2. Volumetric

The volumetric method entails determining the physical size of the reservoir, the pore volume within the rock matrix, and the fluid content within the void space. This provides an estimate of the hydrocarbons-in-place, from which ultimate recovery can be estimated by using an appropriate recovery factor. Each of the factors used in the calculation have inherent uncertainties that, when combined, cause significant uncertainties in the reserves estimate. Figure 4 is a typical geological net pay isopach map that is often used in the volumetric method.

![Figure 4: A typical geological net pay isopach map](image)

The estimated ultimate recovery (EUR) of an oil reservoir, STB, is given by:

\[
EUR = N(t) RF
\]

Where \( N(t) \) is the oil in place at time \( t \), STB, and \( RF \) is the recovery factor, fraction. The volumetric method for calculating the amount of oil in place \( (N) \) is given by the following equation:

\[
N(t) = \frac{V_b \phi S_o(t)}{B_o(p)}
\]

Where:

- \( N(t) \) = oil in place at time \( t \), STB
- \( V_b \) = bulk reservoir volume, \( RB = 7758 \) A h
- \( 7758 \) = \( RB/\)acre-ft
- \( A \) = reservoir area, acres
- \( h \) = average reservoir thickness, ft
- \( \phi \) = average reservoir porosity, fraction
- \( S_o(t) \) = average oil saturation, fraction
- \( B_o(p) \) = oil formation volume factor at reservoir pressure \( p \), \( RB/STB \)

Similarly, for a gas reservoir, the volumetric method is given by:

\[
EUR = G(t) RF
\]
Where $G(t)$ is the gas in place at time $t$, SCF, and $RF$ is the recovery factor, fraction.

The volumetric method for calculating the amount of gas in place ($G$) is given by the following equation:

$$G(t) = \frac{V_b \phi S_g(t)}{B_g(p)}$$

Where:

- $G(t) = \text{gas in place at time } t, \text{ SCF}$
- $V_b = \text{bulk reservoir volume, CF} = 43560 \ \text{A} \ \text{h}$
- $43560 = \text{CF/acre-ft}$
- $A = \text{reservoir area, acres}$
- $h = \text{average reservoir thickness, ft}$
- $\phi = \text{average reservoir porosity, fraction}$
- $S_g(t) = \text{average gas saturation, fraction}$
- $B_g(p) = \text{gas formation volume factor at reservoir pressure } p, \text{ CF/SCF}$

Note that the reservoir area ($A$) and the recovery factor ($RF$) are often subject to large errors. They are usually determined from analogy or correlations. The following examples should clarify the errors that creep in during the calculations of oil and gas reserves.

**Example #1: Given the following data for the Hout oil field in Saudi Arabia**

- Area = 26,700 acres
- Net productive thickness = 49 ft
- Porosity = 8%
- Average $S_{wi}$ = 45%
- Initial reservoir pressure, $p_i$ = 2980 psia
- Abandonment pressure, $p_a$ = 300 psia
- $B_o$ at $p_i$ = 1.68 bbl/STB
- $B_o$ at $p_a$ = 1.15 bbl/STB
- $S_g$ at $p_a$ = 34%
- $S_o$ after water invasion = 20%

The following quantities will be calculated:

1. Initial oil in place
2. Oil in place after volumetric depletion to abandonment pressure
3. Oil in place after water invasion at initial pressure
4. Oil reserve by volumetric depletion to abandonment pressure
5. Oil reserve by full water drive
6. Discussion of results

**Solution:**

Let’s start by calculating the reservoir bulk volume:

$$V_b = 7758 \times A \times h = 7758 \times 26,700 \times 49 = 10.15 \text{ MMM bbl}$$
1. The initial oil in place is given by:

\[ N_i = \frac{V_b \phi (1 - S_w)}{B_{oi}} \]

this yields:

\[ N_i = \frac{10.15 \times 10^6 (0.08)(1 - 0.45)}{1.68} \approx 266 \text{ MM STB} \]

2. The oil in place after volumetric depletion to abandonment pressure is given by:

\[ N = \frac{V_b \phi (1 - S_w - S_g)}{B_o} \]

this yields:

\[ N_i = \frac{10.15 \times 10^6 (0.08)(1 - 0.45 - 0.34)}{1.15} \approx 148 \text{ MM STB} \]

3. The oil in place after water invasion at initial reservoir pressure is given by:

\[ N = \frac{V_b \phi S_{or}}{B_o} \]

this yields:

\[ N_2 = \frac{10.15 \times 10^6 (0.08)0.20}{1.68} \approx 97 \text{ MM STB} \]

4. The oil reserve by volumetric depletion:

\[ (N_i - N_i) = (266 - 148) \times 10^6 = 118 \text{ MM STB} \]

i.e. RF = 118/266 = 44%

5. The oil reserve by full water drive

\[ (N_i - N_2) = (266 - 97) \times 10^6 = 169 \text{ MM STB} \]

i.e. RF = 169/266 = 64%

6. Discussion of results: For oil reservoirs under *volumetric control*; i.e. no water influx, the produced oil must be replaced by gas the saturation of which increases as oil saturation decreases. If \( S_g \) is the gas saturation and \( B_o \) the oil formation volume factor at abandonment pressure, then oil in place at abandonment pressure is given by:
On the other hand, for oil reservoirs under *hydraulic control*, where there is no appreciable decline in reservoir pressure, water influx is either *edge-water drive* or *bottom-water drive*. In edge-water drive, water influx is inward and parallel to bedding planes. In bottom-water drive, water influx is upward where the producing oil zone is underlain by water. In this case, the oil remaining at abandonment is given by:

\[ N = \frac{V_b \phi (1 - S_w - S_e)}{B_o} \]

This concludes the solution.

**Example #2: Given the following data for the Bell gas field**

Area = 160 acres  
Net productive thickness = 40 ft  
Initial reservoir pressure = 3250 psia  
Porosity = 22%  
Connate water = 23%  
Initial gas FVF = 0.00533 ft³/SCF  
Gas FVF at 2500 psia = 0.00667 ft³/SCF  
Gas FVF at 500 psia = 0.03623 ft³/SCF  
Sₜ after water invasion = 34%

The following quantities will be calculated:

1. Initial gas in place  
2. Gas in place after volumetric depletion to 2500 psia  
3. Gas in place after volumetric depletion to 500 psia  
4. Gas in place after water invasion at 3250 psia  
5. Gas in place after water invasion at 2500 psia  
6. Gas in place after water invasion at 500 psia  
7. Gas reserve by volumetric depletion to 500 psia  
8. Gas reserve by full water drive; i.e. at 3250 psia  
9. Gas reserve by partial water drive; i.e. at 2500 psia  
10. Gas reserve by full water drive if there is one un-dip well  
11. Discussion of results

**Solution:**

Let’s start by calculating the reservoir bulk volume:

\[ V_b = 43,560 \times A \times h = 43,560 \times 160 \times 40 = 278,784 \text{ MM ft}^3 \]

1. Initial gas in place is given by:
\[ G_i = \frac{V_s \phi_i (I - S_w)}{B_g} \]

this yields:

\[ G_i = \frac{278.784 \times 10^6 (0.22)(1 - 0.23)}{0.00533} = 8860 \text{ MM SCF} \]

2. Gas in place after volumetric depletion to 2500 psia:

\[ G_1 = \frac{278.784 \times 10^6 (0.22)(1 - 0.23)}{0.00667} = 7080 \text{ MM SCF} \]

3. Gas in place after volumetric depletion to 500 psia:

\[ G_2 = \frac{278.784 \times 10^6 (0.22)(1 - 0.23)}{0.003623} = 1303 \text{ MM SCF} \]

4. Gas in place after water invasion at 3250 psia:

\[ G_3 = \frac{278.784 \times 10^6 (0.22)(0.34)}{0.00533} = 3912 \text{ MM SCF} \]

5. Gas in place after water invasion at 2500 psia:

\[ G_4 = \frac{278.784 \times 10^6 (0.22)(0.34)}{0.00667} = 3126 \text{ MM SCF} \]

6. Gas in place after water invasion at 500 psia:

\[ G_5 = \frac{278.784 \times 10^6 (0.22)(0.34)}{0.03623} = 576 \text{ MM SCF} \]

7. Gas reserve by volumetric depletion to 500 psia:

\[ G_i - G_2 = (8860 - 1303) \times 10^6 = 7557 \text{ MM SCF} \]

i.e. \( RF = 7557/8860 = 85\% \)

8. Gas reserve by water drive at 3250 psia (full water drive):

\[ G_i - G_3 = (8860 - 3912) \times 10^6 = 4948 \text{ MM SCF} \]

i.e. \( RF = 4948/8860 = 56\% \)
9. Gas reserve by water drive at 2500 psia (partial water drive):

\[ G_i - G_f = (8860 - 3126) \times 10^6 = 5734 \text{ MM SCF} \]

i.e. \( RF = \frac{5734}{8860} = 65\% \)

10. Gas reserve by water drive at 3250 psia if there is one un-dip well:

\[ \frac{1}{2} (G_i - G_f) = \frac{1}{2} (8860 - 3912) \times 10^6 = 2474 \text{ MM SCF} \]

i.e. \( RF = \frac{2474}{8860} = 28\% \)

11. Discussion of results

The RF for volumetric depletion to 500 psia (no water drive) is calculated to be 85%. On the other hand, the RF for partial water drive is 65%, and for the full water drive is 56%. This can be explained as follows: As water invades the reservoir, the reservoir pressure is maintained at a higher level than if there were no water encroachment. This leads to higher abandonment pressures for water-drive reservoirs. Recoveries, however, are lower because the main mechanism of production in gas reservoirs is depletion or gas expansion. In water-drive gas reservoirs, it has been found that gas recoveries can be increased by:

1. Outrunning technique: This is accomplished by increasing gas production rates. This technique has been attempted in Bierwang Field in West Germany where the field production rate has been increased from 50 to 75 MM SCF/D, and they found that the ultimate recovery increased from 69 to 74%.

2. Co-production technique: This technique is defined as the simultaneous production of gas and water, see Fig. 1. In this process, as down-dip wells begin to be watered out, they are converted to high-rate water producers, while the up-dip wells are maintained on gas production. This technique enhances production as follows:
   - The high-rate down-dip water producers act as a pressure sink for the water. This retards water invasion into the gas zone, therefore prolonging its productive life.
   - The high-rate water production lowers the average reservoir pressure, allowing for more gas expansion and therefore more gas production.
   - When the average reservoir pressure is lowered, the immobile gas in the water-swept portion of the reservoir could become mobile and hence producible. It has been reported that this technique has increased gas production from 62% to 83% in Eugene Island Field of Louisiana.

This concludes the solution.