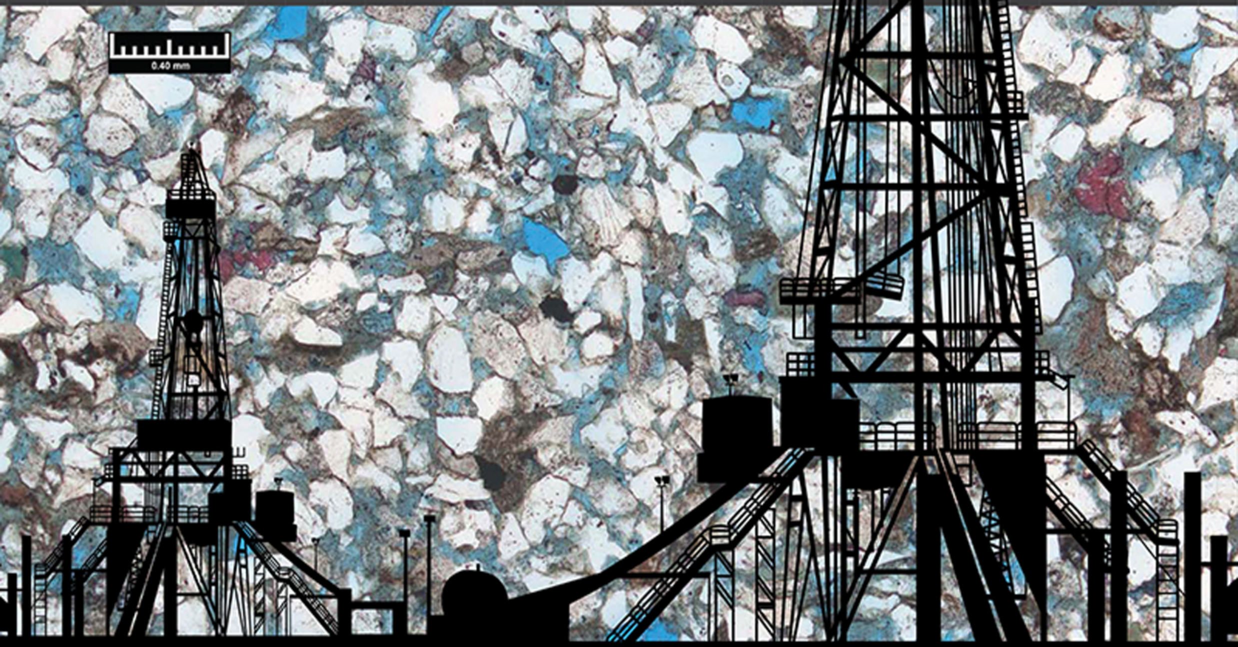
B.C. CRAFT • M. HAWKINS

APPLIED PETROLEUM RESERVOIR ENGINEERING

THIRD EDITION



REVISED BY

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Compositions of high-pressure gas and liquid = Table 5.2, columns 2 and 3
Molar volume at 15.025 psia and 60°F = 371.2 ft^3/mol

Solution

Note that column numbers refer to Table 5.2:

1. Columns 1, 2, and 3 are given. This information typically comes from a lab test performed on a sample taken from the separator. Column 4 is additional information that can also be found in Table 2.1. Using this information, calculate the mole proportions in which to recombine the separator gas and liquid. Multiply the mole fraction of each component in the liquid (column 3) by its molecular weight (column 4) and enter the products in column 5. The sum of column 5 is the molecular weight of the separator liquid, 127.48. Next, the ratio of liquid barrel per mole is needed for each component. This information is also found in Table 2.1. The last column of Table 2.1 is the estimated gal/lb-mol—these data will need to be converted to bbl/mol. The next several steps are used to match the quantity of produced liquid to produced gas and determine the com-

   gravity of the separator liquid is 0.7675 at 880 psig and 60°F, the moles per barrel is

   $$\frac{0.7675 \times 350 \text{ lb/bbl}}{127.48 \text{ lb/mole}} = 2.107 \text{ moles/bbl for the separator liquid}$$

   The separator liquid rate is 31.1 STB/day × 1.235 sep. bbl/STB so that the separator gas-oil ratio is

   $$\frac{842,600}{31.1 \times 1.235} = 21,940 \text{ SCF sep. gas/bbl sep. liquid}$$

   Because the 21,940 SCF is 21,940/371.2, or 59.11 mols, the separator gas and liquid must be recombined in the ratio of 59.11 mols of gas to 2.107 mols of liquid.
   vity of the separator liquid is not available, the mole per barrel
   ws. Multiply the mole fraction of each component in the

   Table 2.1, and enter the product in column 7. The sum of column 7, 0.46706, is the number of barrels of separator liquid per mole of separator liquid, and the reciprocal is 2.141 mols/bbl (versus 2.107 measured).
2. Now that the ratio of the gas to liquid produced is known, recombine 59.11 mols of gas and 2.107 mols of liquid. Multiply the mole fraction of each component in the gas, column 2, by 59.11 mols, and enter in column 8. Multiply the mole fraction of each component in the liquid, column 3, by 2.107 mols, and enter the solution in column 9. Enter the sum of the moles of each component in the gas and liquid, column 8, plus column 9, in column 10. Di

12 is the critical pressure for each component; it is also found in Table 2.1. With that information, the partial critical pressure (column 13) can be found. The same will be done for columns 14 and 15 for temperature. Calculate the pseudocritical temperature 379.23°R and pressure 668.23 psia from the composition by summing the partial temperature and partial pressure v -
doreduced criticals and then the deviation factor at 4350 psia and 217°F, which is 0.963.

3. Find the gas and oil (condensate) in place per acre-foot of net reservoir rock. From the gas law, the initial moles per acre-foot at 17.4% hydrocarbon porosity is

$$\frac{pV}{zRT} = \frac{4350 \times (43,560 \times 0.174)}{0.963 \times 10.73 \times 677} = 4713 \text{ mols/ac-ft}$$

$$\text{Gas mole fraction} = \frac{59.11}{59.11 + 2.107} = 0.966$$

$$\text{Initial gas in place} = \frac{0.966 \times 4713 \times 371.2}{1000} = 1690 \text{ MCF/ac-ft}$$

$$\text{Initial oil in place} = \frac{(1 - 0.966) \times 4713}{2.107 \times 1.235} = 61.6 \text{ STB/ac-ft}$$

Because the high-pressure gas is 96.6% of the total mole production, the daily gas-condensate production expressed in standard cubic feet is

$$\Delta G_p = \frac{\text{Daily separator gas}}{\text{Gas mole fraction}} = \frac{842,600}{0.966} = 872,200 \text{ SCF/day}$$

The daily reservoir voidage at 4350 psia is

$$\Delta V = 872,200 \times \frac{677}{520} \times \frac{15.025}{4350} \times 0.963 = 3777 \text{ ft}^3\text{/day}$$

5.3 The Performance of Volumetric Reservoirs

The behavior of single-phase gas reservoirs is treated in Chapter 4. Since no liquid phase develops within the reservoir, where the temperature is above the cricondentherm, the calculations are

When the reservoir temperature is below the cricondentherm, however, a liquid phase develops within the reservoir when pressure declines below the dew point, owing to retrograde condensation, and the treatment is considerably more complex, even for volumetric reservoirs.

One solution is to closely duplicate the reservoir depletion by laboratory studies on a representative sample of the initial, single-phase reservoir The sample is placed in a high-pressure cell at reservoir temperature and initial reservoir pressure. During the depletion, the volume of the cell is held constant to duplicate a volumetric reservoir, and care is taken to remove only gas-phase hydrocarbons from the cell because, for most reservoirs, the retrograde condensate liquid that forms is trapped as an immobile liquid phase within the pore spaces of the reservoir.

Laboratory experiments have shown that, with most rocks, the oil phase is essentially immobile until it builds up to a saturation in the range of 10% to 20% of the pore space, depending on the nature of the rock pore spaces and the connate water. Because the liquid saturations for most retrograde fluids seldom exceed 10%, this is a reasonable assumption for most retrograde condensate reservoirs. In this same connection, it should be pointed out that, in the vicinity of the wellbore, retrograde liquid saturations often build up to higher values so that there is two-phase flow, both gas and retrograde liquid. This buildup of liquid occurs as the one-phase gas suffers a pressure drop as it approaches the wellbore. Continued flow increases the retrograde liquid saturation until there is liquid flow. Although this phenomenon does not affect the overall performance seriously or enter into the present performance predictions, it can (1) reduce, sometimes seriously, the flow rate of gas-condensate wells and (2) affect the accuracy of well samples taken, assuming one-phase flow into the wellbore.

The continuous depletion of the gas phase (only) of the cell at constant volume can be closely duplicated by the following more convenient technique. The content of the cell is expanded from the initial volume to a larger volume at a pressure a few hundred psi below the initial pressure by withdrawing mercury from the bottom of the cell or otherwise increasing the volume. Time is allowed for equilibrium to be established between the gas phase and the retrograde liquid phase that has formed and for the liquid to drain to the bottom of the cell so that only gas-phase hydrocarbons are produced from the top of the cell. Mercury is injected into the bottom of the cell and gas is removed at the top at such a rate as to maintain constant pressure in the cell. Thus the volume of gas removed, measured at this lower pressure and cell (reservoir) temperature, equals the volume of mercury injected when the hydrocarbon volume, now two phase, is returned to the initial cell volume. The volume of retrograde liquid is measured, and the cycle—expansion to a next lower pressure followed by the removal of a second increment of gas—is repeated down to any selected abandonment pressure. Each increment of gas removed is analyzed to find its composition, and the volume of each increment of produced gas is measured at subatmospheric pressure to determine the standard volume, using the ideal gas law. From this, the gas deviation factor at cell pressure and temperature may be calculated using the real gas law. Alternatively, the gas deviation factor at cell pressure and temperature may be calculated from the composition of the increment.

Figure 5.4 and Table 5.3 give the composition of a retrograde gas-condensate reservoir fluid at initial pressure and the composition of the gas removed from a pressure-volume-temperature (PVT) cell in each of five increments, as previously described. Table 5.3 also gives the volume of retrograde liquid in the cell at each pressure and the gas deviation factor and volume of the produced gas increments at cell pressure and temperature. As shown in Fig. 5.4, the produced gas composition changes as the pressure of the cell decreases. For example, 2500 psia shows a substantial decrease in the mole fraction of the heptanes-plus, a smaller decrease for the hexanes, even smaller for pentanes, and so on, compared to the 3000 psia composition. The lighter hydrocarbons have a corresponding increase in their mole fraction of the composition over that same interval. The trend is for the heavier hydrocarbons to selectively condense in the cell, and, therefore, they are not produced. As the cell continues to be depleted, the pressure reaches the point, as shown by point B_2 in Fig. 1.4, when the heavier components begin to revaporize. For this reason, as shown in Fig. 5.4 and Table 5.3, the trend from the 1000 psia to the 500 psia increments shows an increase of the mole fraction of the heavier hydrocarbons and a decrease in the mole fraction of the lighter hydrocarbons.

The liquid recovery from the gas increments produced from the cell may be measured by passing the gas through small-scale separators, or it may be calculated from the composition for usual separation methods or for gasoline plant methods.[8,9,10] Liquid recovery of the pentanes-plus is somewhat greater in gasoline plants than in separation and much greater for the propanes and butanes, commonly called petroleum gas (LPG). For simplicity, the liquid recovery from the

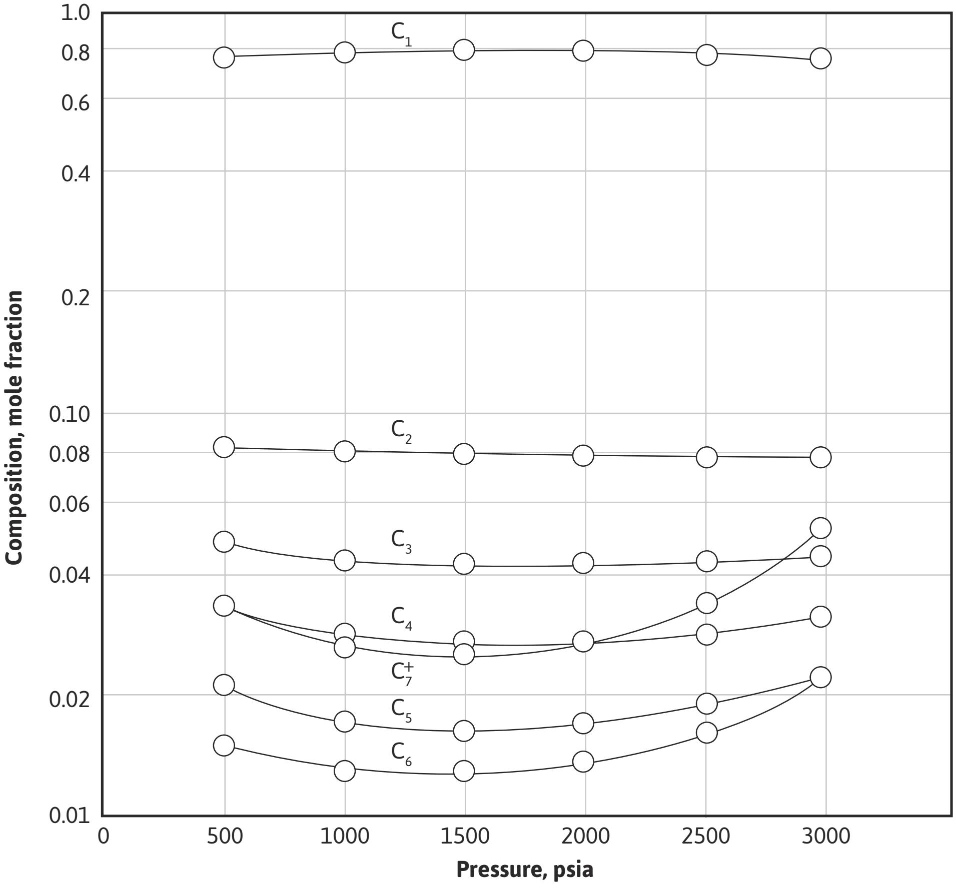

Figure 5.4 Variations in the composition of the produced gas phase material of a retrograde Table 5.3).

gas increments of Table 5.3 is calculated in Example 5.3, assuming 25% of the butanes, 50% of the pentanes, 75% of the hexanes, and 100% of the heptanes-plus are recovered as liquid.

Example 5.3 Calculating the Volumetric Depletion Performance of a Retrograde Gas-Condensate Reservoir Based on the Laboratory Tests Given in Table 5.3

Given

Initial pressure (dew point) = 2960 psia
Abandonment pressure = 500 psia
Reservoir temperature = 195°F
Connate water = 30%
Porosity = 25%
Standard conditions = 14.7 psia and 60°F
Initial cell volume = 947.5 cm^3
Molecular weight of C_7^+
vity of C $_7^+$ °F
Compositions, volumes, and deviation factors given in Table 5.3

vity for the C $_7^+$ content for all produced gas. Also assume liquid recovery from the gas is 25% of the butanes, 50% of the pentanes, 75% of the hexanes, and 100% of the heptanes and heavier gases.

Solution

Note that column numbers refer to Table 5.4.

1. Calculate the increments of gross production in M SCF per ac-ft of net, bulk reservoir rock. First, calculate V_{HC}, the hydrocarbon volume per acre-ft of reservoir. Enter the following in column 2:

$$V_{HC} = 43{,}560 \times 0.25 \times (1 - 0.30) = 7623 \text{ ft}^3\text{/ac-ft}$$

For the increment produced from 2960 to 2500 psia, for example, the hydrocarbon volume will be multiplied by the ratio of the produced gas (from Table 5.3) to the cell volume given. That volume is then converted to standard units as shown.

$$\Delta V = 7623 \times \frac{175.3 \text{ cu cm}}{947.5 \text{ cu cm}} = 1410 \text{ ft}^3\text{/ac-ft at 2500 psia and 195°F}$$

$$G_p = \frac{379.4 pV}{1000 zRT} = \frac{379.4 \times 2500 \times 1410}{1000 \times 0.794 \times 10.73 \times 655} = 239.7 \text{ MSCF/ac-ft}$$

Find the cumulative gross gas production, $G_p = \Sigma \Delta G_p$, and enter in column 3.

Table 5.3 Volume, Composition, and Gas Deviation Factors for a Retrograde Condensate Fluid

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Pressure (psia)	**Composition of produced gas increments (mole fraction)**							**Produced gas (cm^3 at 195 °F and cell pressure)**	**Retrograde liquid volume (cm^3 cell volume, 947.5 cm^3)**	**Retrograde volume (percent of hydrocarbon volume)**	**Gas deviation factor (at 195°F and cell pressure)**
	C_1	C_2	C_3	C_4	C_5	C_6	C_7^+				
2960	0.752	0.077	0.044	0.031	0.022	0.022	0.052	0.0	0.0	0.0	0.771
2500	0.783	0.077	0.043	0.028	0.019	0.016	0.034	175.3	62.5	6.6	0.794
2000	0.795	0.078	0.042	0.027	0.017	0.014	0.027	227.0	77.7	8.2	0.805
1500	0.798	0.079	0.042	0.027	0.016	0.013	0.025	340.4	75.0	7.9	0.835
1000	0.793	0.080	0.043	0.028	0.017	0.013	0.026	544.7	67.2	7.1	0.875
500	0.768	0.082	0.048	0.033	0.021	0.015	0.033	1080.7	56.9	6.0	0.945