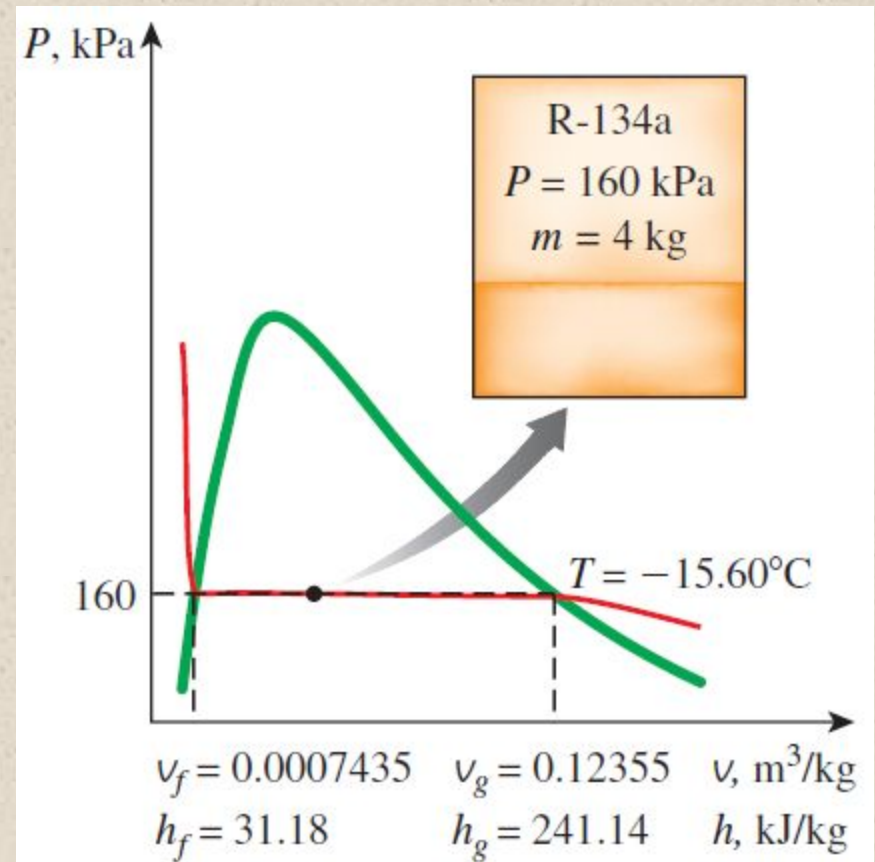
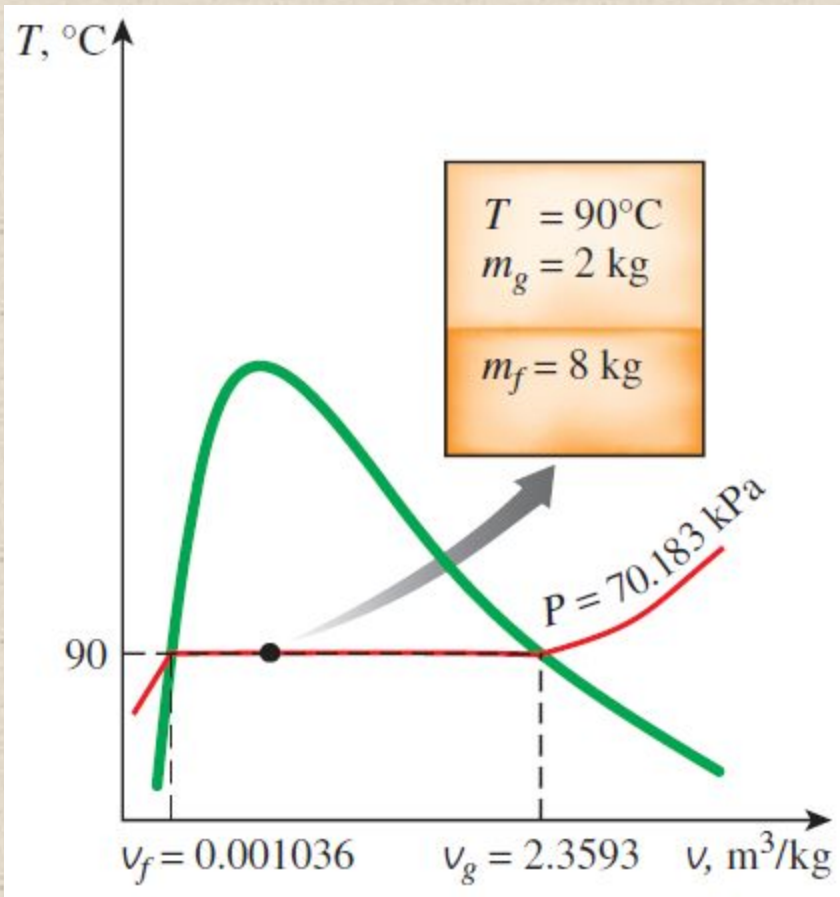


**Examples:** Saturated liquid-vapor mixture states on  $T$ - $v$  and  $P$ - $v$  diagrams.



In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor.

In this region, temperature and pressure are independent properties.

## Superheated Vapor

Compared to saturated vapor, superheated vapor is characterized by

Lower pressures ( $P < P_{\text{sat}}$  at a given  $T$ )

Higher temperatures ( $T > T_{\text{sat}}$  at a given  $P$ )

Higher specific volumes ( $v > v_g$  at a given  $P$  or  $T$ )

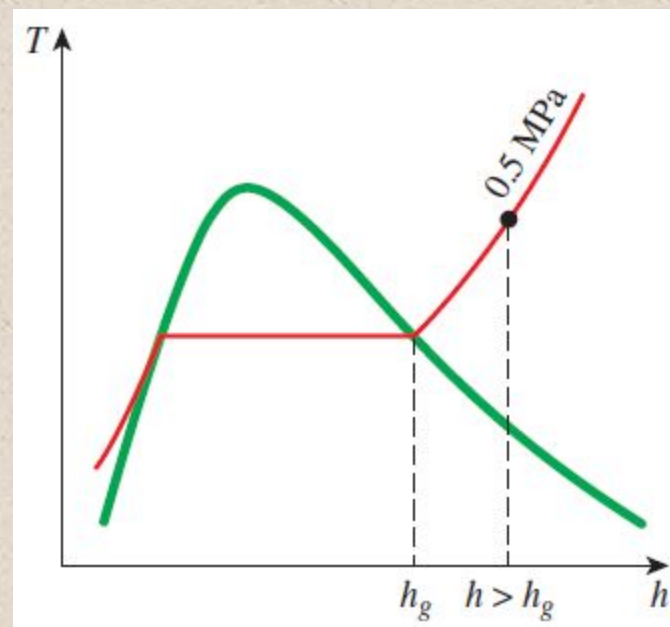
Higher internal energies ( $u > u_g$  at a given  $P$  or  $T$ )

Higher enthalpies ( $h > h_g$  at a given  $P$  or  $T$ )

$T, ^\circ\text{C}$	$v$ $\text{m}^3/\text{kg}$	$u$ $\text{kJ/kg}$	$h$ $\text{kJ/kg}$
$P = 0.1 \text{ MPa} (99.61^\circ\text{C})$			
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
$\vdots$	$\vdots$	$\vdots$	$\vdots$
1300	7.2605	4687.2	5413.3
$P = 0.5 \text{ MPa} (151.83^\circ\text{C})$			
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

At a specified  $P$ , superheated vapor exists at a higher  $h$  than the saturated vapor.

A partial listing of Table A-6.



The compressed liquid properties depend on temperature much more strongly than they do on pressure.

$$y \cong y_{f@T} \quad y \rightarrow v, u, \text{ or } h$$

A more accurate relation for  $h$

$$h \cong h_{f@T} + v_{f@T}(P - P_{\text{sat}@T})$$

Given:  $P$  and  $T$

$$\begin{aligned} v &\cong v_{f@T} \\ u &\cong u_{f@T} \\ h &\cong h_{f@T} \end{aligned}$$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

## Compressed Liquid

Compressed liquid is characterized by

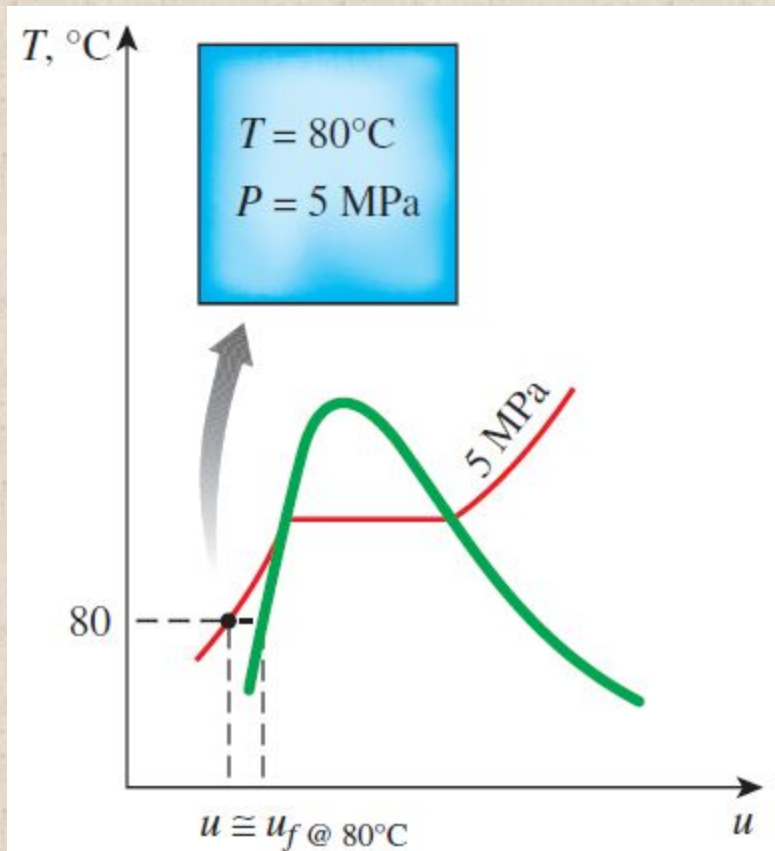
Higher pressures ( $P > P_{\text{sat}}$  at a given  $T$ )

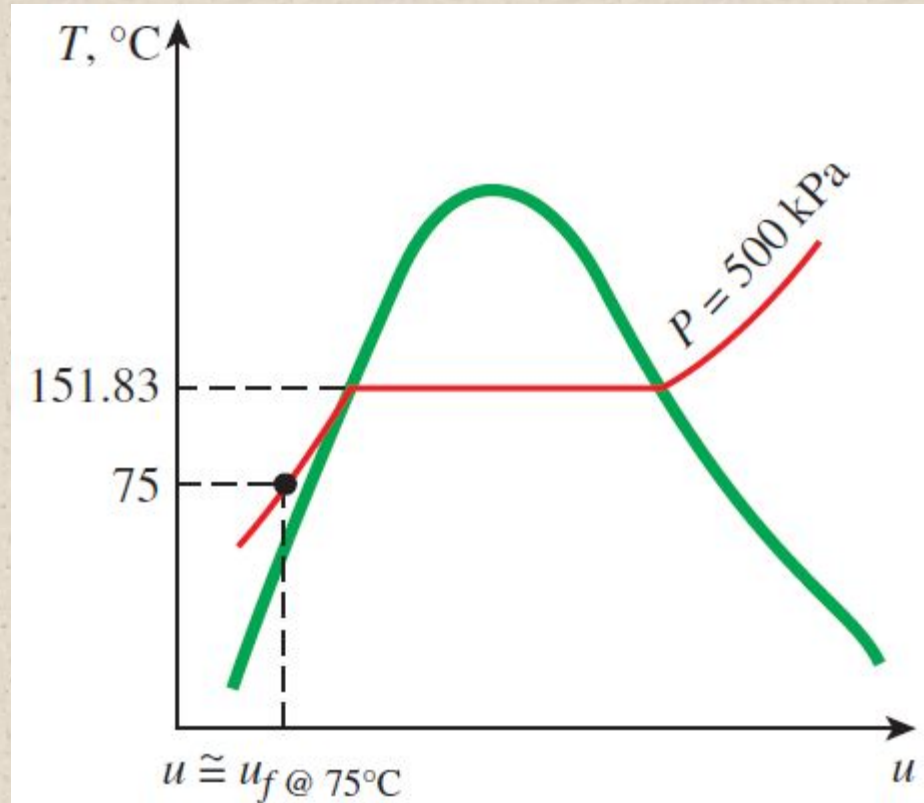
Lower temperatures ( $T < T_{\text{sat}}$  at a given  $P$ )

Lower specific volumes ( $v < v_f$  at a given  $P$  or  $T$ )

Lower internal energies ( $u < u_f$  at a given  $P$  or  $T$ )

Lower enthalpies ( $h < h_f$  at a given  $P$  or  $T$ )





**FIGURE 3–41**

At a given  $P$  and  $T$ , a pure substance will exist as a compressed liquid if  $T < T_{\text{sat}} @ P$ .



# Reference State and Reference Values

- The values of  $u$ ,  $h$ , and  $s$  cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- However, those relations give the *changes* in properties, not the values of properties at specified states.
- Therefore, we need to choose a convenient *reference state* and assign a value of *zero* for a convenient property or properties at that state.
- The reference state for water is  $0.01^\circ\text{C}$  and for R-134a is  $-40^\circ\text{C}$  in tables.
- Some properties may have negative values as a result of the reference state chosen.
- Sometimes different tables list different values for some properties at the same state as a result of using a different reference state.
- However, In thermodynamics we are concerned with the *changes* in properties, and the reference state chosen is of no consequence in calculations.

Saturated water—Temperature table

Temp., $T$ °C	Sat. press., $P_{\text{sat}}$ kPa	Specific volume, $\text{m}^3/\text{kg}$		Internal energy, $\text{kJ/kg}$			Enthalpy, $\text{kJ/kg}$			Entropy, $\text{kJ/kg} \cdot \text{K}$		
		Sat. liquid, $v_f$	Sat. vapor, $v_g$	Sat. liquid, $u_f$	Evap., $u_{fg}$	Sat. vapor, $u_g$	Sat. liquid, $h_f$	Evap., $h_{fg}$	Sat. vapor, $h_g$	Sat. liquid, $s_f$	Evap., $s_{fg}$	Sat. vapor, $s_g$
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

Saturated refrigerant-134a—Temperature table

Temp., $T$ °C	Sat. press., $P_{\text{sat}}$ kPa	Specific volume, $\text{m}^3/\text{kg}$		Internal energy, $\text{kJ/kg}$			Enthalpy, $\text{kJ/kg}$			Entropy, $\text{kJ/kg} \cdot \text{K}$		
		Sat. liquid, $v_f$	Sat. vapor, $v_g$	Sat. liquid, $u_f$	Evap., $u_{fg}$	Sat. vapor, $u_g$	Sat. liquid, $h_f$	Evap., $h_{fg}$	Sat. vapor, $h_g$	Sat. liquid, $s_f$	Evap., $s_{fg}$	Sat. vapor, $s_g$
-40	51.25	0.0007054	0.36081	-0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

# THE IDEAL-GAS EQUATION OF STATE

- **Equation of state:** Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the  $P$ - $v$ - $T$  behavior of a gas quite accurately within some properly selected region.

$$P = R \left( \frac{T}{v} \right) \quad P v = R T \quad \text{Ideal gas equation of state}$$

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

$R$ : gas constant

$M$ : molar mass (kg/kmol)

$R_u$ : universal gas constant

$$R_u = \begin{cases} 8.31447 \text{ kJ/kmol} \cdot \text{K} \\ 8.31447 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 0.0831447 \text{ bar} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 1.98588 \text{ Btu/lbmol} \cdot \text{R} \\ 10.7316 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R} \\ 1545.37 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R} \end{cases}$$

Substance	$R$ , kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants.

Mass = Molar mass  $\times$  Mole number

$$m = MN \quad (\text{kg})$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Ideal gas equation at two states for a fixed mass

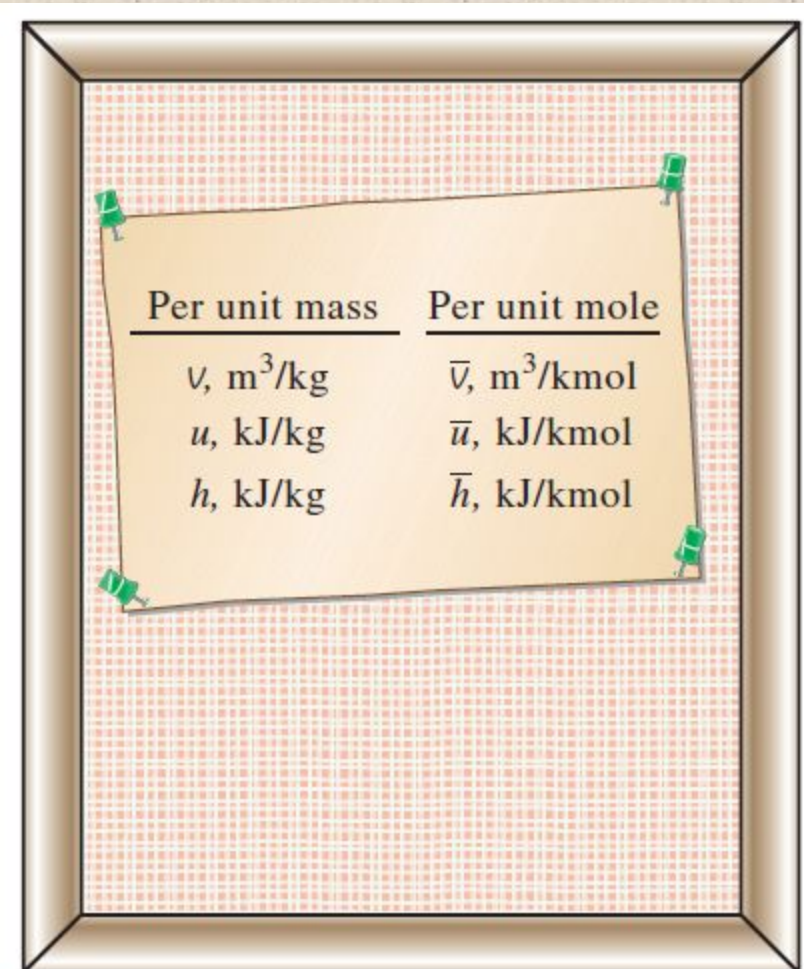
Various expressions of ideal gas equation

$$V = m\upsilon \longrightarrow P\upsilon = mRT$$

$$mR = (MN)R = NR_u \longrightarrow P\upsilon = NR_u T$$

$$V = N\bar{\upsilon} \longrightarrow P\bar{\upsilon} = R_u T$$

Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).



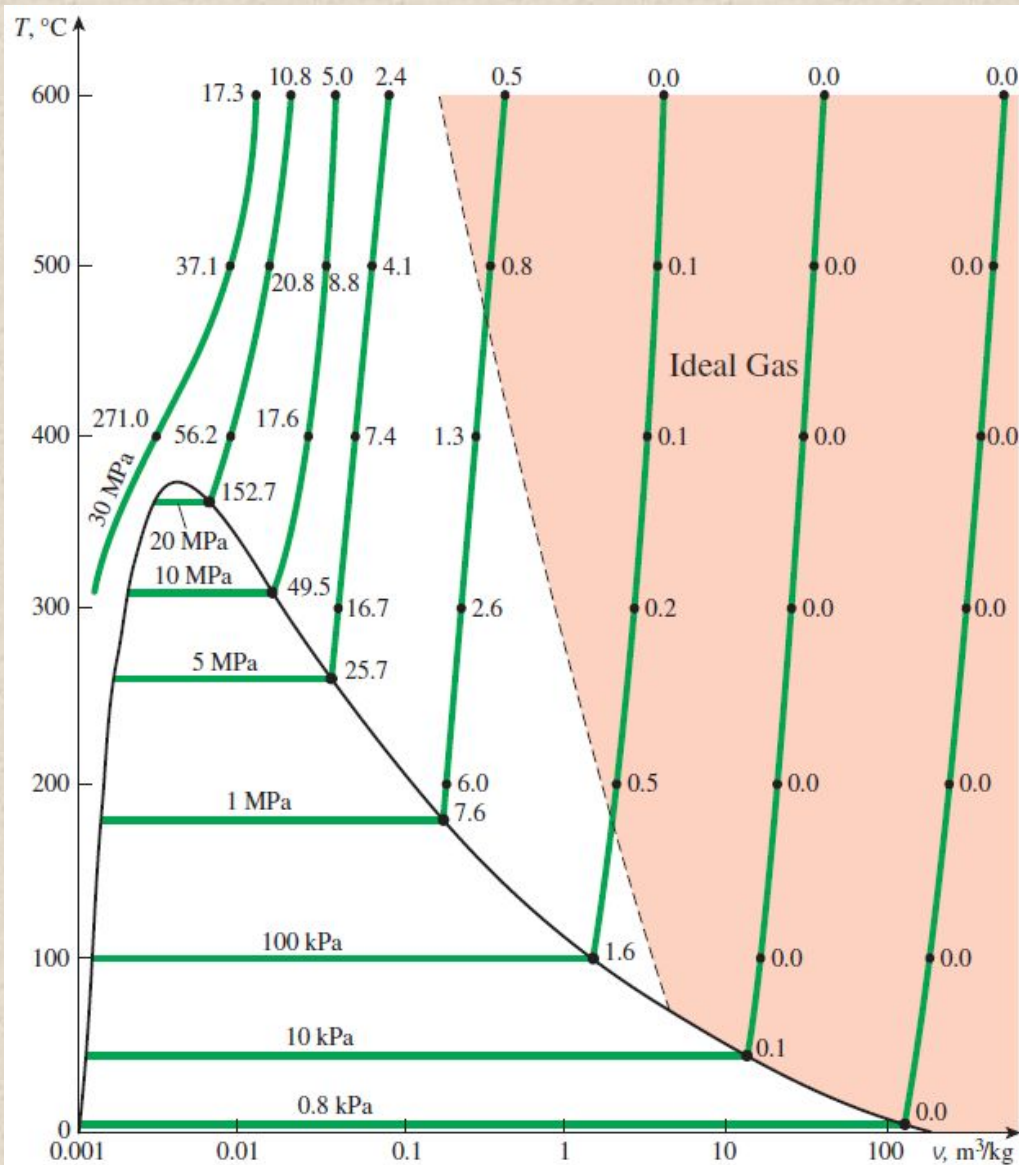
Per unit mass	Per unit mole
$\upsilon, \text{m}^3/\text{kg}$	$\bar{\upsilon}, \text{m}^3/\text{kmol}$
$u, \text{kJ/kg}$	$\bar{u}, \text{kJ/kmol}$
$h, \text{kJ/kg}$	$\bar{h}, \text{kJ/kmol}$

**FIGURE 3–43**

Properties per unit mole are denoted with a bar on the top.



# Is Water Vapor an Ideal Gas?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.
- In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?
- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error  

$$\left( \frac{|v_{\text{table}} - v_{\text{ideal}}|}{v_{\text{table}}} \times 100 \right)$$
  
 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

## Compressibility factor $Z$

A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$PV = ZRT$$

$$Z = \frac{PV}{RT}$$

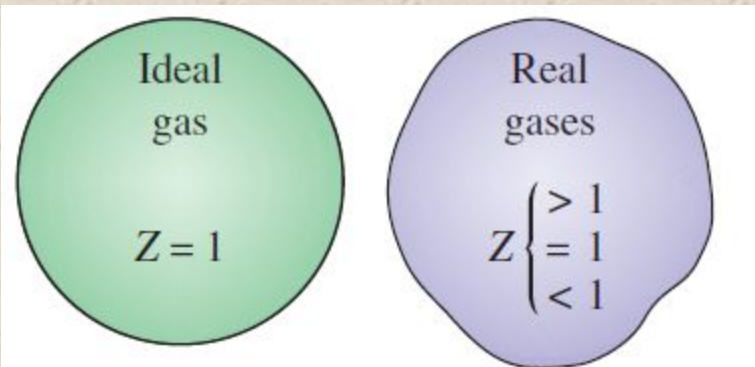
$$Z = \frac{V_{\text{actual}}}{V_{\text{ideal}}}$$

The farther away  $Z$  is from unity, the more the gas deviates from ideal-gas behavior.

*Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).*

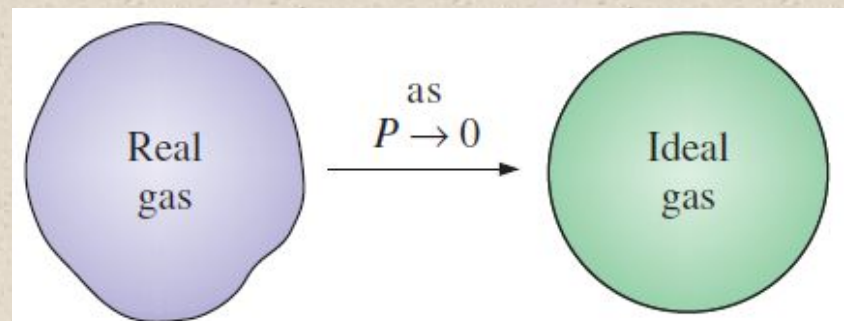
**Question:** What is the criteria for low pressure and high temperature?

**Answer:** The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.



**FIGURE 3–46**

The compressibility factor is unity for ideal gases.



**FIGURE 3–48**

At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

$$P_R = \frac{P}{P_{cr}}$$

Reduced  
pressure

$$T_R = \frac{T}{T_{cr}}$$

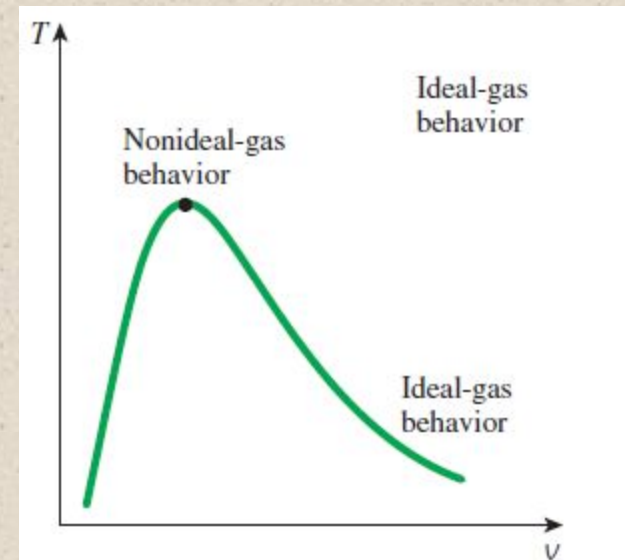
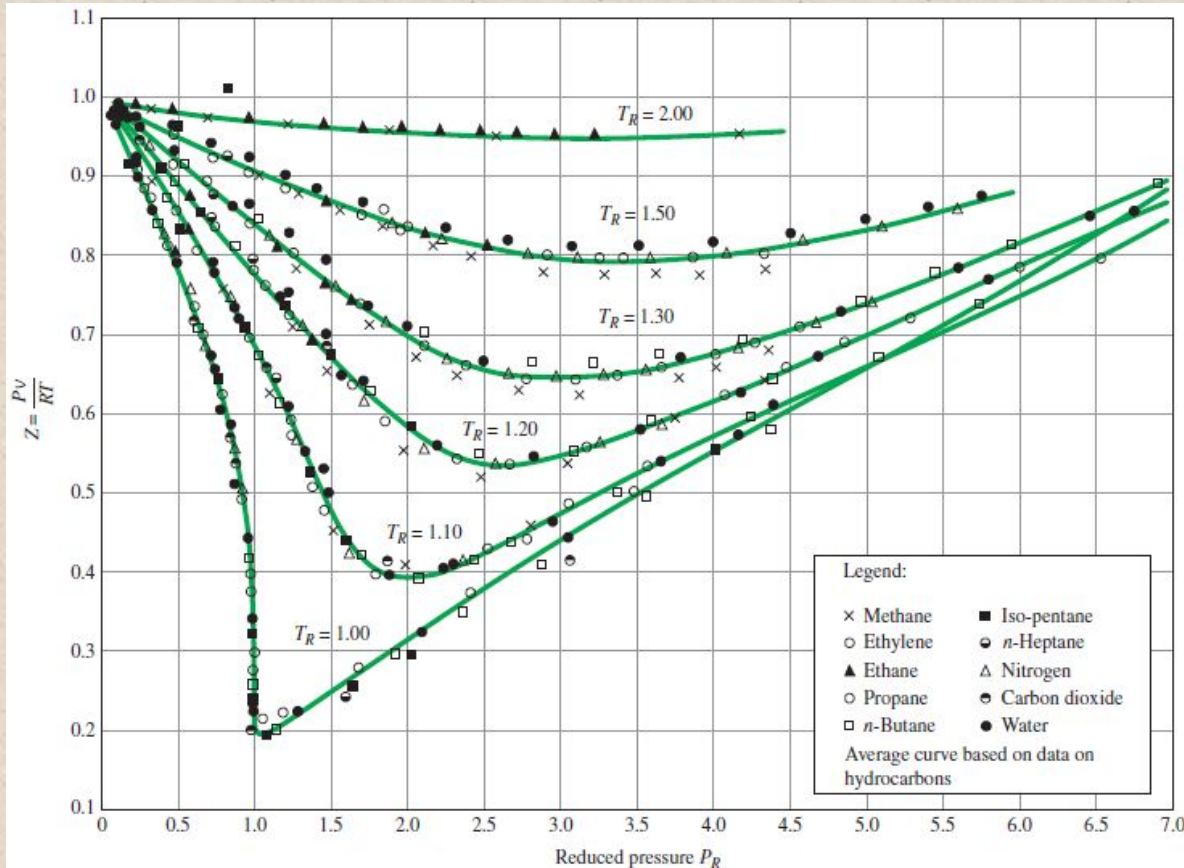
Reduced  
temperature

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$

Pseudo-reduced  
specific volume

$$\left. \begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned} \right\} Z = \dots \quad (\text{Fig. A-15})$$

Z can also be determined from  
a knowledge of  $P_R$  and  $v_R$ .



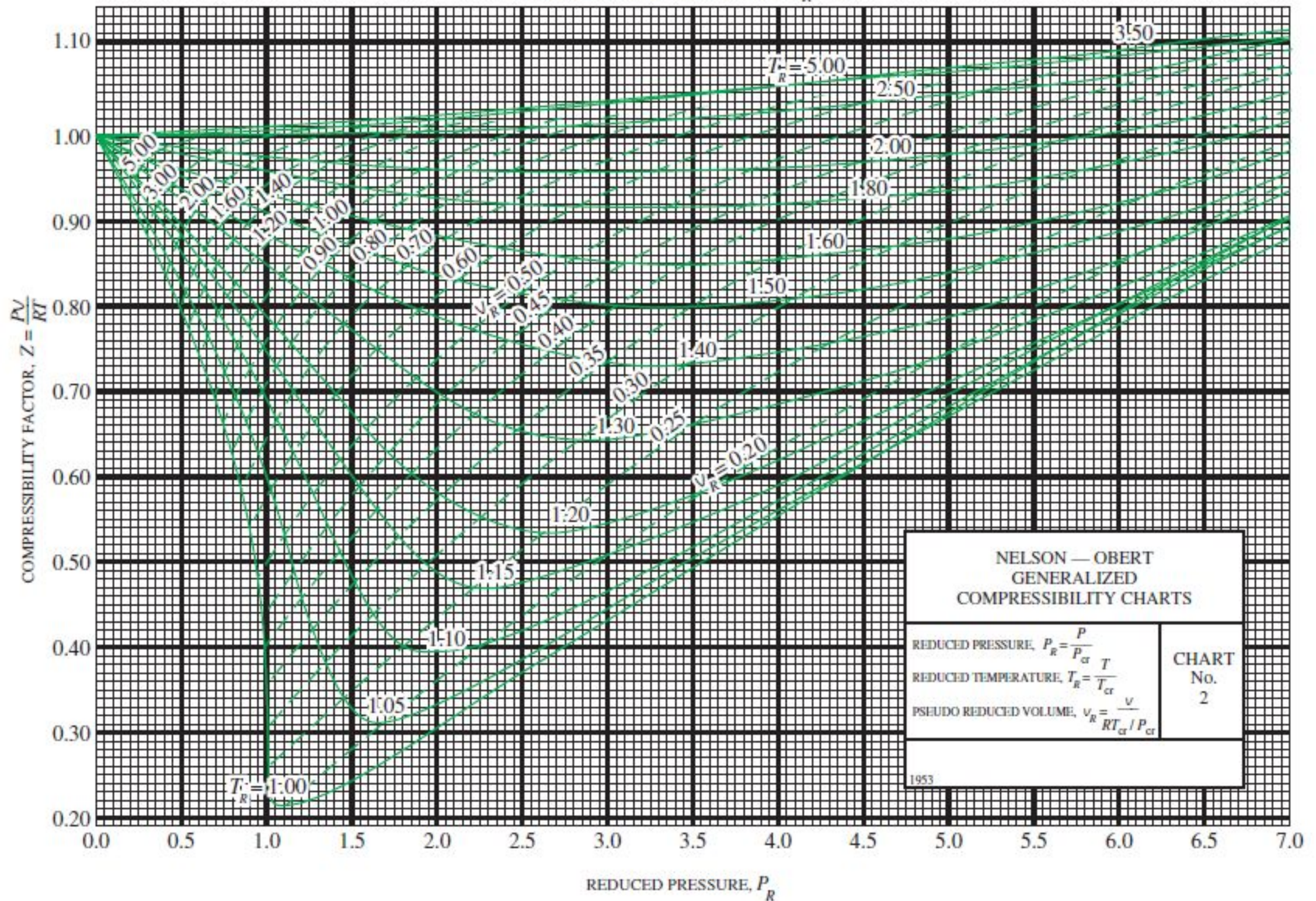
**FIGURE 3-49**

Gases deviate from the ideal-gas behavior the most in the neighborhood of the critical point.

Comparison of Z factors for various gases.

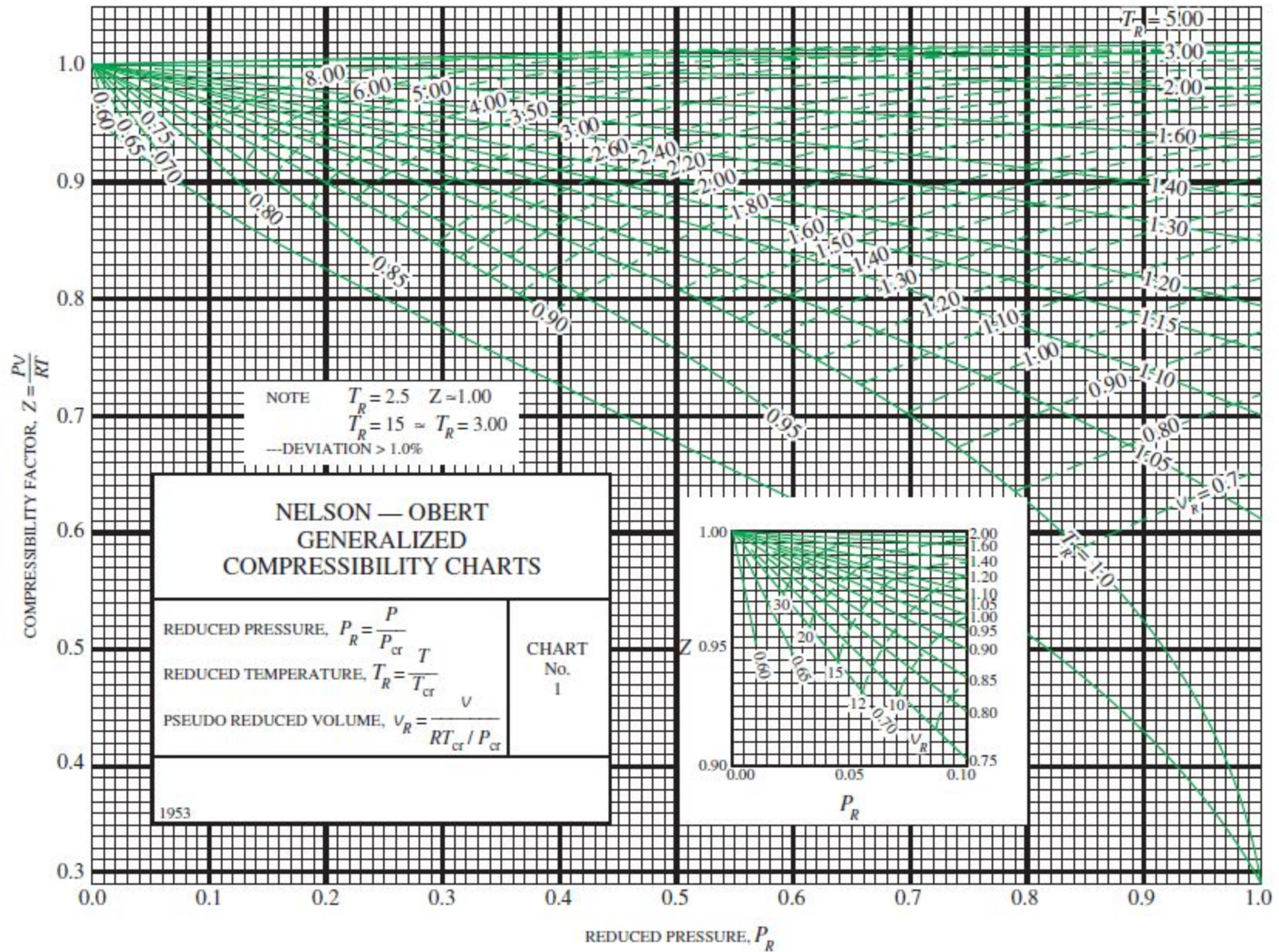


(b) Intermediate pressures,  $0 < P_R < 7$





(a) Low pressures,  $0 < P_R < 1.0$



# OTHER EQUATIONS OF STATE

Several equations have been proposed to represent the  $P$ - $v$ - $T$  behavior of substances accurately over a larger region with no limitations.

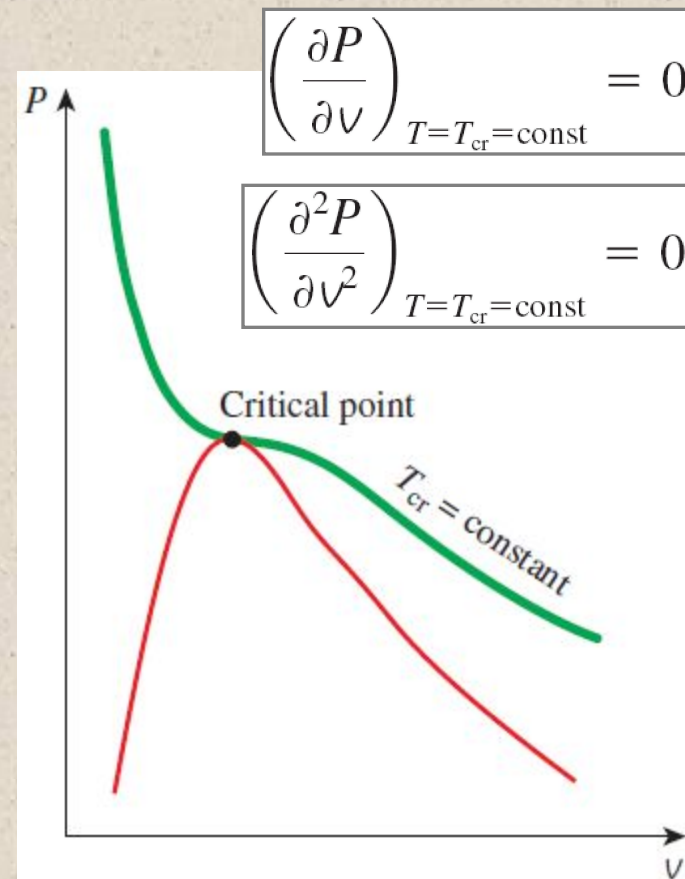
## Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

$$a = \frac{27R^2T_{\text{cr}}^2}{64P_{\text{cr}}} \quad b = \frac{RT_{\text{cr}}}{8P_{\text{cr}}}$$

This model includes two effects not considered in the ideal-gas model: *the intermolecular attraction forces and the volume occupied by the molecules themselves*. The accuracy of the van der Waals equation of state is often inadequate.

Critical isotherm of a pure substance has an inflection point at the critical state.



van der Waals  
Berthelet  
Redlich-Kwang  
Beattie-Bridgeman  
Benedict-Webb-Rubin  
Strobridge  
Virial