat. liquid $v_f$ | Specific volume $m^3/kg$: Sat. vapor $v_g$ |
|---|---|---|---|
| 85 | 57.83 | 0.001 033 | 2.828 |
| 90 | 70.14 | 0.001 036 | 2.361 |
| 95 | 84.55 | 0.001 040 | 1.982 |

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

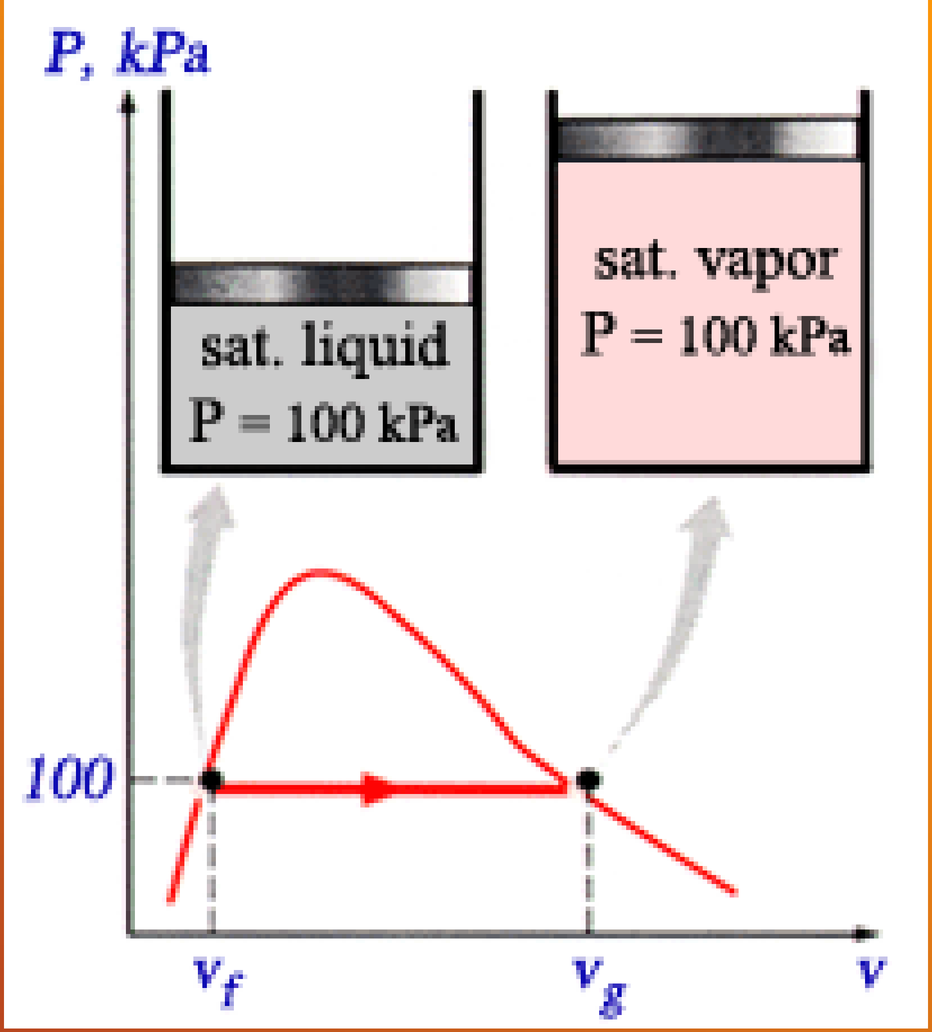
Specific volume of saturated vapor

# Saturated Liquid and Saturated Vapor States

| $T$,°C | $\upsilon$, m$^3$/kg | $u$, kJ/kg | $h$, kJ/kg |
|---|---|---|---|
| | $P$ = 0.1 MPa (99.63°C) | | |
| Sat. | 1.6940 | 2506.1 | 2675.5 |
| 100 | 1.6958 | 2506.7 | 2676.2 |
| 150 | 1.9364 | 2582.8 | 2776.4 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 1300 | 7.260 | 4683.5 | 5409.5 |
| | $P$ = 0.5 MPa (151.86°C) | | |
| Sat. | 0.3749 | 2561.2 | 2748.7 |
| 200 | 0.4249 | 2642.9 | 2855.4 |
| 250 | 0.4744 | 2723.5 | 2960.7 |

# Example

A mass of 200 gm of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine the volume change of the water.



# Saturated Liquid-Vapor Mixture

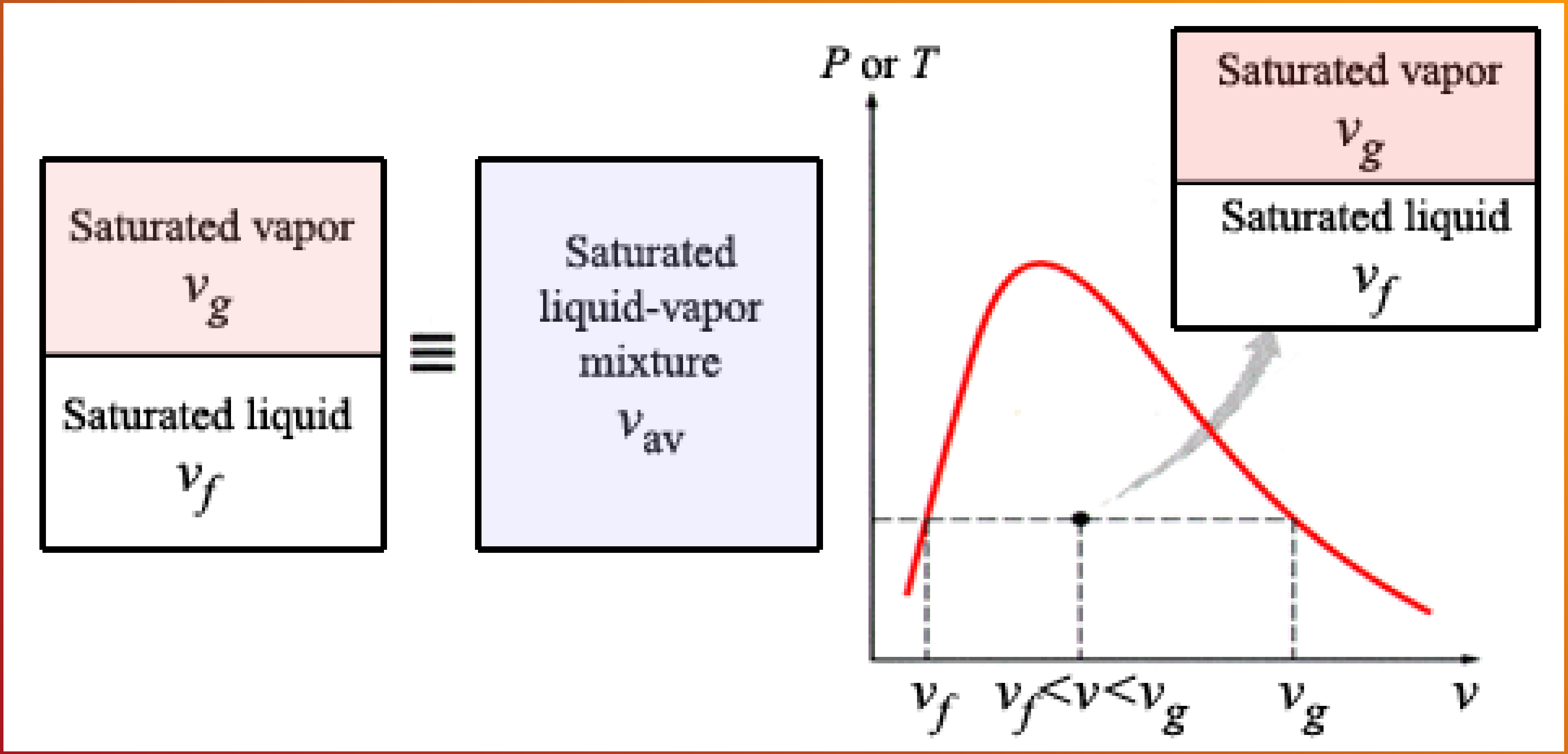
To analyze the mixture of saturated liquid and saturated vapor, the proportions of the liquid and vapor phases in the mixture needs to be known.

Quality :: $x = \dfrac{m_{vapor}}{m_{total}}$

where $m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$

# Saturated Liquid-Vapor Mixture

## Saturated Liquid-Vapor Mixture



# Saturated Liquid-Vapor Mixture

Average value of specific volume and quality

$$V = V_f + V_g$$

$$m_t v_{av} = m_f v_f + m_g v_g$$

$$m_t v_{av} = (m_t - m_g) v_f + m_g v_g$$

$$v_{av} = (1 - x) v_f + x v_g$$

$$v_{av} = v_f + x v_{fg}$$

$$x = \frac{v_{av} - v_f}{v_{fg}}$$

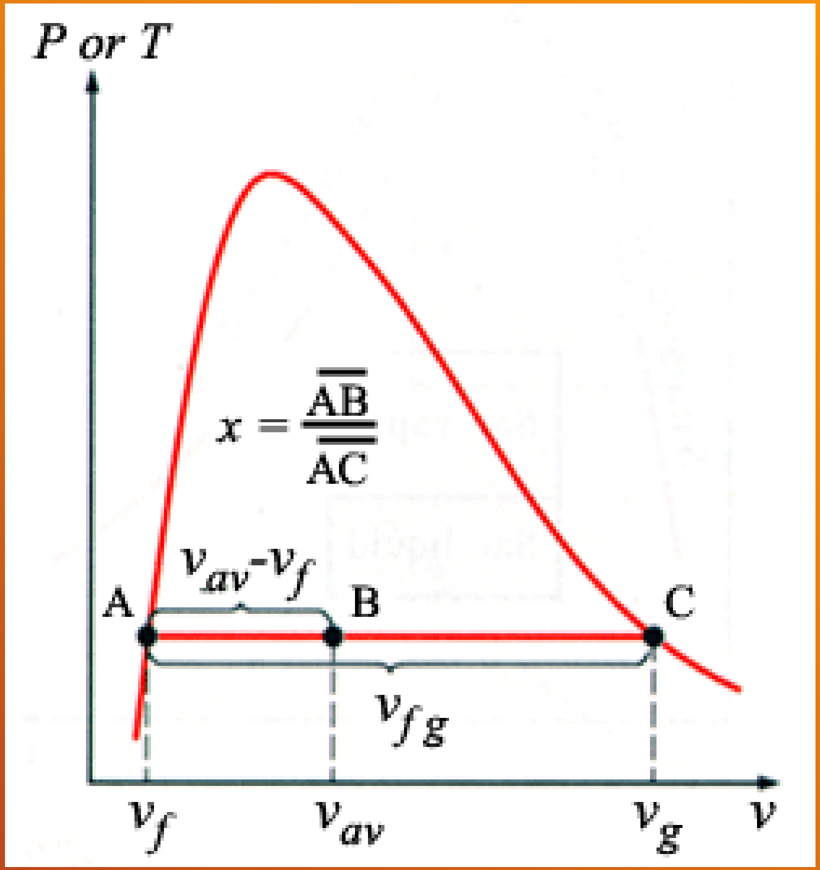
# Saturated Liquid-Vapor Mixture

Average of internal energy, enthalpy and other properties

$$u_{av} = u_f + xu_{fg}$$

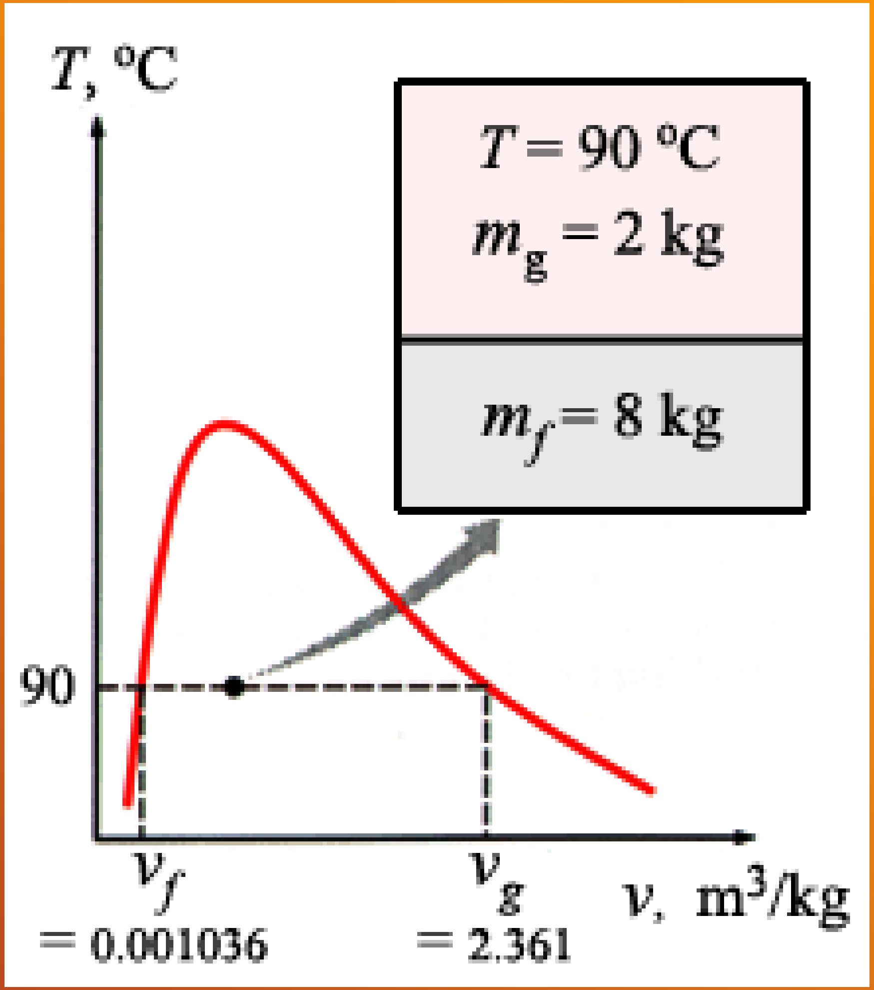
$$h_{av} = h_f + xh_{fg}$$

$$y_{av} = y_f + xy_{fg}$$



# Example

A rigid tank contains 10 kg of water at 90 °C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine
(a) the pressure in the tank and
(b) the volume of the tank.



# Example

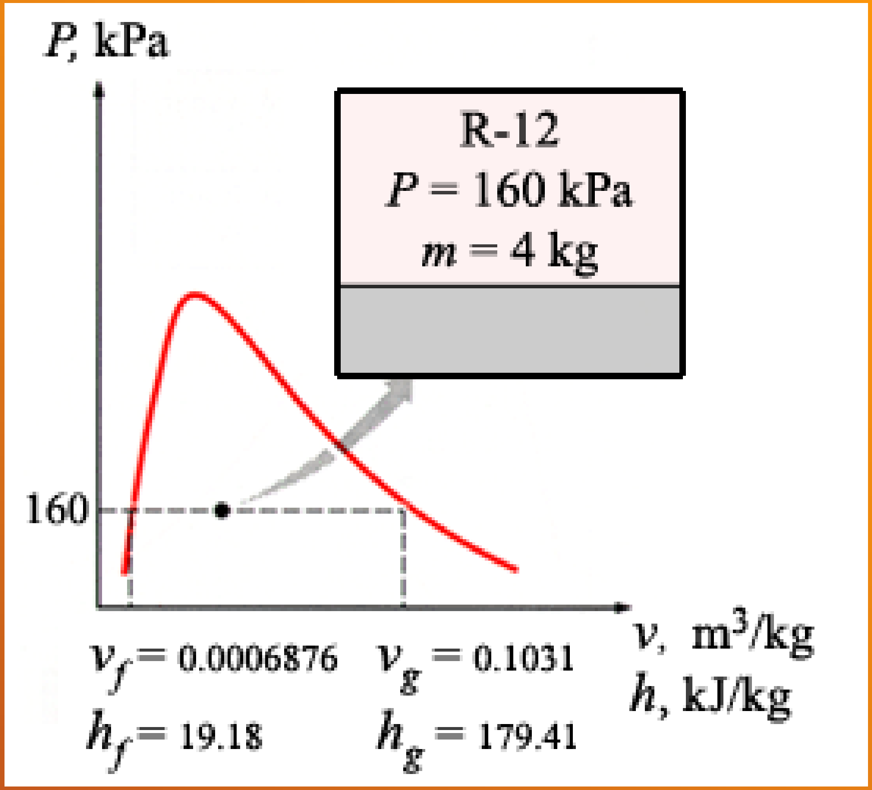
An 80-L vessel contains 4 kg of refrigerant-12 at a pressure of 160 kPa. Determine

(a) the temperature of the refrigerant,

(b) the quality,

(c) the enthalpy of the refrigerant, and

(d) the volume occupied by the vapor phase.



# Superheated Vapor

- Lower pressures
  ($P < P_{sat}$ at a given $T$)
- Higher temperatures
  ($T > T_{sat}$ at a given $P$)
- Higher specific volumes
  ($v > v_g$ at a given $P$ or $T$)
- Higher internal energies
  ($u > u_g$ at a given $P$ or $T$)
- Higher enthalpies
  ($h > h_g$ at a given $P$ or $T$)

| $T$, °C | $v$, m³/kg | $u$, kJ/kg | $h$, kJ/kg |
|---|---|---|---|
| | $P$ = 0.1 MPa (99.63°C) | | |
| Sat. | 1.6940 | 2506.1 | 2675.5 |
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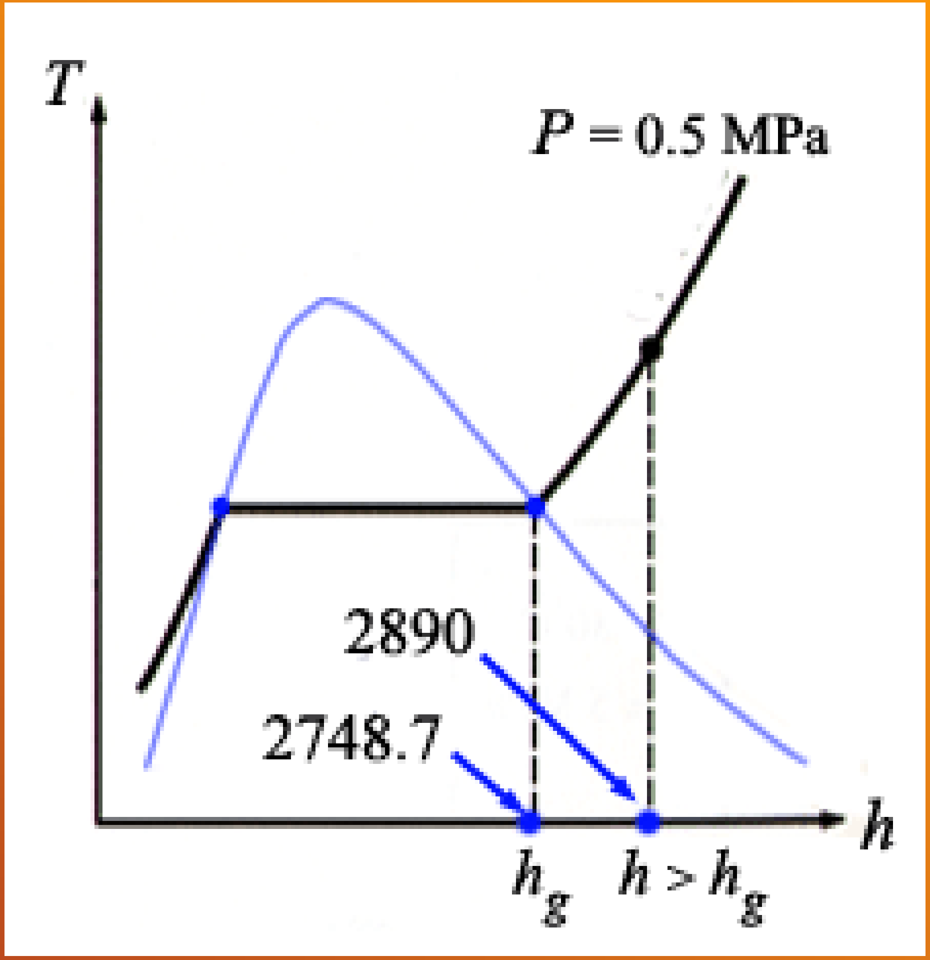
# Example

Determine the temperature of water at a state of $P$ = 0.5 MPa and $h$ = 2890 kJ/kg.



# Compressed Liquid

- Variation of properties in compressed liquid with pressure is very mild.
- A general approximation is to *treat compressed liquid as saturated liquid* ***at the given temperature***.

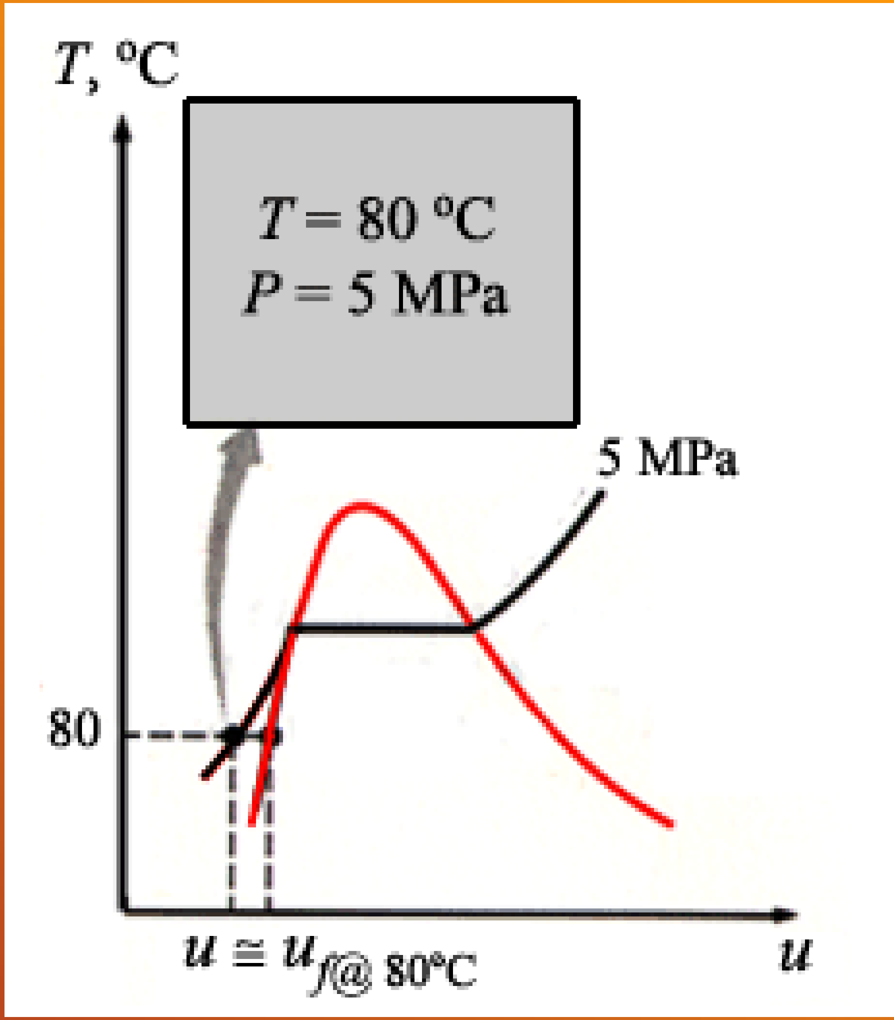
$$y \approx y_{f@T}$$

# Compressed Liquid

- Higher pressures ($P > P_{sat}$ at a given $T$)
- Lower temperatures ($T < T_{sat}$ at a given $P$)
- Lower specific volumes ($v < v_g$ at a given $P$ or $T$)
- Lower internal energies ($u < u_g$ at a given $P$ or $T$)
- Lower enthalpies ($h < h_g$ at a given $P$ or $T$)

# Example

Determine the internal energy of compressed liquid water at 80°C and 5 MPa, using
(a) data from the compressed liquid table and
(b) saturated liquid data.
What is the error involved in the second case?



# Reference State and Reference Values

- The value of *u*, *h*, and *s* can not be measured directly.
- They are calculated relatively between thermodynamic properties, not the value at that state.
- Reference state will give the reference value of zero.
- Example reference state:
  - Water : saturated liquid at 0.01°C
  - R134a : saturated liquid at -40°C

# The Ideal-Gas Equation of State

- Any equation that relates the pressure, temperature, and specific volume of a substance is call an **equation of state**.
- Property relations that involves other properties of a substance at equilibrium state are also called **equation of state**.

# The Ideal-Gas Equation of State

- The *vapor* phase of a substance is call a *gas* when it is above the critical temperature.
- *Vapor* usually implies a *gas* that is not far from a state of condensation.
- At low pressures the volume of a gas is proportional to its temperature.

$$P = R\left(\frac{T}{v}\right) \quad \text{or} \quad Pv = RT$$

# The Ideal-Gas Equation of State

- The gas constant $R$ is determine from

$$R = \frac{R_u}{M} \quad (\mathrm{kJ/kg \cdot K \ or \ kPa \cdot m^3/kg \cdot K})$$

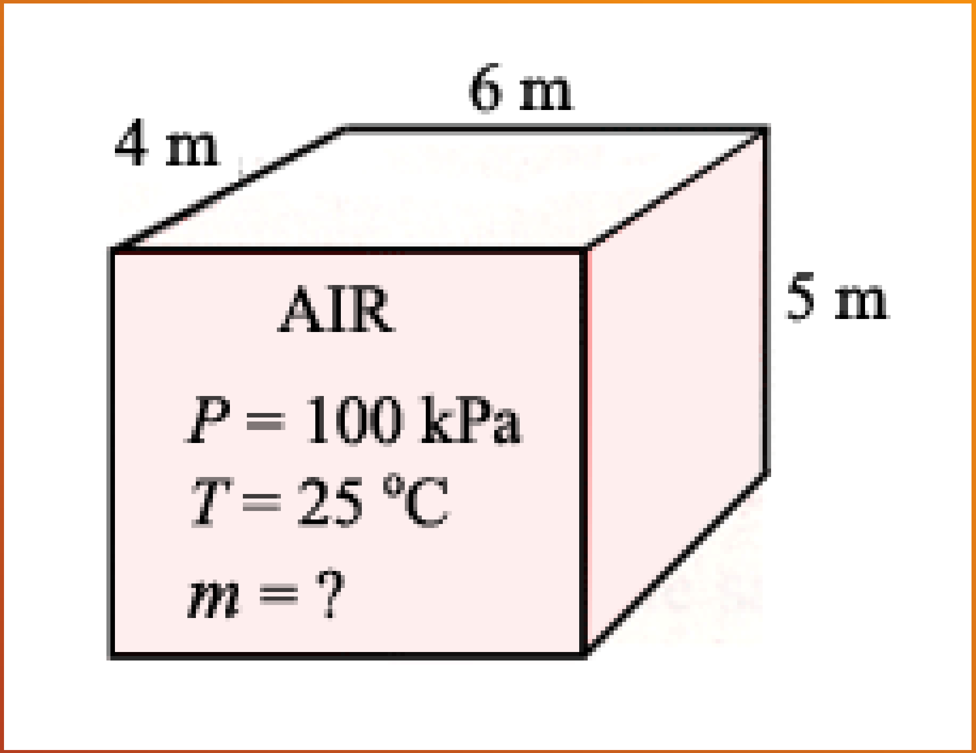
$$R_u = \begin{cases} 8.314 \ \mathrm{kJ/kmol \cdot K} \\ 8.314 \ \mathrm{kPa \cdot m^3/kg \cdot K} \\ 0.08314 \ \mathrm{bar \cdot m^3/kg \cdot K} \\ 1.986 \ \mathrm{Btu/lbmol \cdot R} \\ 10.73 \ \mathrm{psia \cdot ft^3/lbmol \cdot R} \\ 1545 \ \mathrm{ft \cdot lbf/lbmol \cdot R} \end{cases}$$

***Molar mass M : the mass of one mole called gram-mole of a substance in grams or the mass of one kmol called kilogram-mole in kilograms.***

**Universal gas constant**

# Example

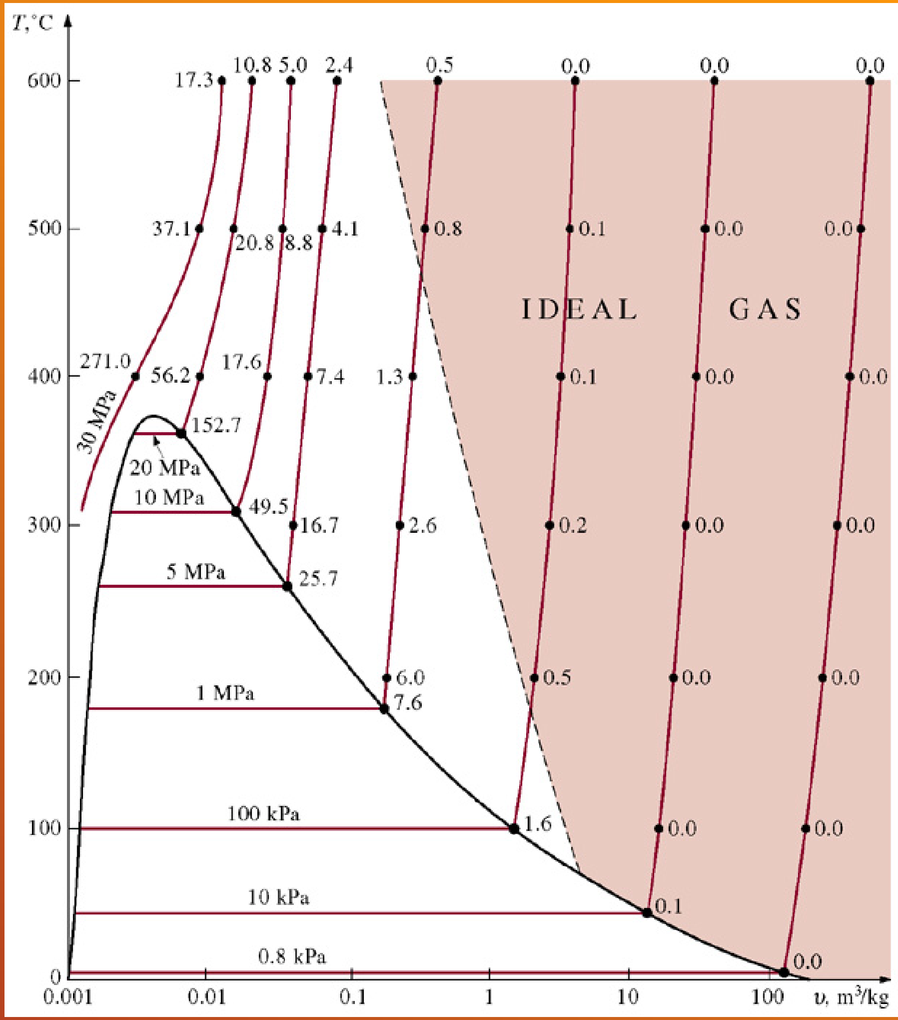
Determine the mass of the air in a room whose dimension are 4m×5m×6m at 100 kPa and 25°C.



# Compressibility Factor

## A Measure of Deviation from Ideal-Gas Behavior

Percentage of error involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.



# Compressibility Factor

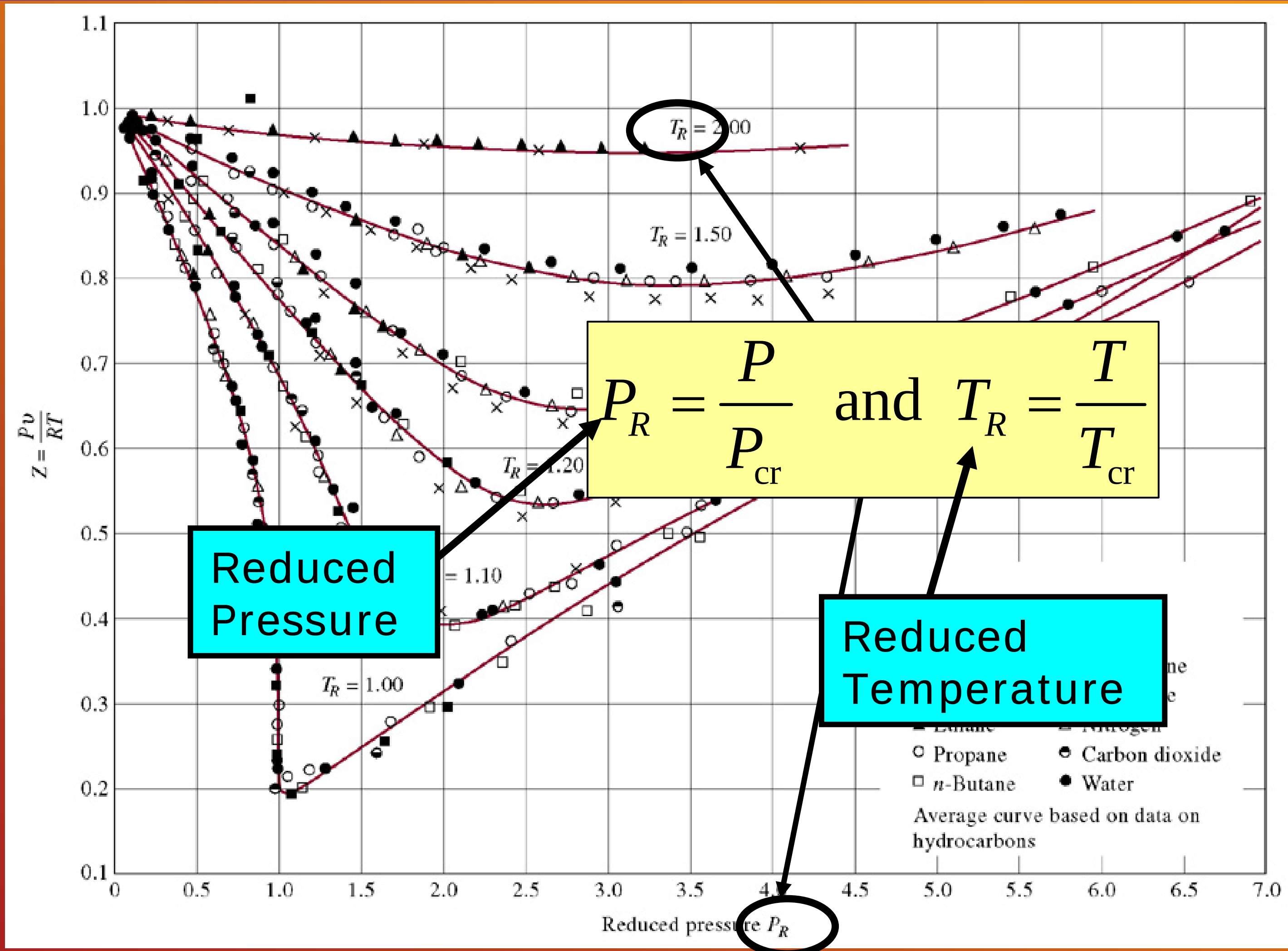
## A Measure of Deviation from Ideal-Gas Behavior

- The deviation from ideal-gas behavior at a given temperature and pressure can accurately be accounted for by a correction factor called compressibility factor, *Z*.

$$Z = \frac{Pv}{RT} \quad \text{or} \quad Pv = ZRT \quad \text{or} \quad Z = \frac{v_{\text{actual}}}{v_{\text{ideal}}}$$

# Compressibility Factor

## A Measure of Deviation from Ideal-Gas Behavior




$$P_R = \frac{P}{P_{cr}} \quad \text{and} \quad T_R = \frac{T}{T_{cr}}$$

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# Engineering Equation Solver