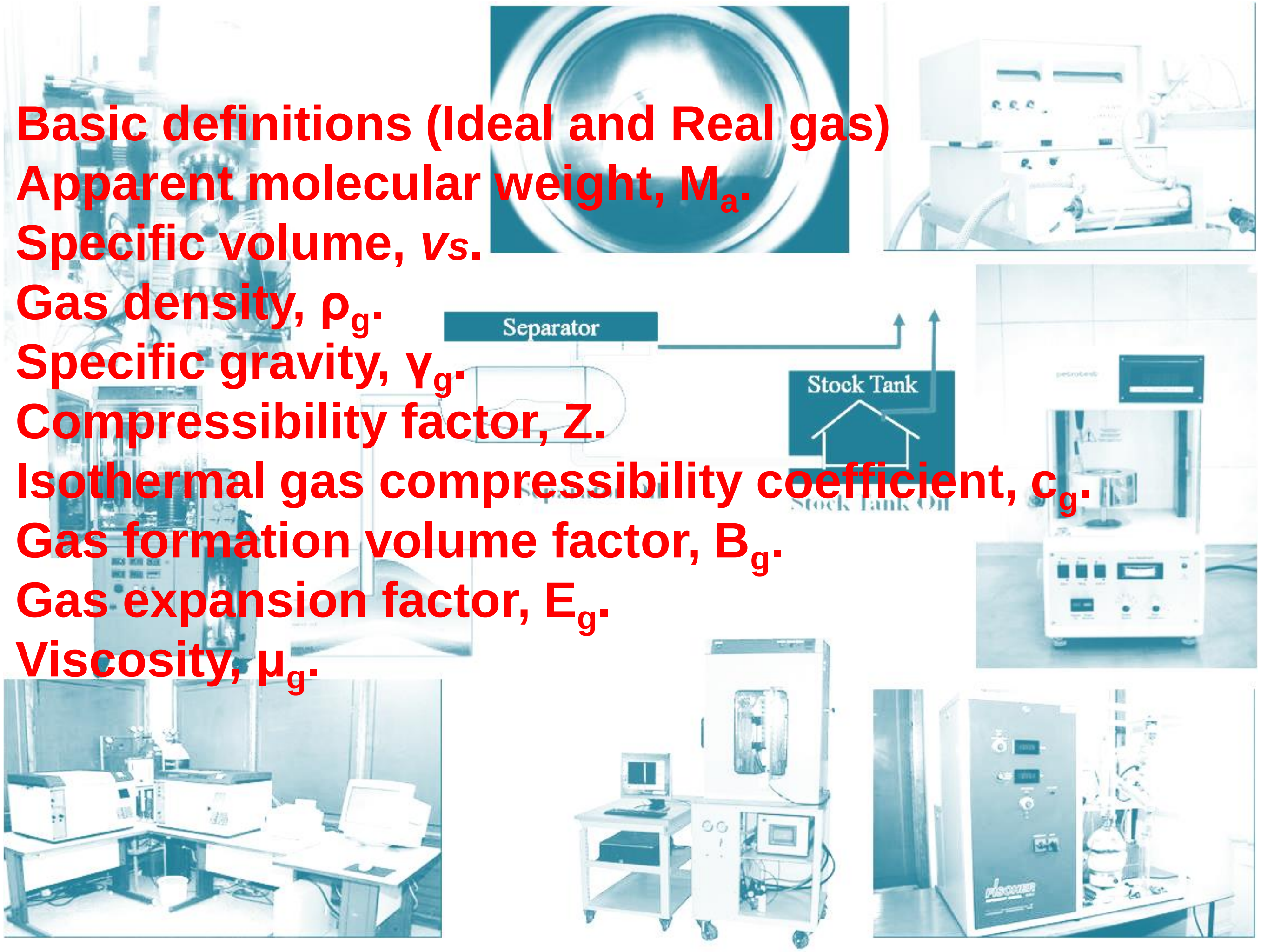
Natural Gas Properties



- **Basic definitions (Ideal and Real gas)**
- **Apparent molecular weight, M_a.**
- **Specific volume, *vs*.**
- **Gas density, ρ_g.**
- **Specific gravity, γ_g.**
- **Compressibility factor, Z.**
- **Isothermal gas compressibility coefficient, c_g.**
- **Gas formation volume factor, B_g.**
- **Gas expansion factor, E_g.**
- **Viscosity, μ_g.**

Behavior of Ideal Gases

The kinetic theory of gases:

- the gas is composed of a very large number of particles called molecules.
- For an **ideal gas**:
  - the volume of these molecules is **insignificant** compared with the total volume occupied by the gas.
  - these molecules have **no attractive or repulsive forces** between them.
  - it is assumed that **no loss of energy due to collision**.

⬇

$$pV = nRT \tag{3–1}$$

where

p = absolute pressure, psia
V = volume, ft^3
T = absolute temperature, °R
n = number of moles of gas, lb-mole
R = the universal gas constant that, for these units, has the value 10.73 psia ft^3/lb-mole °R

$$n = \frac{m}{M} \qquad (3\text{–}2)$$

$$pV = \left(\frac{m}{M}\right)RT \qquad (3\text{–}3)$$

where

m = weight of gas, lb
M = molecular weight, lb/lb-mole

$$\rho_g = \frac{m}{V} = \frac{pM}{RT} \qquad (3\text{–}4)$$

where ρ_g = density of the gas, lb/ft^3.

Mixture of Gases

Petroleum engineers usually are interested in the behavior of **mixtures** and rarely deal with pure component gases. Because natural gas is a mixture of hydrocarbon components, the overall physical and chemical properties can be determined from the physical properties of the individual components in the mixture by using appropriate mixing rules.

Apparent Molecular Weight, M_a

$$M_a = \sum_{i=1} y_i M_i \tag{3–5}$$

where

M_a = apparent molecular weight of a gas mixture
M_i = molecular weight of the ith component in the mixture
y_i = mole fraction of component i in the mixture

$$y_i = \frac{n_i}{n} = \frac{n_i}{\sum_i n_i}$$

It is convenient in many engineering calculations to convert from mole fraction to weight fraction and vice versa. The procedure is given in the following steps.

$$w_i = \frac{m_i}{m} = \frac{m_i}{\sum_i m_i} \qquad v_i = \frac{V_i}{V} = \frac{V_i}{\sum_i V_i}$$

1. Since the composition is one of the intensive properties and independent of the quantity of the system, assume that the total number of gas is 1; that is, $n = 1$.
2. From the definitions of mole fraction and number of moles (see equation 3–2),

$$y_i = \frac{n_i}{n} = \frac{n_i}{1} = n_i$$
$$m_i = n_i M_i = y_i M_i$$

3. From the above two expressions, calculate the weight fraction to give

$$w_i = \frac{m_i}{m} = \frac{m_i}{\sum_i m_i} = \frac{y_i M_i}{\sum_i y_i M_i} = \frac{y_i M_i}{M_a}$$

4. Similarly,

$$y_i = \frac{w_i / M_i}{\sum_i w_i / M_i}$$

Standard Volume, V_{sc}

- ➢The volume occupied by l lb-mole of gas at a reference pressure and temperature.
- ➢These reference conditions are usually 14.7 psia and 60°F and are commonly referred to as **standard conditions**.

$$V_{sc} = \frac{(1)RT_{sc}}{p_{sc}} = \frac{(1)(10.73)(520)}{14.7}$$

$$\boxed{V_{sc} = 379.4 \text{ scf/lb-mole}} \qquad (3\text{–}6)$$

where

V_{sc} = standard volume, scf/lb-mole
scf = standard cubic feet
T_{sc} = standard temperature, °R
p_{sc} = standard pressure, psia

Gas Density, ρ_g

The density of an ideal gas mixture is calculated by simply replacing the molecular weight, M, of the pure component in equation (3–4) with the apparent molecular weight, M_a, of the gas mixture to give

$$\rho_g = \frac{pM_a}{RT} \tag{3–7}$$

where ρ_g = density of the gas mixture, lb/ft^3, and M_a = apparent molecular weight.

Specific Volume, v

The specific volume is defined as the volume occupied by a unit mass of the gas. For an ideal gas, this property can be calculated by applying equation (3–3):

$$v = \frac{V}{m} = \frac{RT}{pM_a} = \frac{1}{\rho_g} \tag{3–8}$$

where v = specific volume, ft^3/lb, and ρ_g = gas density, lb/ft^3.

Specific Gravity, γ_g

The specific gravity is defined as the ratio of the gas density to that of the air. Both densities are measured or expressed at the same pressure and temperature. Commonly, the standard pressure, p_{sc}, and standard temperature, T_{sc}, are used in defining the gas specific gravity.

$$\gamma_g = \frac{\text{gas density @ 14.7 and 60°}}{\text{air density @ 14.7 and 60°}} = \frac{\rho_g}{\rho_{\text{air}}} \tag{3–9}$$

Assuming that the behavior of both the gas mixture and the air is described by the ideal gas equation, the specific gravity can be then expressed as

$$\gamma_g = \frac{\dfrac{p_{sc} M_a}{R T_{sc}}}{\dfrac{p_{sc} M_{\text{air}}}{R T_{sc}}}$$

or

$$\gamma_g = \frac{M_a}{M_{\text{air}}} = \frac{M_a}{28.96} \tag{3–10}$$

where

γ_g = gas specific gravity, 60°/60°
ρ_{air} = density of the air
M_{air} = apparent molecular weight of the air = 28.96
M_a = apparent molecular weight of the gas
p_{sc} = standard pressure, psia
T_{sc} = standard temperature, °R

Behavior of Real Gases

In dealing with gases at a very low pressure, the ideal gas relationship is a convenient and generally satisfactory tool. At higher pressures, the use of the ideal gas equation of state may lead to errors as great as 500%, as compared to errors of 2–3% at atmospheric pressure.

$$pV = ZnRT \tag{3–11}$$

Z-factor; gas compressibility factor; gas deviation factor

.

$$Z = \frac{V_{\text{actual}}}{V_{\text{ideal}}} = \frac{V}{(nRT)/p}.$$

a. Without non-hydrocarbon component

- Based on the concept of **pseudo-reduced properties**, Standing and Katz (1942) presented a generalized gas compressibility factor chart as shown in Figure 3–1.

- The chart represents the compressibility factors of sweet natural gas as a function of p_{pr} and T_{pr}.

- This chart is generally reliable for natural gas with a minor amount of non-hydrocarbons.

- It is one of the most widely accepted correlations in the oil and gas industry.

So, at first, we need to calculate p_{pr} and T_{pr}

Standing and Katz chart

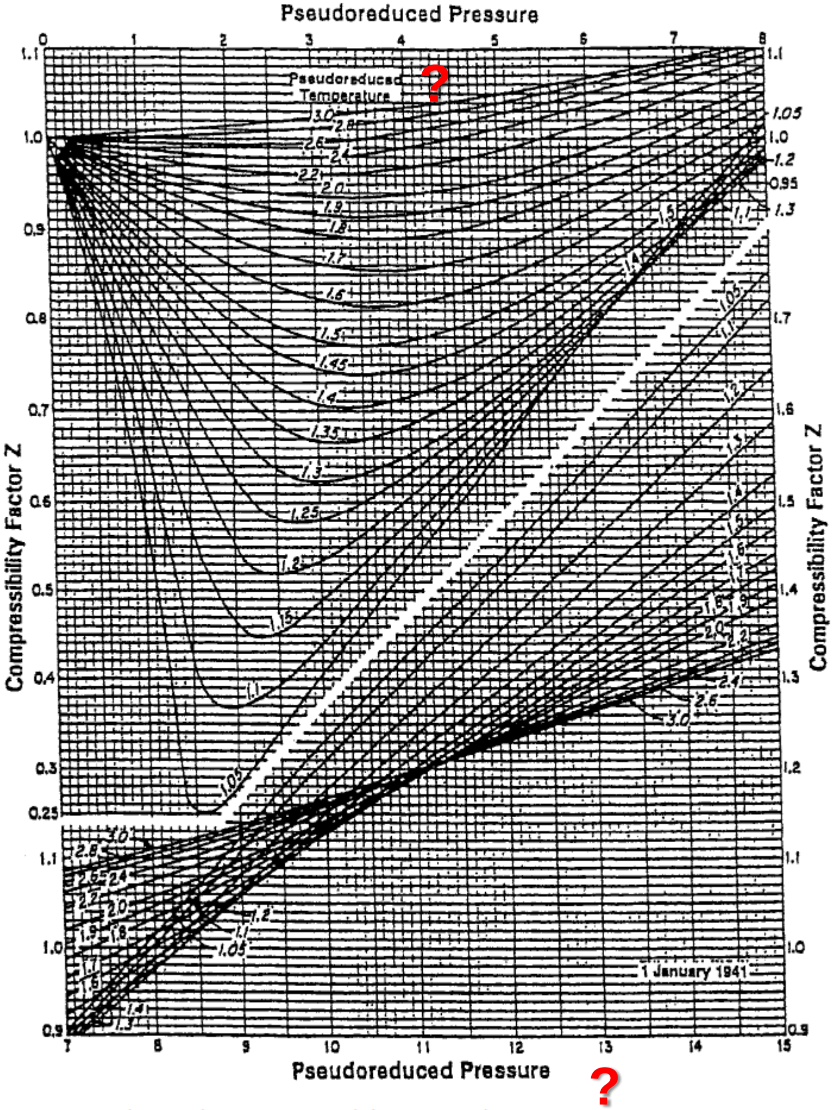


FIGURE 3–1 *Standing and Katz compressibility factors chart.*

Source: GPSA Engineering Data Book, 10th ed. Tulsa, OK: Gas Processors Suppliers Association, 1987. Courtesy of the Gas Processors Suppliers Association.

p_{pr} and T_{pr}

$$p_{pr} = \frac{p}{p_{pc}} \tag{3–12}$$

$$T_{pr} = \frac{T}{T_{pc}} \tag{3–13}$$

where

p = system pressure, psia
p_{pr} = pseudo-reduced pressure, dimensionless
T = system temperature, °R
T_{pr} = pseudo-reduced temperature, dimensionless

So, we need to calculate p_{pc} and T_{pc}

Calculation of p_{pc} and T_{pc} (composition of gas is available)

p_{pc}, T_{pc} = pseudo-critical pressure and temperature, respectively, defined by the following relationships:

$$p_{pc} = \sum_{i=1} y_i p_{ci} \tag{3–14}$$

$$T_{pc} = \sum_{i=1} y_i T_{ci} \tag{3–15}$$

It should be pointed out that these pseudo-critical properties, that is, p_{pc} and T_{pc}, do not represent the actual critical properties of the gas mixture. These pseudo properties are used as correlating parameters in generating gas properties.

we can read Pc and T for each component from a table, But
for plus fraction???

Matthews et al. (1942) correlated the critical properties of the C_{7+} fraction as a function of the molecular weight and specific gravity:

$$(p_c)_{C_{7+}} = 1188 - 431 \log(M_{C_{7+}} - 61.1) + [2319 - 852 \log(M_{C_{7+}} - 53.7)]\,(\gamma_{C_{7+}} - 0.8)$$

$$(T_c)_{C_{7+}} = 608 + 364 \log(M_{C_{7+}} - 71.2) + [2450 \log(M_{C_{7+}}) - 3800] \log(\gamma_{C_{7+}})$$

Real Gas Density

Equation (3–11) can be written in terms of the apparent molecular weight, M_a, and the weight of the gas, m:

$$pV = Z\left(\frac{m}{M_a}\right)RT$$

Solving this relationship for the gas's specific volume and density give

$$v = \frac{V}{m} = \frac{ZRT}{pM_a} \tag{3–16}$$

$$\rho_g = \frac{1}{v} = \frac{pM_a}{ZRT} \tag{3–17}$$

where

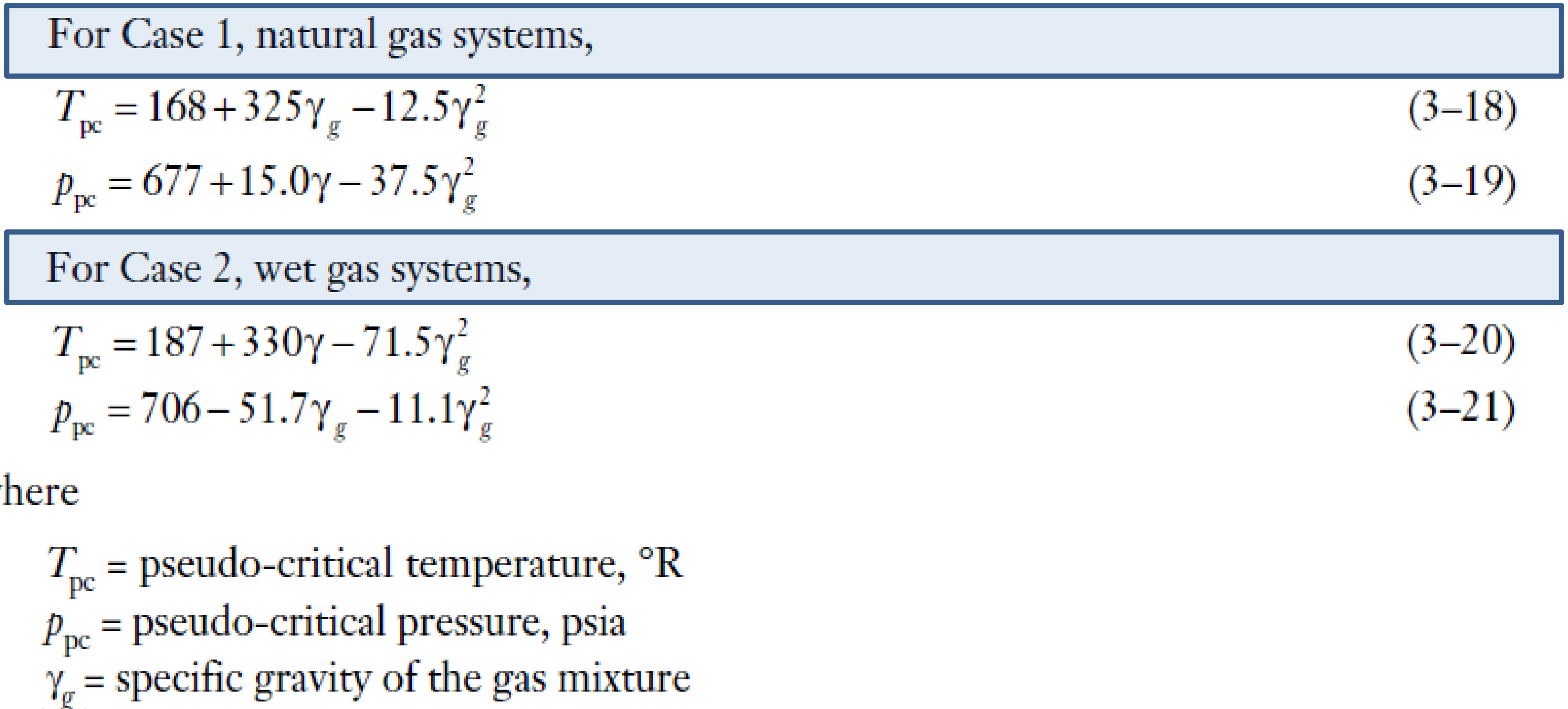
v = specific volume, ft^3/lb

ρ_g = density, lb/ft^3

Calculation of p_{pc} and T_{pc} (composition of gas is not available)

Pseudo-critical T&p - Brown et al. (1948)

In cases where the composition of a natural gas is not available, the pseudo-critical properties, p_{pc} and T_{pc}, can be predicted solely from the specific gravity of the gas. Brown et al. (1948) presented a graphical method for a convenient approximation of the pseudo-critical pressure and pseudo-critical temperature of gases when only the specific gravity of the gas is available. The correlation is presented in Figure 3–2. Standing (1977) expressed this graphical correlation in the following mathematical forms.



For Case 1, natural gas systems,

$$T_{pc} = 168 + 325\gamma_g - 12.5\gamma_g^2 \quad (3\text{–}18)$$

$$p_{pc} = 677 + 15.0\gamma - 37.5\gamma_g^2 \quad (3\text{–}19)$$

For Case 2, wet gas systems,

$$T_{pc} = 187 + 330\gamma - 71.5\gamma_g^2 \quad (3\text{–}20)$$

$$p_{pc} = 706 - 51.7\gamma_g - 11.1\gamma_g^2 \quad (3\text{–}21)$$

where

T_{pc} = pseudo-critical temperature, °R
p_{pc} = pseudo-critical pressure, psia
γ_g = specific gravity of the gas mixture

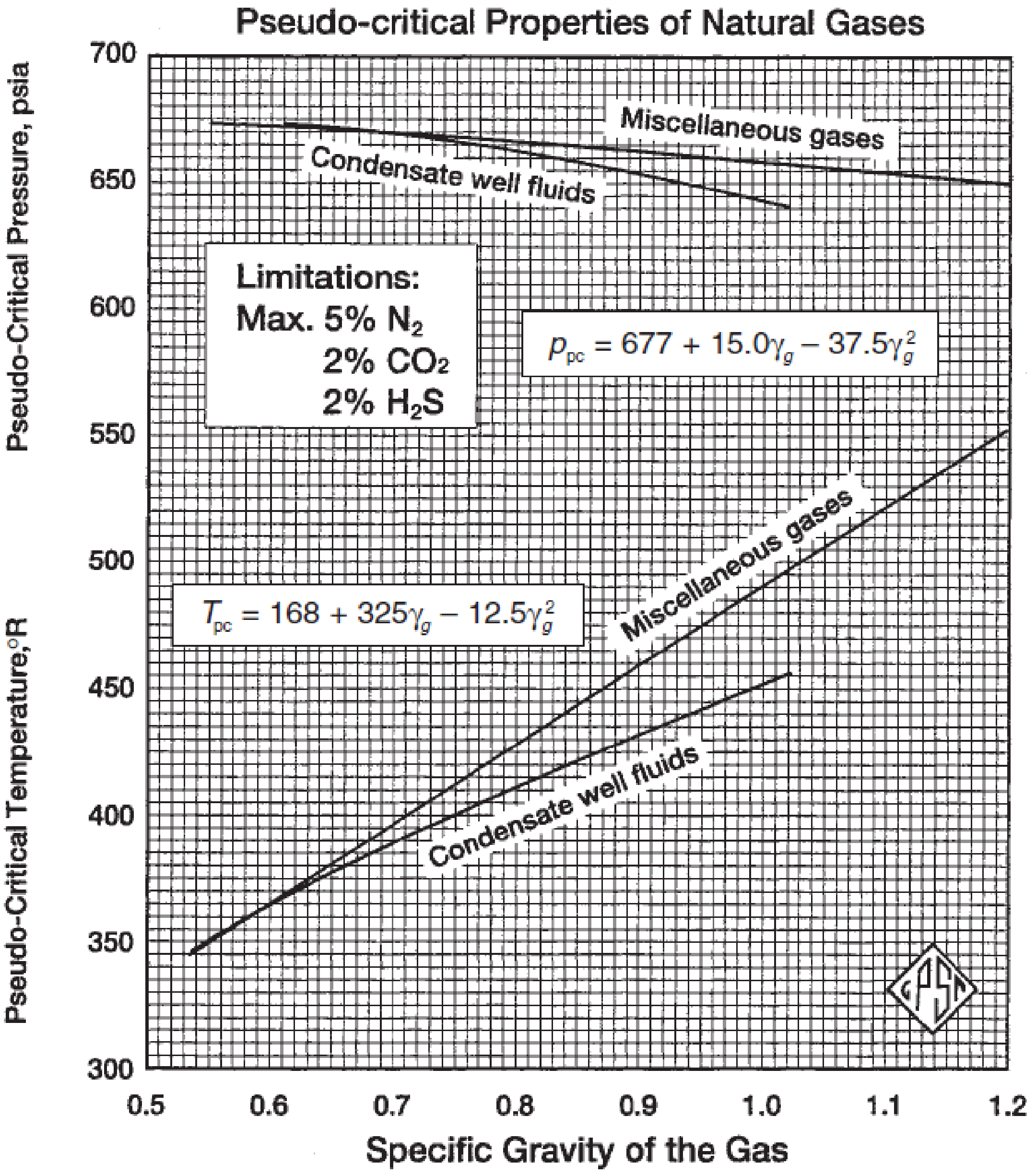


FIGURE 3–2 *Pseudo-critical properties for natural gases.*

Source: GPSA Engineering Data Book, 10th ed. Tulsa, OK: Gas Processors Suppliers Association, 1987. Courtesy of the Gas Processors Suppliers Association.

b. Without non-hydrocarbon component

Effect of Nonhydrocarbon Components on the Z-Factor

- Natural gases frequently contain materials other than hydrocarbon components, such as nitrogen, carbon dioxide, and hydrogen sulfide.
- Hydrocarbon gases are classified as sweet or sour depending on the hydrogen sulfide content.

- Both sweet and sour gases may contain nitrogen, carbon dioxide, or both.

- A hydrocarbon gas is termed a sour gas if it contains 1 grain of H2S per 100 cubic feet.

1 gram = 15 grains

- Concentrations of up to 5% of these non-hydrocarbon components do not seriously affect accuracy. Errors in compressibility factor calculations as large as 10% may occur in higher concentrations of non-hydrocarbon components in gas mixtures.

So we need make a correction in p_{pc} and T_{pc}

Non-hydrocarbon Adjustment Methods

1. Wichert-Aziz method
2. Carr-Kobayashi-Burrows

Wichert-Aziz correction method

This method permits the use of the Standing-Katz Z-factor chart (Figure 3–1), by using a pseudo-critical temperature adjustment factor ε, which is a function of the concentration of CO2 and H2S in the sour gas. This correction factor then is used to adjust the pseudo-critical temperature and pressure according to the following expressions:

$$T'_{pc} = T_{pc} - \varepsilon \tag{3–22}$$

$$p'_{pc} = \frac{p_{pc} T'_{pc}}{T_{pc} + B(1 - B)\varepsilon} \tag{3–23}$$

where

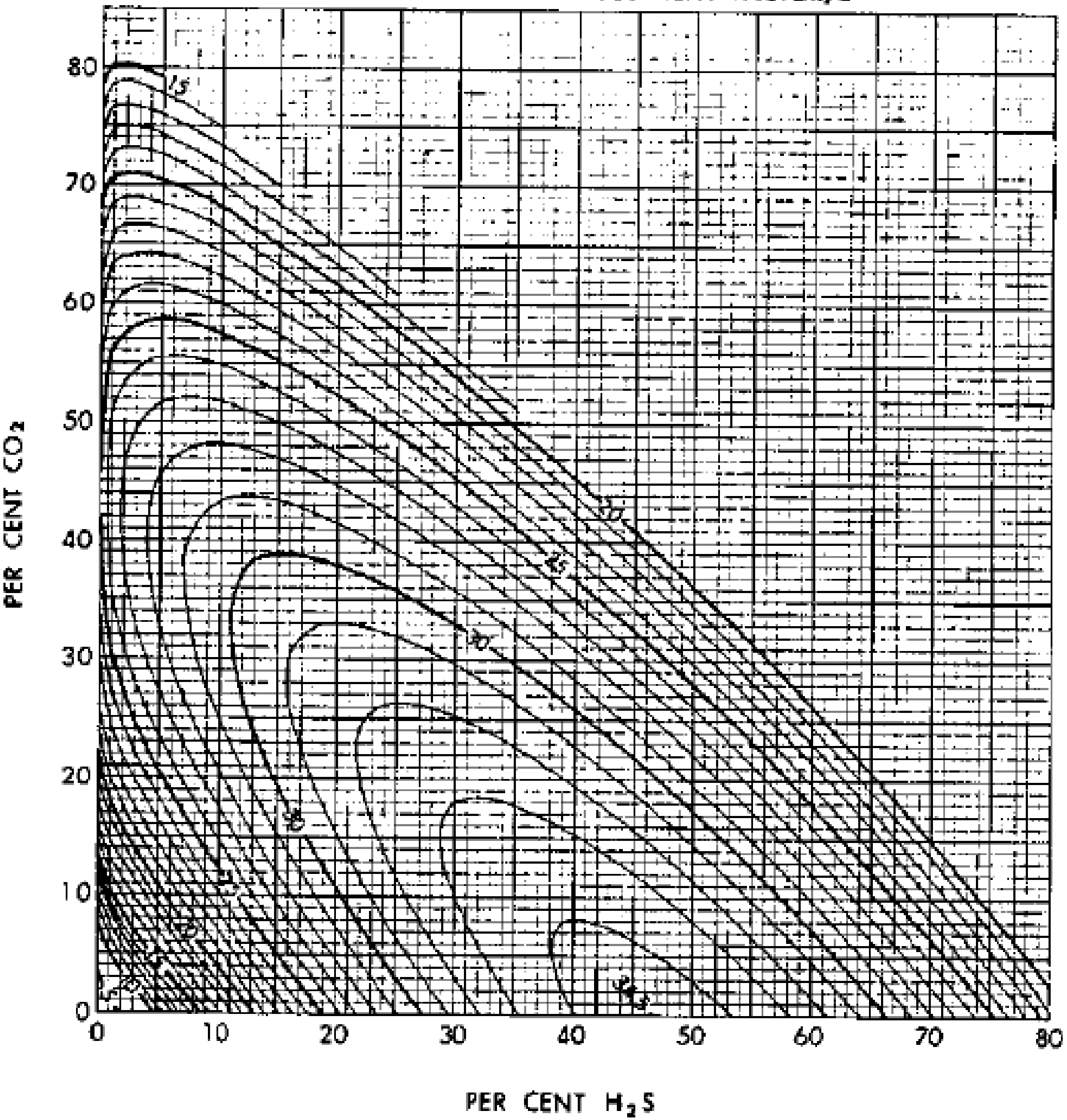
T_{pc} = pseudo-critical temperature, °R
p_{pc} = pseudo-critical pressure, psia
T'_{pc} = corrected pseudo-critical temperature, °R
p'_{pc} = corrected pseudo-critical pressure, psia
B = mole fraction of H_2S in the gas mixture
ε = pseudo-critical temperature adjustment factor, defined mathematically by the following expression:

$$\varepsilon = 120[A^{0.9} - A^{1.6}] + 15(B^{0.5} - B^{4.0}) \tag{3–24}$$

where the coefficient A is the sum of the mole fraction H_2S and CO_2 in the gas mixture:

$$A = y_{H_2S} + y_{CO_2}$$

PSEUDO - CRITICAL TEMPERATURE ADJUSTMENT FACTOR, ∈



Whitson and Brule (2000) Recommendation

Whitson and Brule (2000) point out that, when only the gas specific gravity and non-hydrocarbon content are known (including nitrogen, y_{N2}), the following procedure is recommended:

- Calculate hydrocarbon specific gravity γ_{gHC} (excluding the nonhydrocarbon components) from the following relationship:

$$\gamma_{gHC} = \frac{28.96\gamma_g - (y_{N_2}M_{N_2} + y_{CO_2}M_{CO_2} + y_{H_2S}M_{H_2S})}{28.96\,(1 - y_{N_2} - y_{CO_2} - y_{H_2S})}$$

- Using the calculated hydrocarbon specific gravity, γ_{gHC}, determine the pseudo-critical properties from equations (3–18) and (3–19):

$$(T_{pc})_{HC} = 168 + 325\gamma_{gHC} - 12.5\gamma_{gHC}^2$$

$$(p_{pc})_{HC} = 677 + 150\gamma_{gHC} - 37.5\gamma_{gHC}^2$$

- Adjust these two values to account for the nonhydrocarbon components by applying the following relationships:

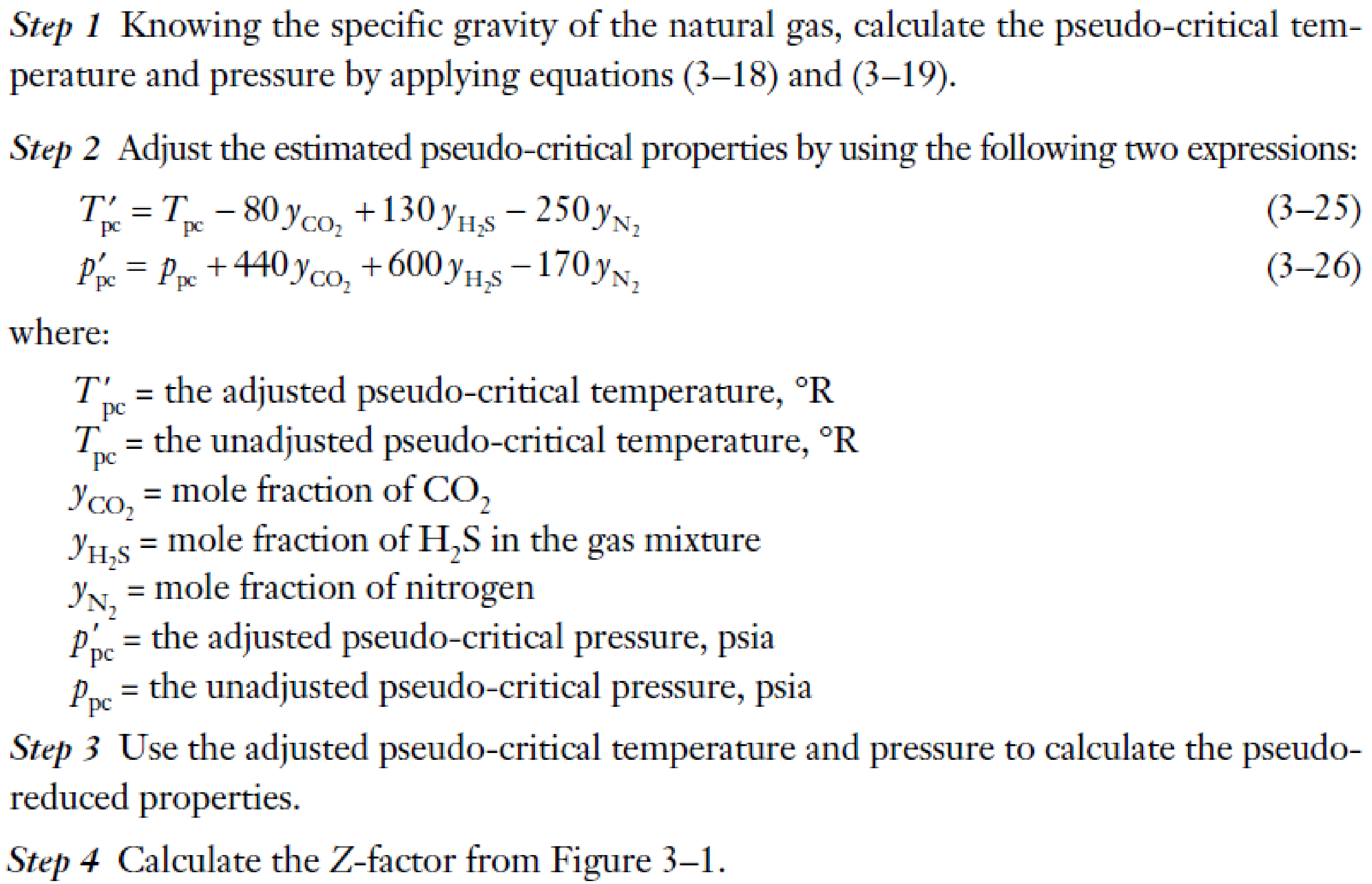
$$p_{pc} = (1 - y_{N_2} - y_{CO_2} - y_{H_2S})(p_{pc})_{HC} + y_{N_2}(p_c)_{N_2} + y_{CO_2}(p_c)_{CO_2} + y_{H_2S}(p_c)_{H_2S}$$

$$T_{pc} = (1 - y_{N_2} - y_{CO_2} - y_{H_2S})(T_{pc})_{HC} + y_{N_2}(T_c)_{N_2} + y_{CO_2}(T_c)_{CO_2} + y_{H_2S}(T_c)_{H_2S}$$

- Use the above calculated pseudo-critical properties in equations (3–22) and (3–23) to obtain the adjusted properties for Wichert-Aziz metod of calculating the Z-factor.

Carr-Kobayashi-Burrows's Correction Method

Carr, Kobayashi, and Burrows (1954) proposed a simplified procedure to adjust the pseudo-critical properties of natural gases when nonhydrocarbon components are present. The method can be used when the composition of the natural gas is not available. The proposed procedure is summarized in the following steps.



Step 1 Knowing the specific gravity of the natural gas, calculate the pseudo-critical temperature and pressure by applying equations (3–18) and (3–19).

Step 2 Adjust the estimated pseudo-critical properties by using the following two expressions:

$$T'_{pc} = T_{pc} - 80\,y_{CO_2} + 130\,y_{H_2S} - 250\,y_{N_2} \qquad (3\text{–}25)$$

$$p'_{pc} = p_{pc} + 440\,y_{CO_2} + 600\,y_{H_2S} - 170\,y_{N_2} \qquad (3\text{–}26)$$

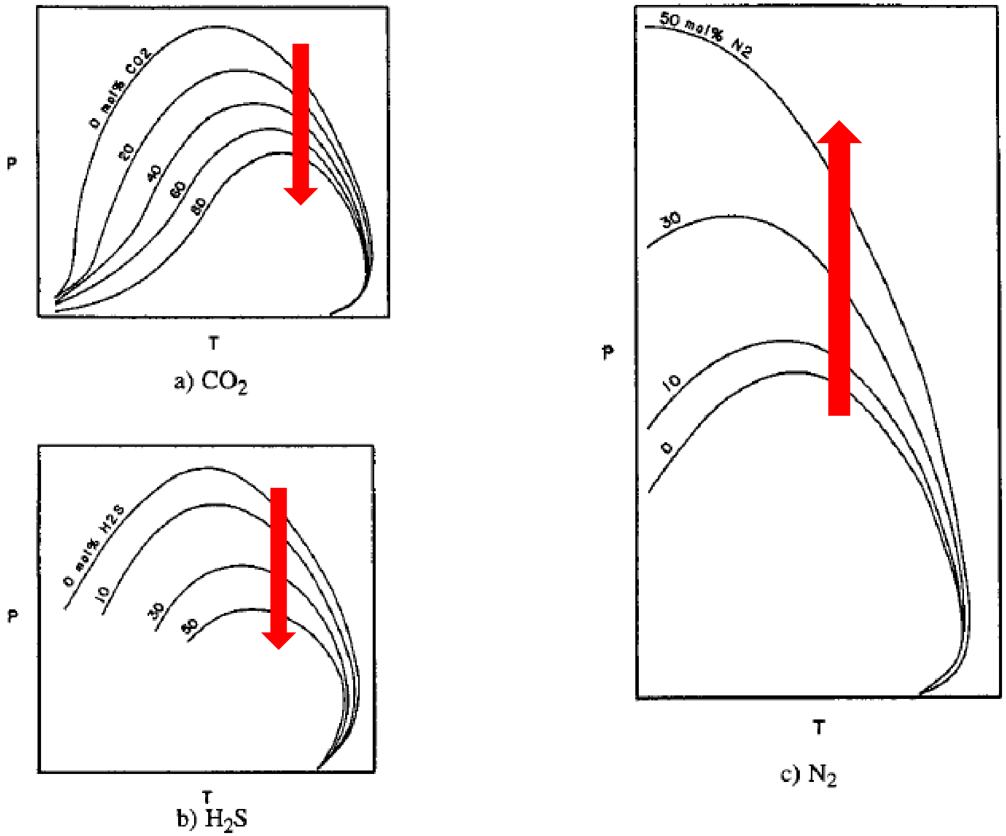
where:

T'_{pc} = the adjusted pseudo-critical temperature, °R
T_{pc} = the unadjusted pseudo-critical temperature, °R
y_{CO_2} = mole fraction of CO_2
y_{H_2S} = mole fraction of H_2S in the gas mixture
y_{N_2} = mole fraction of nitrogen
p'_{pc} = the adjusted pseudo-critical pressure, psia
p_{pc} = the unadjusted pseudo-critical pressure, psia

Step 3 Use the adjusted pseudo-critical temperature and pressure to calculate the pseudo-reduced properties.

Step 4 Calculate the *Z*-factor from Figure 3–1.

May be it is related to increases in polarity of gas that leads to more intendancy to liquefied



a) CO_2

b) H_2S

c) N_2

Figure 4.9 Effect of CO_2, H_2S, and N_2 on Natural Gas Phase Envelope

c. High-Molecular-Weight Gases (Correction)

It should be noted that the Standing and Katz Z-factor chart (Figure 3–1) was prepared from data on binary mixtures of methane with propane, ethane, and butane and on natural gases, thus covering a wide range in composition of hydrocarbon mixtures containing methane. No mixtures having molecular weights in excess of 40 were included in preparing this plot.

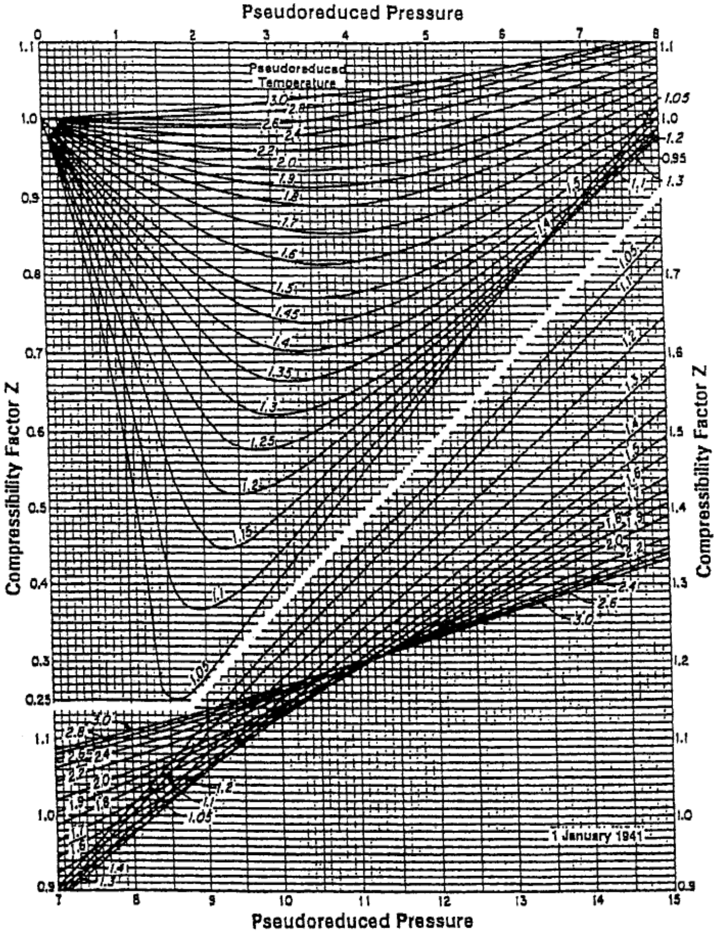


FIGURE 3–1 *Standing and Katz compressibility factors chart.*

Source: GPSA Engineering Data Book, 10th ed. Tulsa, OK: Gas Processors Suppliers Association, 1987. Courtesy of the Gas Processors Suppliers Association.

Correction for High-Molecular-Weight Gases

Problem: unsatisfactory Standing–Katz Z-factors (Fig 3-1) for high molecular-weight reservoir gases.

Sutton (1985) pointed out that Kay's mixing rules should not be used to determine the pseudo-critical pressure and temperature for reservoir gases with **specific gravities greater than about 0.75**.

Sutton proposed that this deviation can be minimized by utilizing the **mixing rules developed by Stewart, Burkhard, and Voo** (1959), together with newly introduced empirical adjustment factors (FJ, EJ, and EK) to account for the presence of the heptanes-plus fraction, C7+, in the gas mixture.

Step 1 Calculate the parameters *J* and *K* from the following relationships:

$$J = \frac{1}{3}\left[\sum_i y_i \left(\frac{T_{ci}}{p_{ci}}\right)\right] + \frac{2}{3}\left[\sum_i y_i \left(\frac{T_{ci}}{p_{ci}}\right)^{0.5}\right]^2 \tag{3–27}$$

$$K = \sum_i \frac{y_i T_{ci}}{\sqrt{p_{ci}}} \tag{3–28}$$

where

J = Stewart-Burkhardt-Voo correlating parameter, °R/psia
K = Stewart-Burkhardt-Voo correlating parameter, °R/psia
y_i = mole fraction of component *i* in the gas mixture

Step 2 Calculate the adjustment parameters F_J, E_J, and E_K from the following expressions:

$$F_J = \frac{1}{3}\left[y\left(\frac{T_c}{p_c}\right) + \frac{2}{3}\left(y\sqrt{\frac{T_c}{p_c}}\right)\right]^2_{C_{7+}} \tag{3–29}$$

$$E_J = 0.6081 F_J + 1.1325 F_J^2 - 14.004 F_J y_{C_{7+}}^2 \tag{3–30}$$

$$E_K = \left[\frac{T}{\sqrt{p_c}}\right]_{C_{7+}} - \left[0.3129 y_{C_{7+}} - 4.8156 (y_{C_{7+}})^2 + 27.3751 (y_{C_{7+}})^3\right] \tag{3–31}$$

where

$y_{C_{7+}}$ = mole fraction of the heptanes-plus component
$(T_c)_{C_{7+}}$ = critical temperature of the C_{7+}
$(p_c)_{C_{7+}}$ = critical pressure of the C_{7+}

Step 3 Adjust the parameters J and K by applying the adjustment factors E_J and E_K, according to these relationships:

$$J' = J - E_J \tag{3–32}$$

$$K' = K - E_K \tag{3–33}$$

where

J, K are calculated from equations (3–27) and (3–28)

E_J, E_K are calculated from equations (3–30) and (3–31)

Step 4 Calculate the adjusted pseudo-critical temperature and pressure from the expressions

$$T'_{\mathrm{pc}} = \frac{(K')^2}{J'} \tag{3–34}$$

$$p'_{\mathrm{pc}} = \frac{T'_{\mathrm{pc}}}{J'} \tag{3–35}$$

Step 5 Having calculated the adjusted T_{pc} and p_{pc}, the regular procedure of calculating the compressibility factor from the Standing and Katz chart is followed.

Direct Calculation of Compressibility Factors
Explicit Calculation

- ➢After four decades of existence, the Standing-Katz Z-factor chart is still widely used as a practical source of natural gas compressibility factors.
- ➢**Papay (1985)** proposed a simple expression for calculating the gas compressibility factor explicitly.

$$Z = 1 - \frac{3.53\,p_{pr}}{10^{0.9813T_{pr}}} + \frac{0.274\,p_{pr}^{2}}{10^{0.8157T_{pr}}}$$

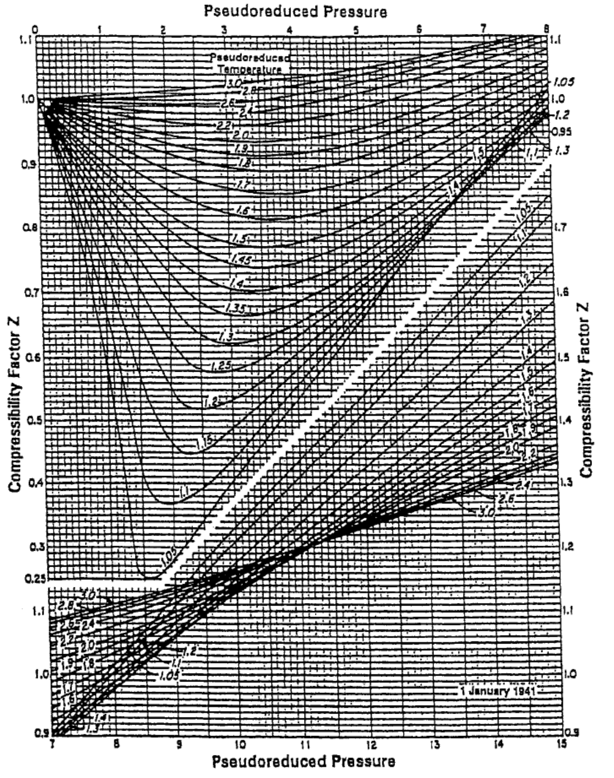


FIGURE 3–1 *Standing and Katz compressibility factors chart.*

Source: GPSA Engineering Data Book, 10th ed. Tulsa, OK: Gas Processors Suppliers Association, 1987. Courtesy of the Gas Processors Suppliers Association.

For example, at $p_{pr} = 3$ and $T_{pr} = 2$, the Z-factor from the preceding equation is

$$Z = 1 - \frac{3.53\,p_{pr}}{10^{0.9813T_{pr}}} + \frac{0.274\,p_{pr}^{2}}{10^{0.8157T_{pr}}} = 1 - \frac{3.53(3)}{10^{0.9813(2)}} + \frac{0.274(3)^{2}}{10^{0.8157(2)}} = 0.9422$$

as compared with value obtained from the Standing and Katz chart of 0.954.

Good approximation

Direct Calculation of Compressibility Factors Numerical Calculation

- Hall-Yarborough
- Dranchuk-Abu-Kassem
- Dranchuk-Purvis-Robinson

Hall-Yarborough's Method (1973)

- Hall and Yarborough pointed out that the method is not recommended for application if the pseudo-reduced temperature is less than 1.
- Hall and Yarborough proposed the following mathematical form:

$$Z = \left[\frac{0.06125 t p_{pr}}{Y} \right] \exp[-1.2(1-t)^2] \qquad (3\text{–}36)$$

?

where

p_{pr} = pseudo-reduced pressure
t = reciprocal of the pseudo-reduced temperature (i.e., T_{pc}/T)
Y = the reduced density, which can be obtained as the solution of the following equation:

$$F(Y) = X_1 + \frac{Y + Y^2 + Y^3 - Y^4}{(1 - Y)} - (X_2)Y^2 + (X_3)Y^{X_4} = 0 \qquad \Rightarrow Y = \checkmark \qquad (3\text{–}37)$$

where

$$X_1 = -0.06125 p_{pr} t \exp[-1.2(1 - t)^2]$$
$$X_2 = (14.76t - 9.76t^2 + 4.58t^3)$$
$$X_3 = (90.7t - 242.2t^2 + 42.4t^3)$$
$$X_4 = (2.18 + 2.82t)$$

Equation (3–37) is a nonlinear equation and can be solved conveniently for the reduced density **Y** by using the Newton-Raphson iteration technique. The computational procedure of solving equation (3–37) at any specified pseudo-reduced pressure, $\mathbf{p_{pr}}$, and temperature, $\mathbf{T_{pr}}$, is summarized in the following steps.

Step by step

Step 1 Make an initial guess of the unknown parameter, Y^k, where k is an iteration counter. An appropriate initial guess of Y is given by the following relationship:

$$Y^k = 0.0125\, p_{pr} t \exp[-1.2(1-\mathrm{t})^2]$$

Step 2 Substitute this initial value in equation (3–37) and evaluate the nonlinear function. Unless the correct value of Y has been initially selected, equation (3–37) will have a nonzero value of $f(Y)$.

Step 3 A new improved estimate of Y, that is, Y^{k+1}, is calculated from the following expression:

$$Y^{k+1} = Y^k - \frac{f(Y^k)}{f'(Y^k)} \tag{3–38}$$

where $f'(Y^k)$ is obtained by evaluating the derivative of equation (3–37) at Y^k, or

$$f'(Y) = \frac{1+4Y+4Y^2-4Y^3+Y^4}{(1-Y)^4} - 2(X_2)Y + (X_3)(X_4)Y^{(X_4-1)} \tag{3–39}$$

Step 4 Steps 2 and 3 are repeated n times until the error, that is, abs($Y^k - Y^{k+1}$), becomes smaller than a preset tolerance, say 10^{-12}.

Step 5 The correct value of Y is then used to evaluate equation (3–36) for the compressibility factor:

$$Z = \left[\frac{0.06125 t p_{pr}}{Y}\right] \exp[-1.2(1-t)^2]$$

Dranchuk and Abu-Kassem's Method (1975)

Dranchuk and Abu-Kassem (1975) derived an analytical expression for calculating the **reduced gas density** that can be used to estimate the gas compressibility factor. The reduced gas density ρ_r is defined as the ratio of the gas density at a specified pressure and temperature to that of the gas at its critical pressure or temperature:

$$\rho_r = \frac{\rho}{\rho_c} = \frac{[pM_a/(ZRT)]}{[p_cM_a/(Z_cRT_c)]} = \frac{[p/(ZT)]}{[p_c/(Z_cT_c)]}$$

The critical gas compressibility factor Z_c is approximately 0.27, which leads to the following simplified expression for the reduced gas density as expressed in terms of the reduced temperature T_r and reduced pressure p_r:

$$\boxed{\rho_r = \frac{0.27\,p_{pr}}{ZT_{pr}}} \qquad (3\text{–}40)$$

If ρ_r =✓ → Z=✓

The authors proposed the following 11-constant equation of state for calculating the reduced gas density:

$$f(\rho_r) = (R_1)\rho_r - \frac{R_2}{\rho_r} + (R_3)\rho_r^2 - (R_4)\rho_r^5 + (R_5)\left(1 + A_{11}\rho_r^2\right)\rho_r^2 \exp\left[-A_{11}\rho_r^2\right] + 1 = 0 \qquad (3\text{–}41)$$

with the coefficients R_1 through R_5 as defined by the following relations:

$$R_1 = A_1 + \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^3} + \frac{A_r}{T_{pr}^4} + \frac{A_t}{T_{pr}^5}$$

$$R_2 = \frac{0.27\, p_{pr}}{T_{pr}}$$

$$R_3 = A_6 + \frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2}$$

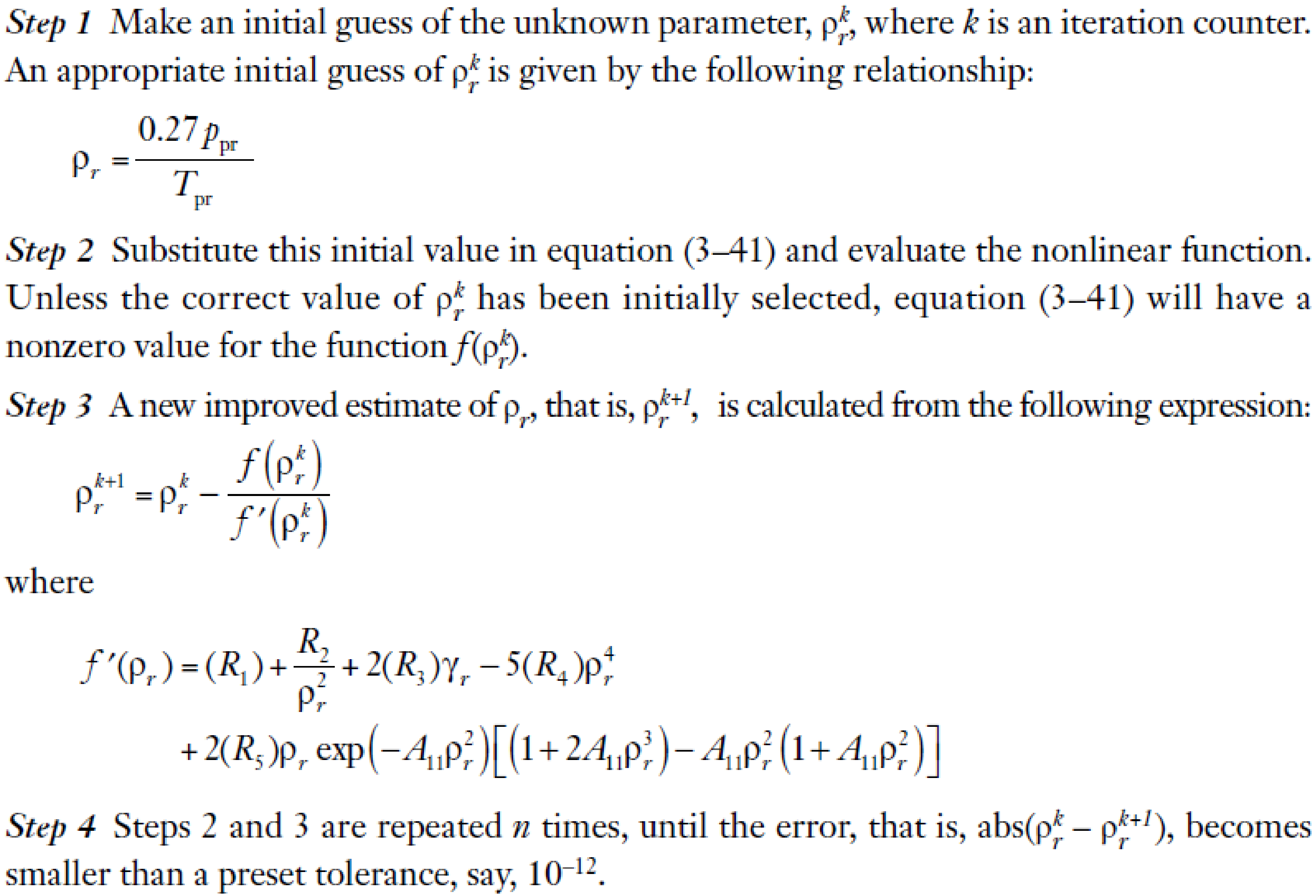
$$R_4 = A_9 \left[\frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2} \right]$$

$$R_5 = \left[\frac{A_{10}}{T_{pr}^3} \right]$$

The constants A_1 through A_{11} were determined by fitting the equation, using nonlinear regression models, to 1500 data points from the Standing and Katz Z-factor chart. The coefficients have the following values:

$A_1 = 0.3265$
$A_2 = -1.0700$
$A_3 = -0.5339$
$A_4 = 0.01569$
$A_5 = -0.05165$
$A_6 = 0.5475$
$A_7 = -0.7361$
$A_8 = 0.1844$
$A_9 = 0.1056$
$A_{10} = 0.6134$
$A_{11} = 0.7210$

Equation (3–41) can be solved for the reduced gas density ρ_r by applying the Newton- Raphson iteration technique as summarized in the following steps.



Step 1 Make an initial guess of the unknown parameter, ρ_r^k, where k is an iteration counter. An appropriate initial guess of ρ_r^k is given by the following relationship:

$$\rho_r = \frac{0.27\, p_{\text{pr}}}{T_{\text{pr}}}$$

Step 2 Substitute this initial value in equation (3–41) and evaluate the nonlinear function. Unless the correct value of ρ_r^k has been initially selected, equation (3–41) will have a nonzero value for the function $f(\rho_r^k)$.

Step 3 A new improved estimate of ρ_r, that is, ρ_r^{k+1}, is calculated from the following expression:

$$\rho_r^{k+1} = \rho_r^k - \frac{f\left(\rho_r^k\right)}{f'\left(\rho_r^k\right)}$$

where

$$f'(\rho_r) = (R_1) + \frac{R_2}{\rho_r^2} + 2(R_3)\gamma_r - 5(R_4)\rho_r^4$$
$$+ 2(R_5)\rho_r \exp\left(-A_{11}\rho_r^2\right)\left[\left(1 + 2A_{11}\rho_r^3\right) - A_{11}\rho_r^2\left(1 + A_{11}\rho_r^2\right)\right]$$

Step 4 Steps 2 and 3 are repeated n times, until the error, that is, $\text{abs}(\rho_r^k - \rho_r^{k+1})$, becomes smaller than a preset tolerance, say, 10^{-12}.

Step 5 The correct value of ρ_r is then used to evaluate equation (3–40) for the compressibility factor:

$$Z = \frac{0.27\, p_{pr}}{\rho_r T_{pr}}$$

The proposed correlation was reported to duplicate compressibility factors from the Standing and Katz chart with an average absolute error of 0.585% and is applicable over the ranges

$$0.2 \le p_{pr} < 30$$
$$1.0 < T_{pr} \le 3.0$$

Dranchuk-Purvis-Robinson Method (1974)

Dranchuk, Purvis, and Robinson (1974) developed a correlation based on the Benedict-Webb-Rubin type of equation of state. Fitting the equation to 1500 data points from the Standing and Katz Z-factor chart optimized the eight coefficients of the proposed equations.

The equation has the following form:

$$1 + T_1\rho_r + T_2\rho_r^2 + T_3\rho_r^5 + \left[T_4\rho_r^2\left(1 + A_8\rho_r^2\right)\exp\left(-A_8\rho_r^2\right)\right] - \frac{T_5}{\rho_r} = 0 \qquad (3\text{–}42)$$

with

$$T_1 = A_1 + \frac{A_2}{T_{\mathrm{pr}}} + \frac{A_3}{T_{\mathrm{pr}}^3}$$

$$T_2 = A_4 + \frac{A_5}{T_{\mathrm{pr}}}$$

$$T_3 = \frac{A_5 A_6}{T_{\mathrm{pr}}}$$

$$T_4 = \frac{A_7}{T_{\mathrm{pr}}^3}$$

$$T_5 = \frac{0.27\, p_{\mathrm{pr}}}{T_{\mathrm{pr}}}$$

where ρ_r is defined by equation (3–41) and the coefficients A_1 through A_8 have the following values:

$$\begin{array}{ll} A_1 = 0.31506237 & A_5 = 0.31506237 \\ A_2 = -1.0467099 & A_6 = -1.0467099 \\ A_3 = -0.57832720 & A_7 = -0.57832720 \\ A_4 = 0.53530771 & A_8 = 0.53530771 \end{array}$$

The solution procedure of equation (3–43) is similar to that of Dranchuk and Abu-Kassem.

The method is valid within the following ranges of pseudo-reduced temperature and pressure:

$$1.05 \le T_{pr} < 3.0$$
$$0.2 \le p_{pr} \le 3.0$$

Compressibility of Natural Gases

$$c_g = \frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T \tag{3–43}$$

where c_g = isothermal gas compressibility, 1/psi.

From the real gas equation of state,

$$V = \frac{nRTZ}{p}$$

n, R, are constant, Z depends on P=Pr. Ppc

Differentiating this equation with respect to pressure at constant temperature T, gives

$$\left(\frac{\partial V}{\partial p}\right) = nRT\left[\frac{1}{p}\left(\frac{\partial Z}{\partial p}\right) - \frac{Z}{p^2}\right]$$

Substituting into equation (3–43) produces the following generalized relationship:

$$c_g = \frac{1}{p} - \frac{1}{Z}\left(\frac{\partial Z}{\partial p}\right)_T \tag{3–44}$$

But how can I calculate $\left(\frac{\partial Z}{\partial p}\right)_T$?any idea?

For an ideal gas, $Z = 1$ and $(\partial Z/\partial p)_T = 0$; therefore,

$$c_g = \frac{1}{p} \tag{3–45}$$

So it is valid only in very very low pressure NOT high pressure

It should be pointed out that equation (3–45) is useful in determining the expected order of magnitude of the isothermal gas compressibility.

Equation (3–44) can be conveniently expressed in terms of the pseudo-reduced pressure and temperature by simply replacing **p** with (**p_{pr} p_{pc}**):

$$c_g = \frac{1}{p} - \frac{1}{Z}\left(\frac{\partial Z}{\partial p}\right)_T$$

$$c_g = \frac{1}{p_{pr}\, p_{pc}} - \frac{1}{Z}\left[\frac{\partial Z}{\partial (p_{pr}\, p_{pc})}\right]_{T_{pr}}$$

Multiplying this equation by p_{pc} yields

$$c_g\, p_{pc} = c_{pr} = \frac{1}{p_{pr}} - \frac{1}{Z}\left[\frac{\partial Z}{\partial p_{pr}}\right]_{T_{pr}} \tag{3–46}$$

The term c_{pr} is called the *isothermal pseudo-reduced compressibility*, defined by the relationship:

$$c_{pr} = c_g\, p_{pc} \tag{3–47}$$

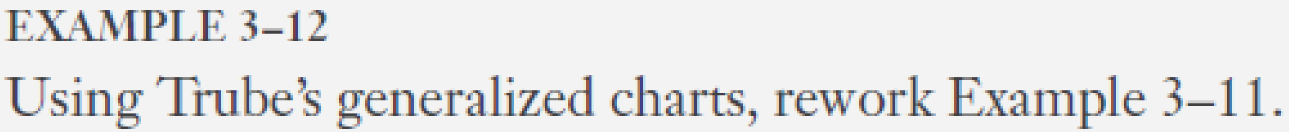
where

c_{pr} = isothermal pseudo-reduced compressibility
c_g = isothermal gas compressibility, psi^{-1}
p_{pc} = pseudo-reduced pressure, psi

Values of $(\partial z / \partial p_{pr})_{T_{pr}}$ can be calculated from the slope of the T_{pr} isotherm on the Standing and Katz *Z*-factor chart.

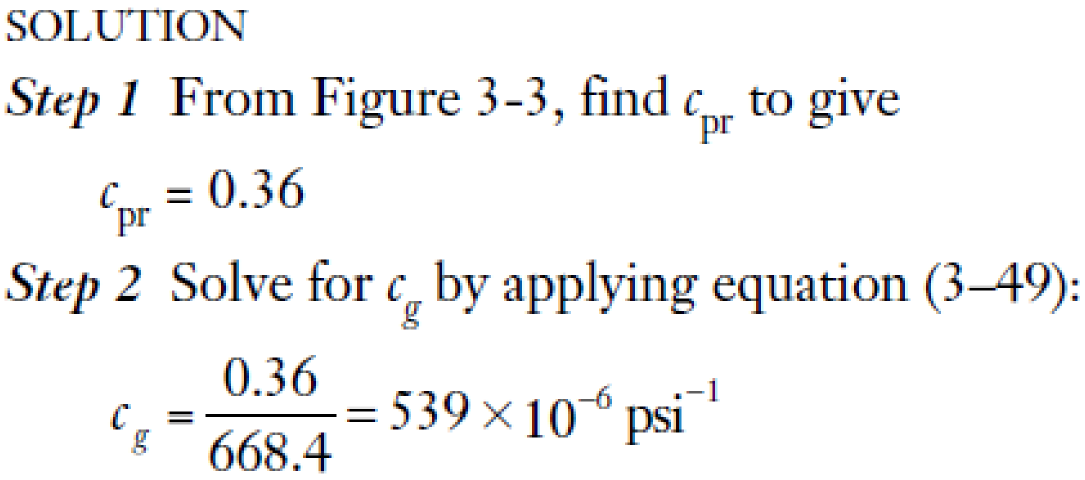
Compressibility of Natural Gases
Trube (1957a and 1957b)

Trube (1957a and 1957b) presented graphs from which the isothermal compressibility of natural gases may be obtained. The graphs, Figures 3–3 and 3–4, give the isothermal pseudo-reduced compressibility as a function of pseudo-reduced pressure and temperature.



EXAMPLE 3–12

Using Trube's generalized charts, rework Example 3–11.



SOLUTION

Step 1 From Figure 3-3, find c_{pr} to give

$$c_{pr} = 0.36$$

Step 2 Solve for c_g by applying equation (3–49):

$$c_g = \frac{0.36}{668.4} = 539 \times 10^{-6}\ \text{psi}^{-1}$$

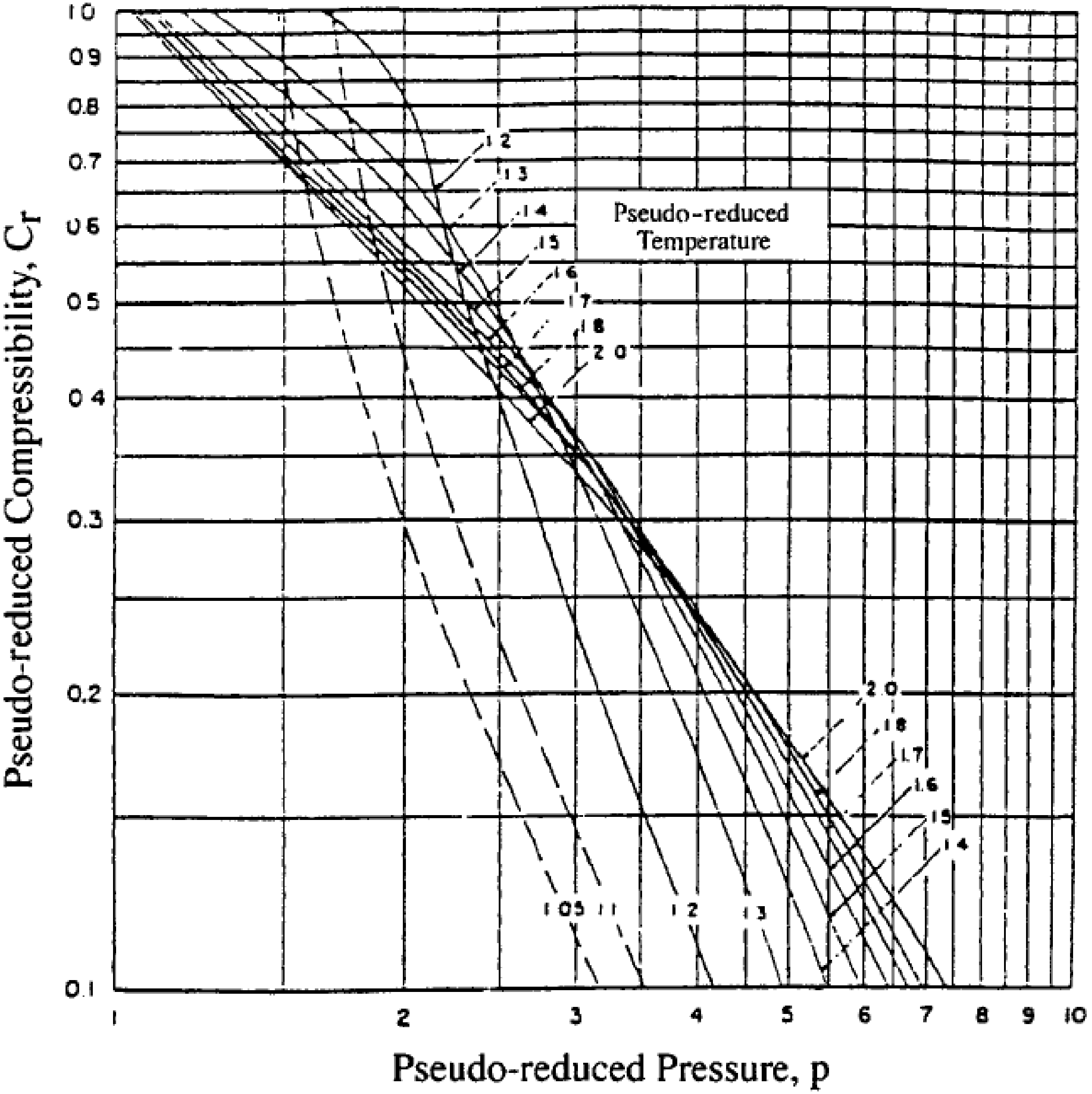


FIGURE 3–3 *Trube's pseudo-reduced compressibility for natural gases.*

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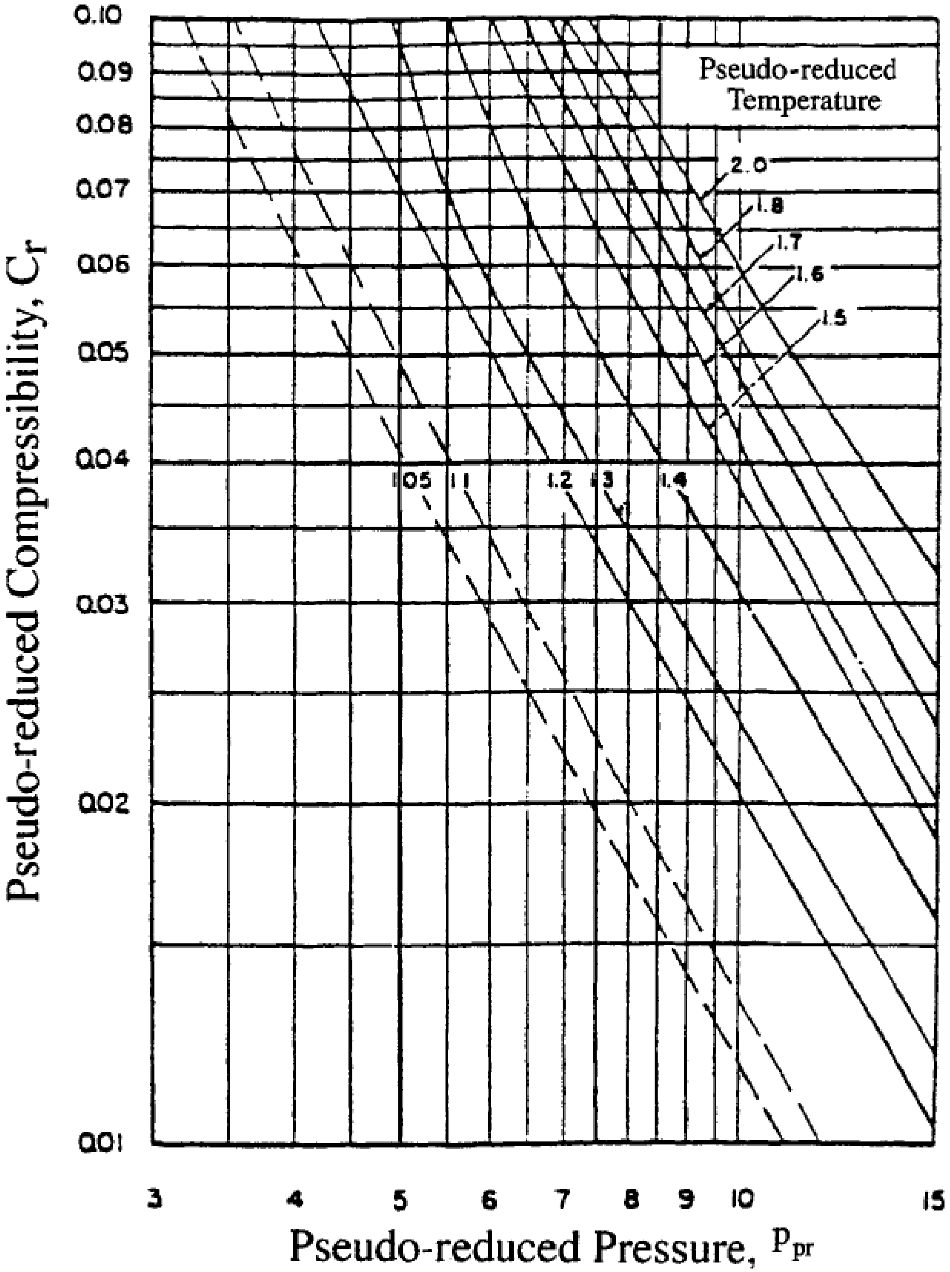

FIGURE 3–4 *Trube's pseudo-reduced compressibility for natural gases.*
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Compressibility of Natural Gases
Mattar, Brar, and Aziz (1975)

Mattar, Brar, and Aziz (1975) presented an analytical technique for calculating the isothermal gas compressibility. The authors expressed c_{pr} as a function of $\partial p/\partial \rho_r$ rather than $\partial p/\partial p_{pr}$.

Equation (3–41) is differentiated with respect to p_{pr} to give

$$\frac{\partial Z}{\partial p_{pr}} = \frac{0.27}{Z^2 T_{pr}} \left[\frac{(\partial Z/\partial \rho_r)_{T_{pr}}}{1 + \frac{\rho_r}{Z}(\partial Z/\partial \rho_r)_{T_{pr}}} \right] \tag{3–48}$$

Equation (3–48) may be substituted into equation (3–46) to express the pseudo-reduced compressibility as

$$c_{pr} = \frac{1}{p_r} - \frac{0.27}{Z^2 T_{pr}} \left[\frac{(\partial Z/\partial \rho_r)_{T_{pr}}}{1 + \frac{\rho_r}{Z}(\partial Z/\partial \rho_r)_{T_{pr}}} \right] \tag{3–49}$$

where ρ_r = pseudo-reduced gas density.

The partial derivative appearing in equation (3–49) is obtained from equation (3–42) to give

$$\left[\frac{\partial Z}{\partial \rho_r}\right]_{T_{pr}} = T_1 + 2T_2\rho_r + 5T_3\rho_r^4 + 2T_4\rho_r\left(1 + A_8\rho_r^2 - A_8^2\rho_r^4\right)\exp\left(-A_8\rho_r^2\right) \tag{3–50}$$

where the coefficients T1 through T4 and A1 through A8 are as defined previously by equation (3–42).

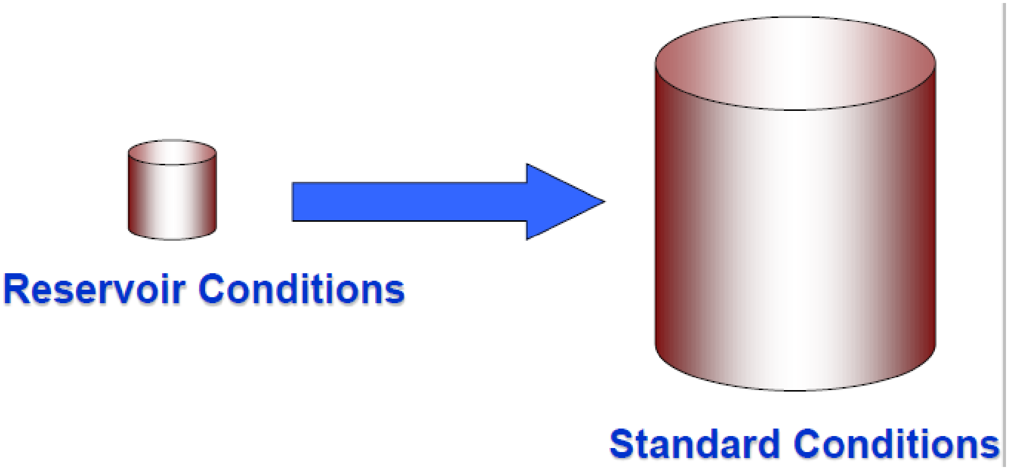
Gas Formation Volume Factor

The gas formation volume factor is used to relate the volume of gas, as measured at reservoir conditions, to the volume of the gas as measured at standard conditions, that is, 60°F and 14.7 psia.

$$B_g = \frac{(V)_{p,T}}{V_{sc}} \tag{3–51}$$

where

B_g = gas formation volume factor, ft^3/scf
$V_{p,T}$ = volume of gas at pressure p and temperature T, ft^3
V_{sc} = volume of gas at standard conditions



Reservoir Conditions

Standard Conditions

Applying the real gas equation of state, equation (3–11), and substituting for the volume V, gives

$$B_g = \frac{\frac{ZnRT}{p}}{\frac{Z_{sc}nRT_{sc}}{p_{sc}}} = \frac{p_{sc}}{T_{sc}}\frac{ZT}{p}$$

where

Z_{sc} = Z-factor at standard conditions = 1.0
p_{sc}, T_{sc} = standard pressure and temperature

Assuming that the standard conditions are represented by p_{sc} = 14.7 psia and T_{sc} = 520, the preceding expression can be reduced to the following relationship:

$$B_g = 0.02827\frac{ZT}{p} \qquad (3\text{–}52)$$

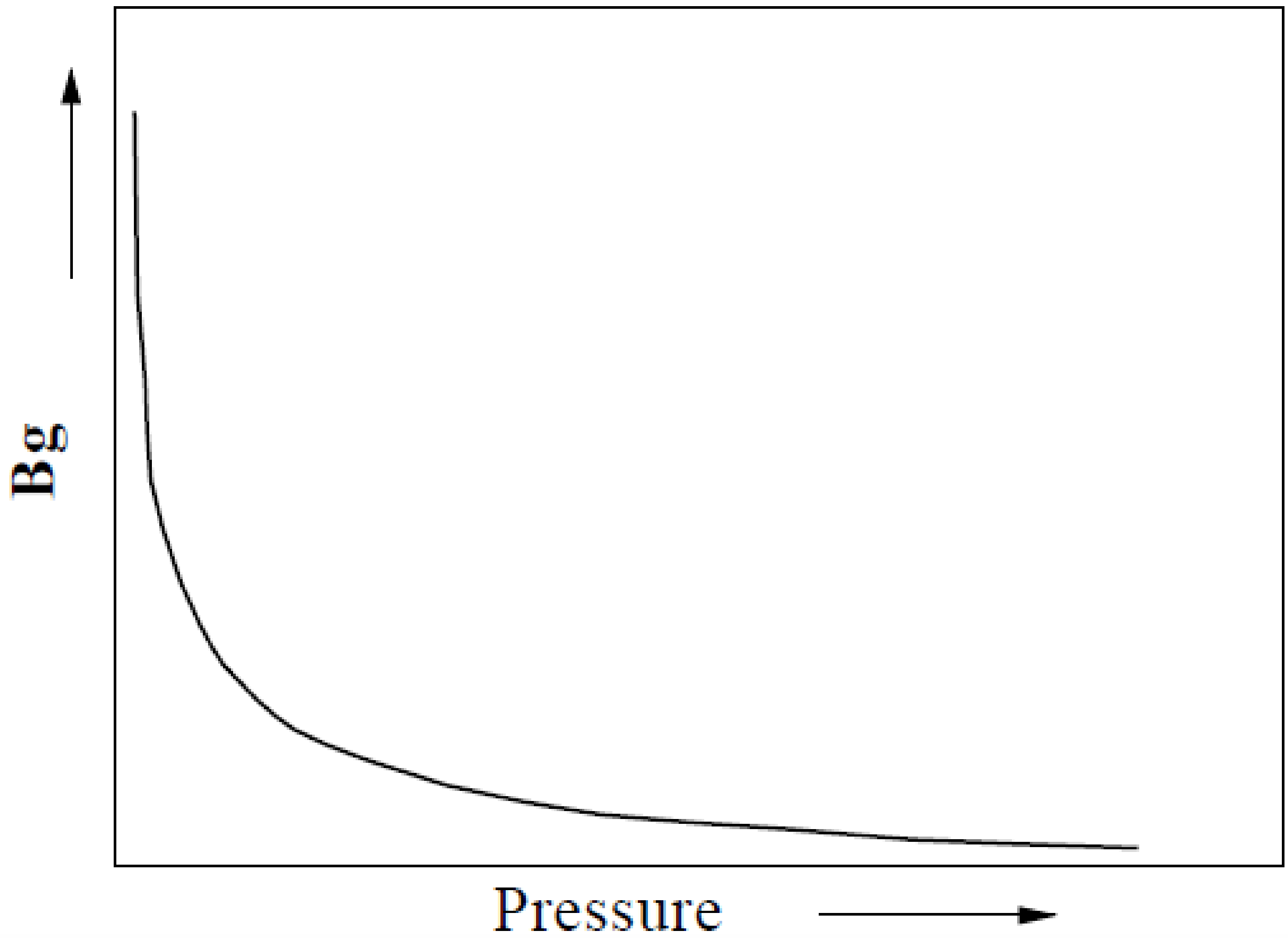
Z??

where

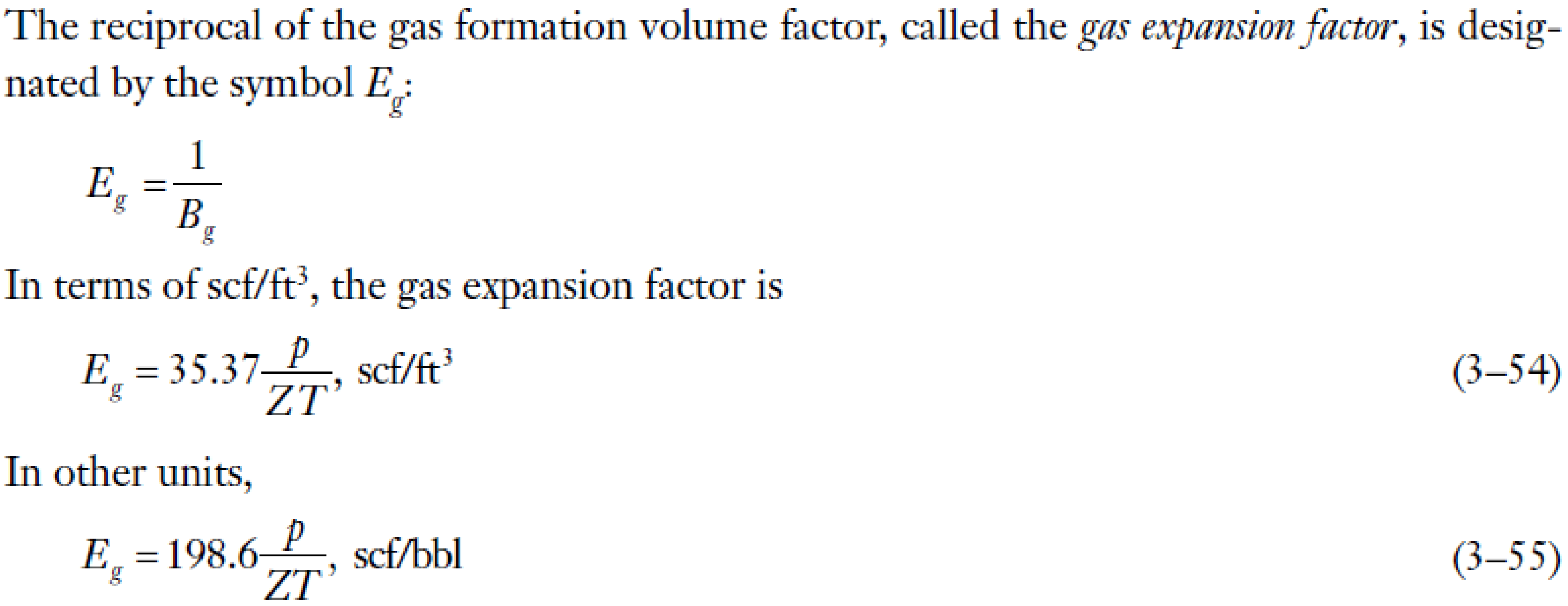
B_g = gas formation volume factor, ft^3/scf
Z = gas compressibility factor
T = temperature, °R

In other field units, the gas formation volume factor can be expressed in bbl/scf, to give

$$B_g = 0.005035\frac{ZT}{p} \qquad (3\text{–}53)$$


Bg
Pressure

Gas Expansion Factor



The reciprocal of the gas formation volume factor, called the *gas expansion factor*, is designated by the symbol E_g:

$$E_g = \frac{1}{B_g}$$

In terms of scf/ft³, the gas expansion factor is

$$E_g = 35.37 \frac{p}{ZT}, \text{ scf/ft}^3 \qquad (3\text{–}54)$$

In other units,

$$E_g = 198.6 \frac{p}{ZT}, \text{ scf/bbl} \qquad (3\text{–}55)$$

Useful Relations

It is also convenient in many engineering calculations to express the gas density in terms of the B_g or E_g. From the definitions of gas density, the gas expansion factor, and gas formation volume factor,

$$\boxed{\rho_g} = \frac{M_a}{R}\left(\frac{p}{ZT}\right)$$

$$\boxed{B_g} = \frac{p_{sc}}{T_{sc}}\left(\frac{ZT}{P}\right)$$

$$\boxed{E_g} = \frac{T_{sc}}{p_{sc}}\left(\frac{p}{ZT}\right)$$

After calculation of Z using one of mentioned methods

Combining the gas density equation with B_g and E_g gives

$$\boxed{\rho_g = \frac{p_{sc} M_a}{T_{sc} R}\left(\frac{1}{B_g}\right) = \frac{0.002635 M_a}{B_g}}$$

$$\rho_g = \frac{p_{sc} M_a}{T_{sc} R}\left(E_g\right) = 0.002635 M_a E_g$$

Gas Viscosity

➢The viscosity of a fluid is a measure of the internal fluid friction (resistance) to flow.

➢Viscosity is the ratio of the shear force per unit area to the local velocity gradient.

$$\begin{aligned}1 \text{ poise} &= 100 \text{ centipoises}\\ &= 1 \times 10^{6} \text{ micropoises}\\ &= 6.72 \times 10^{-2} \text{ lb mass/ft-sec}\\ &= 20.9 \times 10^{-3} \text{ lbf-sec/ft}^{2}\end{aligned}$$

The gas viscosity is not commonly measured in the laboratory because it can be estimated precisely (accurately) from empirical correlations.

$$\mu_g = (p, T, y_i)$$

popular methods that are commonly used in the petroleum industry are:

1. First calculate Atmospheric Viscosity

✓ Carr-Kobayashi-Burrows atmosperic chart

or

✓ Standing correlation

Next

✓ Carr-Kobayashi-Burrow ratio chart

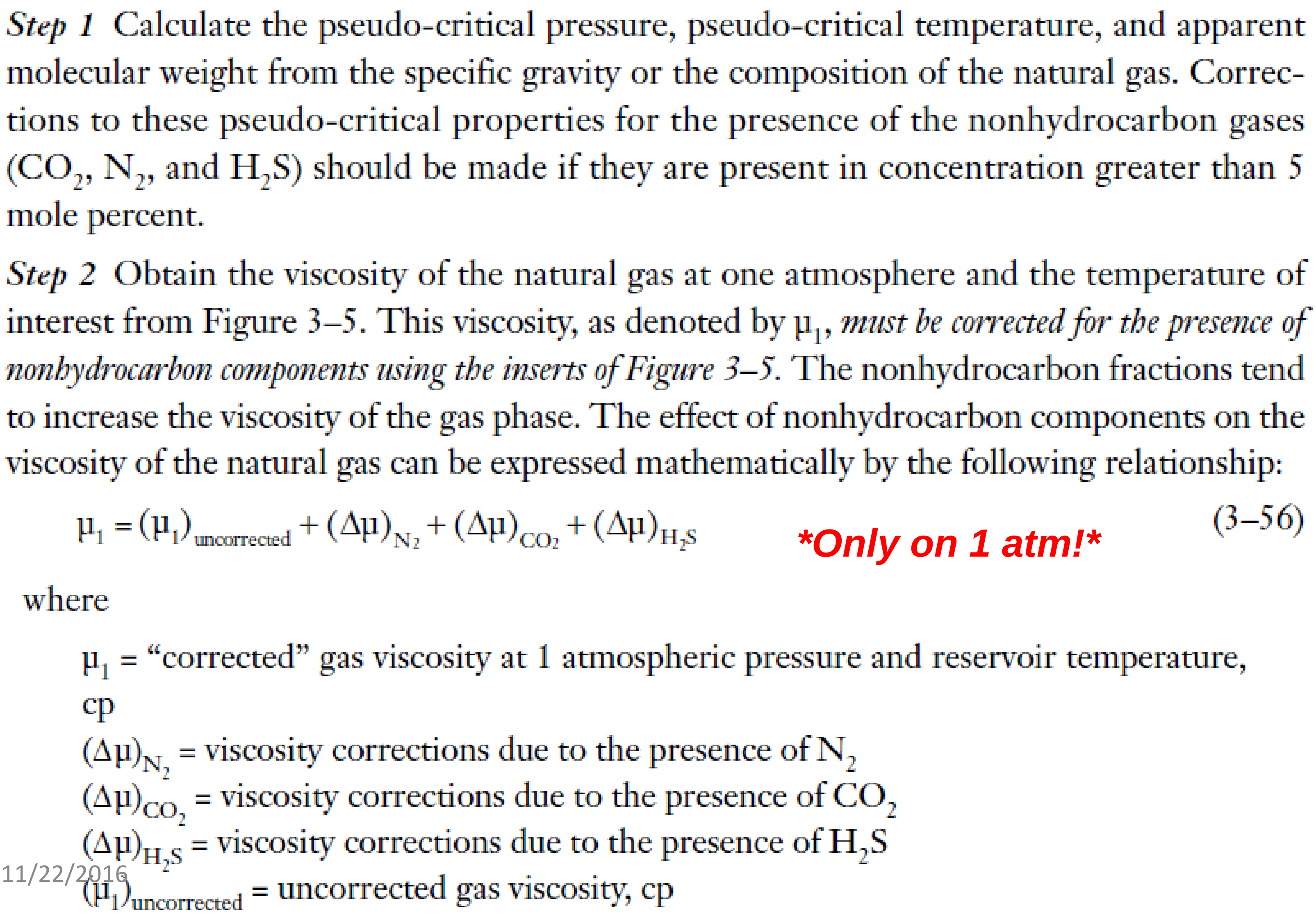
or

✓ Dempsey ratio correlation

1. Lee-Gonzalez-Eakin method

Carr, Kobayashi, and Burrows (1954)

A graphical correlations for estimating the viscosity of natural gas as a function of temperature, pressure, and gas gravity.



Step 1 Calculate the pseudo-critical pressure, pseudo-critical temperature, and apparent molecular weight from the specific gravity or the composition of the natural gas. Corrections to these pseudo-critical properties for the presence of the nonhydrocarbon gases (CO_2, N_2, and H_2S) should be made if they are present in concentration greater than 5 mole percent.

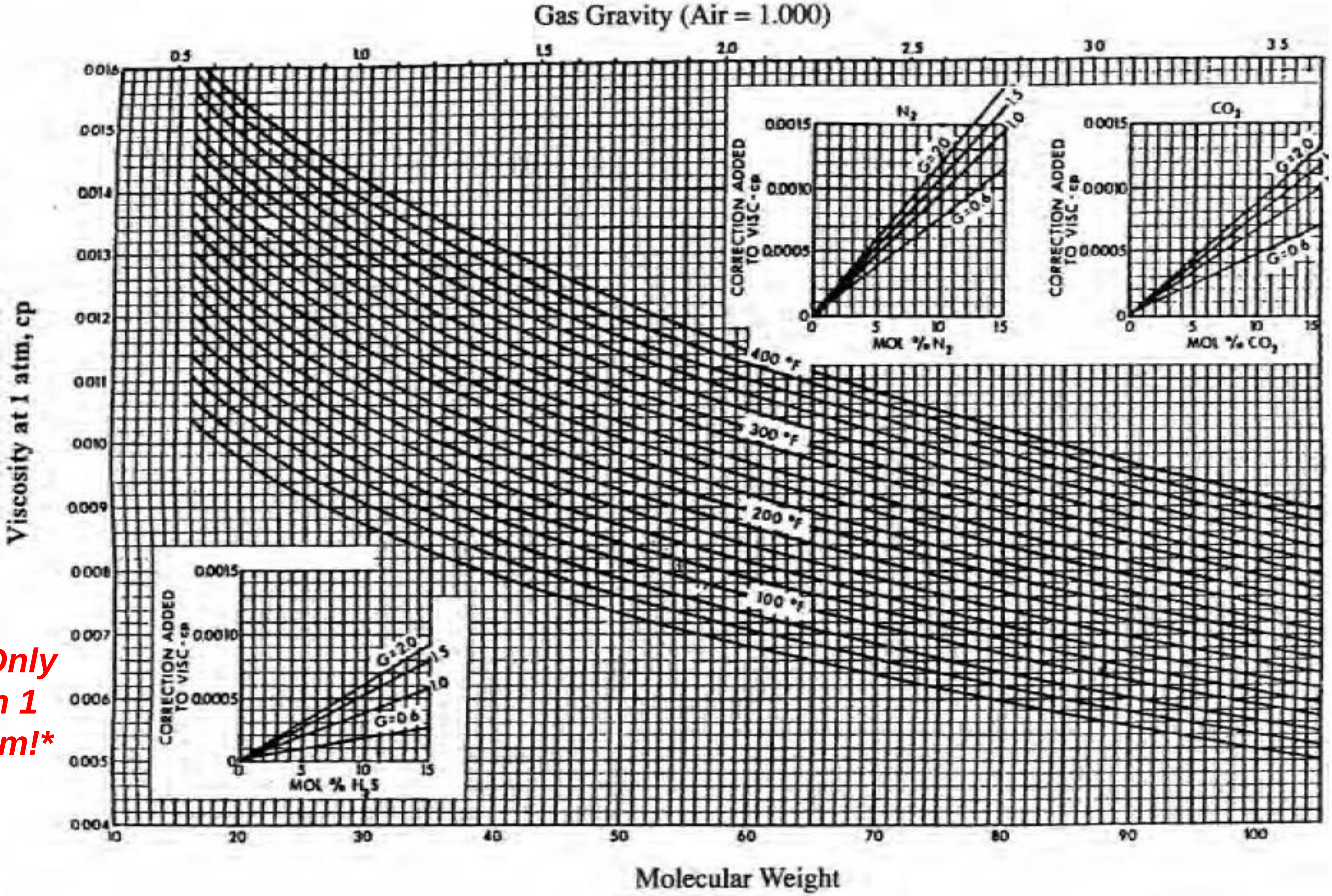
Step 2 Obtain the viscosity of the natural gas at one atmosphere and the temperature of interest from Figure 3–5. This viscosity, as denoted by μ_1, *must be corrected for the presence of nonhydrocarbon components using the inserts of Figure 3–5*. The nonhydrocarbon fractions tend to increase the viscosity of the gas phase. The effect of nonhydrocarbon components on the viscosity of the natural gas can be expressed mathematically by the following relationship:

$$\mu_1 = (\mu_1)_{\text{uncorrected}} + (\Delta\mu)_{N_2} + (\Delta\mu)_{CO_2} + (\Delta\mu)_{H_2S} \tag{3–56}$$

Only on 1 atm!

where

μ_1 = "corrected" gas viscosity at 1 atmospheric pressure and reservoir temperature, cp
$(\Delta\mu)_{N_2}$ = viscosity corrections due to the presence of N_2
$(\Delta\mu)_{CO_2}$ = viscosity corrections due to the presence of CO_2
$(\Delta\mu)_{H_2S}$ = viscosity corrections due to the presence of H_2S
$(\mu_1)_{\text{uncorrected}}$ = uncorrected gas viscosity, cp



Only on 1 atm!

FIGURE 3–5 *Carr et al.'s atmospheric gas viscosity correlation.*

Source: Carr et al., "Viscosity of Hydrocarbon Gases under Pressure," *Transactions of the AIME* 201 (1954): 270–275. Permission to publish from the Society of Petroleum Engineers of the AIME. © SPE-AIME.

Step 3 Calculate the pseudo-reduced pressure and temperature.

Step 4 From the pseudo-reduced temperature and pressure, obtain the viscosity ratio (μ_g/μ_1) from Figure 3-6. The term μ_g represents the viscosity of the gas at the required conditions.

Step 5 The gas viscosity, μ_g, at the pressure and temperature of interest, is calculated by multiplying the viscosity at 1 atmosphere and system temperature, μ_1, by the viscosity ratio.

The following examples illustrate the use of the proposed graphical correlations.

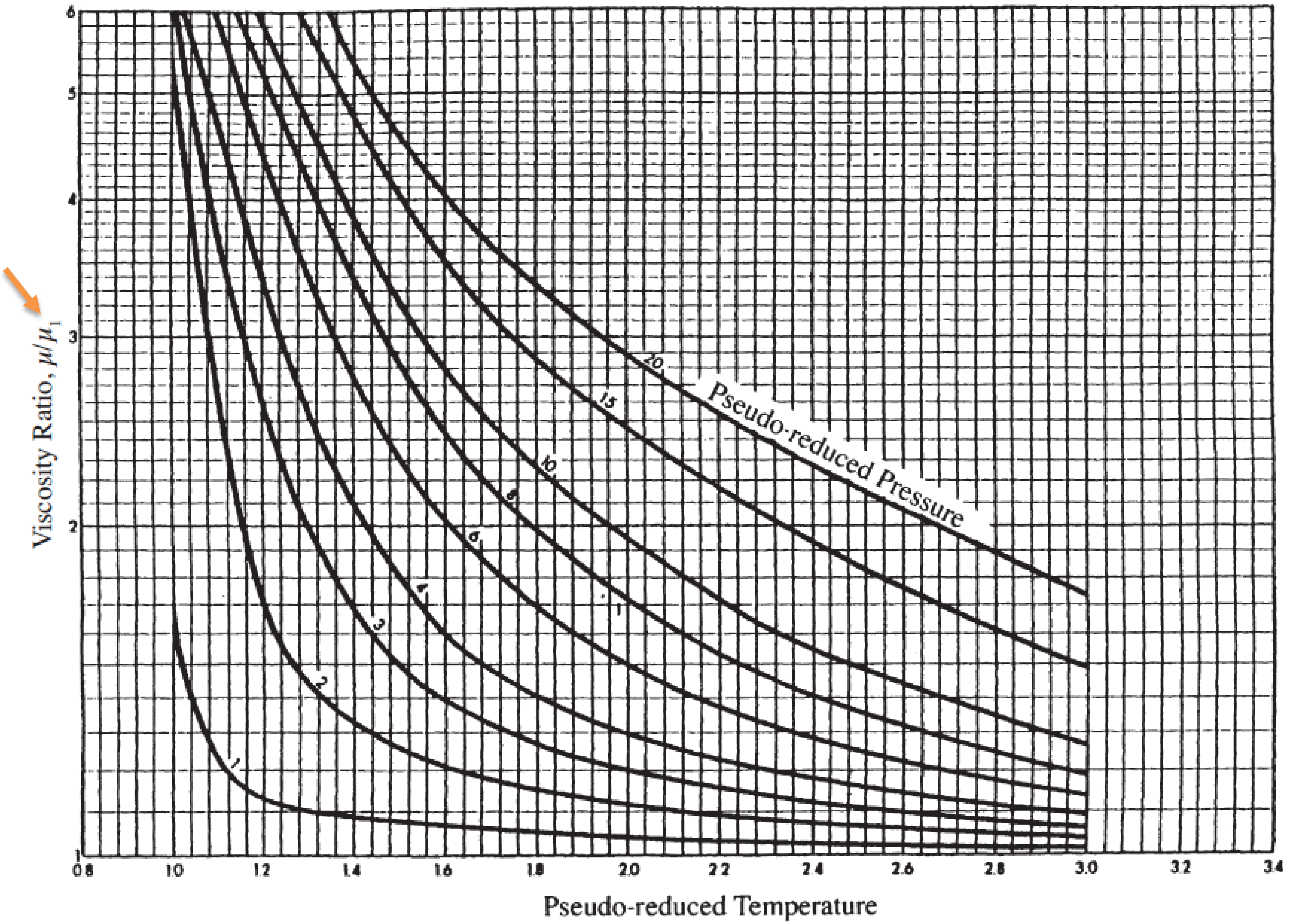


FIGURE 3–6 *Carr et al.'s viscosity ratio correlation.*

Source: Carr et al., "Viscosity of Hydrocarbon Gases under Pressure," *Transactions of the AIME* 201 (1954): 270–275. Permission to publish from the Society of Petroleum Engineers of the AIME. © SPE-AIME.

Atmospheric Gas Viscosity -Standing (1977)

Standing (1977) proposed a convenient mathematical expression for calculating the viscosity of the natural gas at atmospheric pressure and reservoir temperature, μ_1. Standing also presented equations for describing the effects of N2, CO2, and H2S on μ_1. The proposed relationships are

$$\mu_1 = (\mu_1)_{\text{uncorrected}} + (\Delta\mu)_{N_2} + (\Delta\mu)_{CO_2} + (\Delta\mu)_{H_2S} \qquad (3\text{–}57)$$

$$(\mu_1)_{\text{uncorrected}} = 8.118(10^{-3}) - 6.15(10^{-3})\log(\gamma_g) + [1.709(10^{-5}) - 2.062(10^{-6})\gamma_g](T-460) \qquad (3\text{–}58)$$

$$(\Delta\mu)_{N_2} = y_{N_2}[8.48(10^{-3})\log(\gamma_g) + 9.59(10^{-3})] \qquad (3\text{–}59)$$

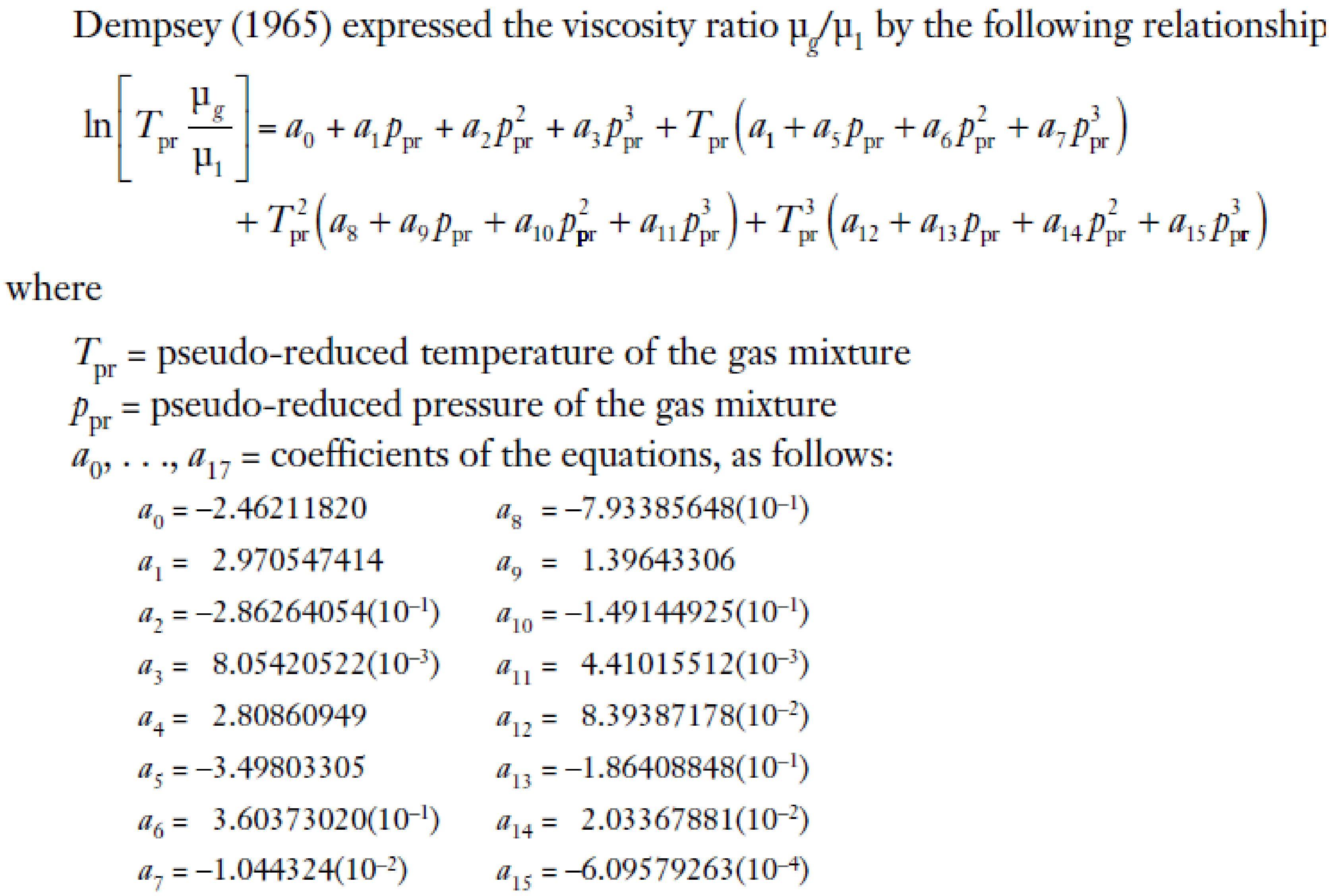
$$(\Delta\mu)_{CO_2} = y_{CO_2}[9.08(10^{-3})\log(\gamma_g) + 6.24(10^{-3})] \qquad (3\text{–}60)$$

$$(\Delta\mu)_{H_2S} = y_{H_2S}[8.49(10^{-3})\log(\gamma_g) + 3.73(10^{-3})] \qquad (3\text{–}61)$$

where

μ_1 = viscosity of the gas at atmospheric pressure and reservoir temperature, cp
T = reservoir temperature, °R
γ_g = gas gravity; $y_{N_2}, y_{CO_2}, y_{H_2S}$ = mole fraction of N_2, CO_2, and H_2S, respectively

Reservoir Pressure Gas Viscosity -Dempsey (1965)



Dempsey (1965) expressed the viscosity ratio μ_g/μ_1 by the following relationship

$$\ln\left[T_{pr}\frac{\mu_g}{\mu_1}\right] = a_0 + a_1 p_{pr} + a_2 p_{pr}^2 + a_3 p_{pr}^3 + T_{pr}\left(a_1 + a_5 p_{pr} + a_6 p_{pr}^2 + a_7 p_{pr}^3\right)$$

$$+ T_{pr}^2\left(a_8 + a_9 p_{pr} + a_{10} p_{\mathbf{pr}}^2 + a_{11} p_{pr}^3\right) + T_{pr}^3\left(a_{12} + a_{13} p_{pr} + a_{14} p_{pr}^2 + a_{15} p_{\mathbf{pr}}^3\right)$$

where

T_{pr} = pseudo-reduced temperature of the gas mixture
p_{pr} = pseudo-reduced pressure of the gas mixture
$a_0, \ldots, a_{17}$ = coefficients of the equations, as follows:

$a_0 = -2.46211820$
$a_1 = 2.970547414$
$a_2 = -2.86264054(10^{-1})$
$a_3 = 8.05420522(10^{-3})$
$a_4 = 2.80860949$
$a_5 = -3.49803305$
$a_6 = 3.60373020(10^{-1})$
$a_7 = -1.044324(10^{-2})$

$a_8 = -7.93385648(10^{-1})$
$a_9 = 1.39643306$
$a_{10} = -1.49144925(10^{-1})$
$a_{11} = 4.41015512(10^{-3})$
$a_{12} = 8.39387178(10^{-2})$
$a_{13} = -1.86408848(10^{-1})$
$a_{14} = 2.03367881(10^{-2})$
$a_{15} = -6.09579263(10^{-4})$

Lee-Gonzalez-Eakin's Method (1966)

Lee, Gonzalez, and Eakin (1966) presented a semi-empirical relationship for calculating the viscosity of natural gases. The authors expressed the gas viscosity in terms of the reservoir temperature, gas density, and the molecular weight of the gas. Their proposed equation is given by

$$\mu_g = 10^{-4} K \exp\left[X \left(\frac{\rho_g}{62.4} \right)^Y \right] \qquad (3\text{–}62)$$

where

$$K = \frac{(9.4 + 0.02 M_a) T^{1.5}}{209 + 19 M_a + T} \qquad (3\text{–}63)$$

$$X = 3.5 + \frac{986}{T} + 0.01 M_a \qquad (3\text{–}64)$$

$$Y = 2.4 - 0.2X \qquad (3\text{–}65)$$

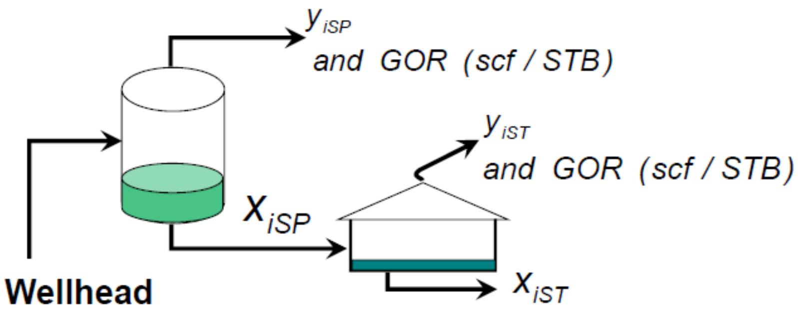
ρ = gas density at reservoir pressure and temperature, lb/ft^3

T = reservoir temperature, °R

M_a = apparent molecular weight of the gas mixture

The proposed correlation can predict viscosity values with a standard deviation of 2.7% and a maximum deviation of 8.99%. The correlation is less accurate for gases with higher specific gravities. The authors pointed out that **the method cannot be used for sour gases**.

"Average Surface Specific Gravity" of Wet Gas Reservoirs



The surface specific gravity of a wet gas, **γ_g**, is described by the weighted-average of the specific gravities of the separated gas from each separator. This weighted average approach is based on the separator gas/oil ratio:

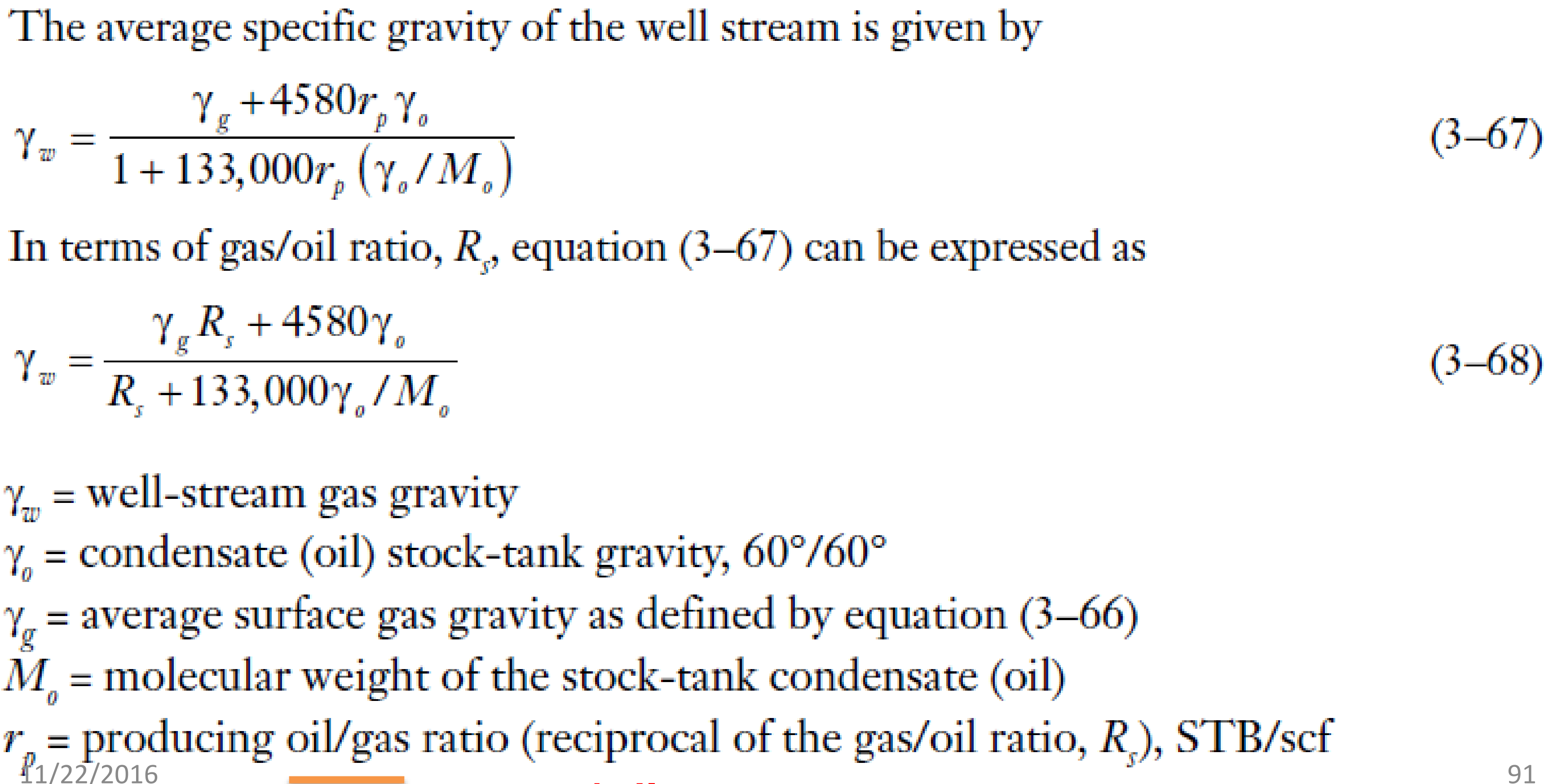
$$\gamma_g = \frac{\sum_{i=1}^{n} \left(R_{\text{sep}}\right)_i \left(\gamma_{\text{sep}}\right)_i + R_{\text{st}}\gamma_{\text{st}}}{\sum_{i=1}^{n} \left(R_{\text{sep}}\right)_i + R_{\text{st}}} \tag{3–66}$$

where

n = number of separators
R_{sep} = separator gas/oil ratio, scf/STB
γ_{sep} = separator gas gravity
R_{st} = gas/oil ratio from the stock tank, scf/STB
γ_{st} = gas gravity from the stock tank

“Well-stream specific Gravity” of Wet Gas Reservoirs

For wet gas reservoirs that produce liquid (condensate) at separator conditions, the produced gas mixtures normally exist as a “single” gas phase in the reservoir and production tubing. To determine the well-stream specific gravity, the produced gas and condensate (liquid) must be recombined in the correct ratio to find the average **specific gravity of the “single-phase” gas reservoir**.



The average specific gravity of the well stream is given by

$$\gamma_w = \frac{\gamma_g + 4580 r_p \gamma_o}{1 + 133{,}000 r_p \left(\gamma_o / M_o\right)} \qquad (3\text{–}67)$$

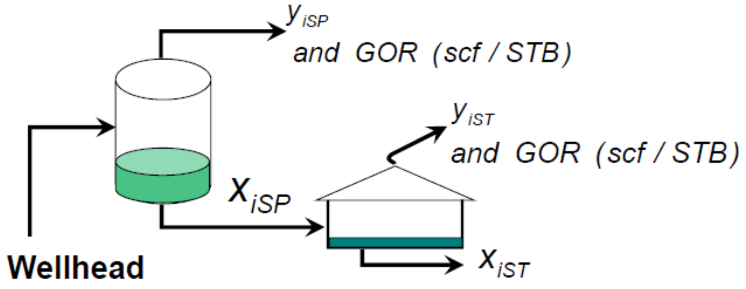
In terms of gas/oil ratio, R_s, equation (3–67) can be expressed as

$$\gamma_w = \frac{\gamma_g R_s + 4580 \gamma_o}{R_s + 133{,}000 \gamma_o / M_o} \qquad (3\text{–}68)$$

γ_w = well-stream gas gravity
γ_o = condensate (oil) stock-tank gravity, 60°/60°
γ_g = average surface gas gravity as defined by equation (3–66)
M_o = molecular weight of the stock-tank condensate (oil)
r_p = producing oil/gas ratio (reciprocal of the gas/oil ratio, R_s), STB/scf

Not Gas/Oil !

The Molecular Weight of the Stock-tank Condensate- Standing (1974)



$$M_o = \frac{6084}{\text{API} - 5.9} \qquad (3\text{–}69)$$

where API is the API gravity of the liquid as given by

$$\text{API} = \frac{141.5}{\gamma_o} - 131.5$$

$$\gamma_w = \frac{\gamma_g R_s + 4580\gamma_o}{R_s + 133{,}000\gamma_o / M_o}$$

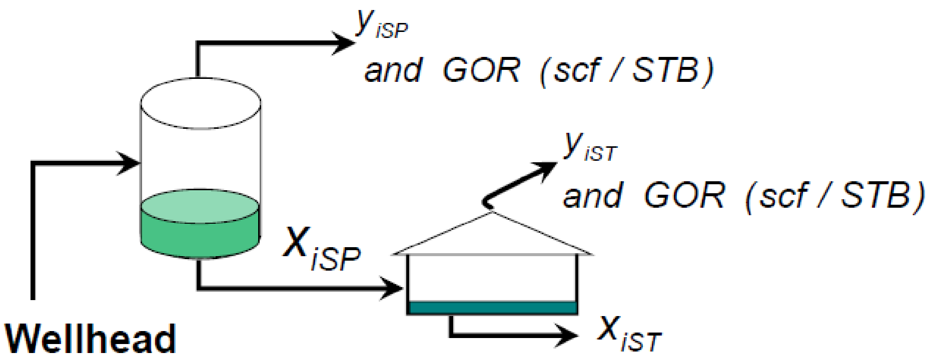
Eilerts (1947) proposed an expression for the ratio **γ_o/M_o** as a function of the condensate stock-tank **API** gravity:

$$\gamma_o / M_o = 0.001892 + 7.35\,(10^{-5})\,\text{API} - 4.52\,(10^{-8})\,(\text{API})^2 \qquad (3\text{–}70)$$

Equation (3–70) should be used only in the range 45° < API < 60°.

Fraction of the Separated Gas Produced

In retrograde and wet gas reservoirs calculations, it is convenient to express the produced separated gas as a fraction of the total system produced. This fraction $\boldsymbol{f_g}$ *can be* expressed in terms of the separated moles of gas and liquid as



$$f_g = \frac{n_g}{n_t} = \frac{n_g}{n_g + n_l} \qquad (3\text{–}71)$$

where

f_g = fraction of the separated gas produced in the entire system
n_g = number of moles of the separated gas
n_l = number of moles of the separated liquid
n_t = total number of moles of the well stream

For a **total producing gas/oil ratio** of **R_s** scf/STB, the equivalent number of moles of gas as described by equation (3–6) is

$$n_g = R_s/379.4 \tag{3–72}$$

The number of moles of 1 STB of the separated condensate is given by

$$n_o = \frac{\text{mass}}{\text{molecular weight}} = \frac{(\text{volume})(\text{density})}{M_o}$$

or

$$n_o = \frac{(1)(5.615)(62.4)\gamma_o}{M_o} = \frac{350.4\gamma_o}{M_o} \tag{3–73}$$

Substituting equations (3–72) and (3–73) into equation (3–71) gives

$$\boxed{f_g = \frac{R_s}{R_s + 133{,}000(\gamma_o/M_o)}} \tag{3–74}$$

#HW Derive the
above equation

Equivalent Gas Volume

When applying the material balance equation for a gas reservoir, it assumes that a volume of gas in the reservoir will remain as a gas at surface conditions. When liquid is separated, the cumulative liquid volume must be converted into an equivalent gas volume, V_{eq}, and added to the cumulative gas production for use in the material balance equation. If $\mathbf{N_p}$ STB of liquid (condensate) has been produced, the equivalent number of moles of liquid is given by equation (3–73) as:

$$n_o = \frac{(N_p)(5.615)(62.4)\gamma_o}{M_o} = \frac{350.4\gamma_o N_p}{M_o}$$

Expressing this number of moles of liquid as **an equivalent gas volume** at standard conditions by applying the ideal gas equation of state gives:

$$V_{\text{eq}} = \frac{n_o R T_{\text{sc}}}{p_{\text{sc}}} = \left(\frac{350.4\gamma_o N_p}{M_o}\right)\frac{(10.73)(520)}{14.7}$$

$$V_{\mathrm{eq}} = 133{,}000 \frac{\gamma_o N_p}{M_o}$$

More conveniently, the equivalent gas volume can be expressed in scf/STB as

$$V_{\mathrm{eq}} = 133{,}000 \frac{\gamma_o}{M_o} \tag{3–75}$$

where

V_{eq} = equivalent gas volume, scf/STB
N_p = cumulative, or daily, liquid volume, STB

γ_0 = specific gravity of the liquid, 60°/60°
M_0 = molecular weight of the liquid