Material Balance Method

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Short Course on

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Presentation Outline

- Introduction
- Material Balance Method- Basic Principle
- Material Balance Equation (MBE)
  - General Form
  - Linear Form
- Applications
  - Oil Reservoirs
  - Gas Reservoirs
- Flowing Material Balance
- Drive Mechanisms
- Conditions for Application
- Conclusions

Introduction

- Reserve Estimation Methods: More than one available.
- Different methods applicable at different stages of development.
- Data requirement different for each method, with some common
- predominant methods:

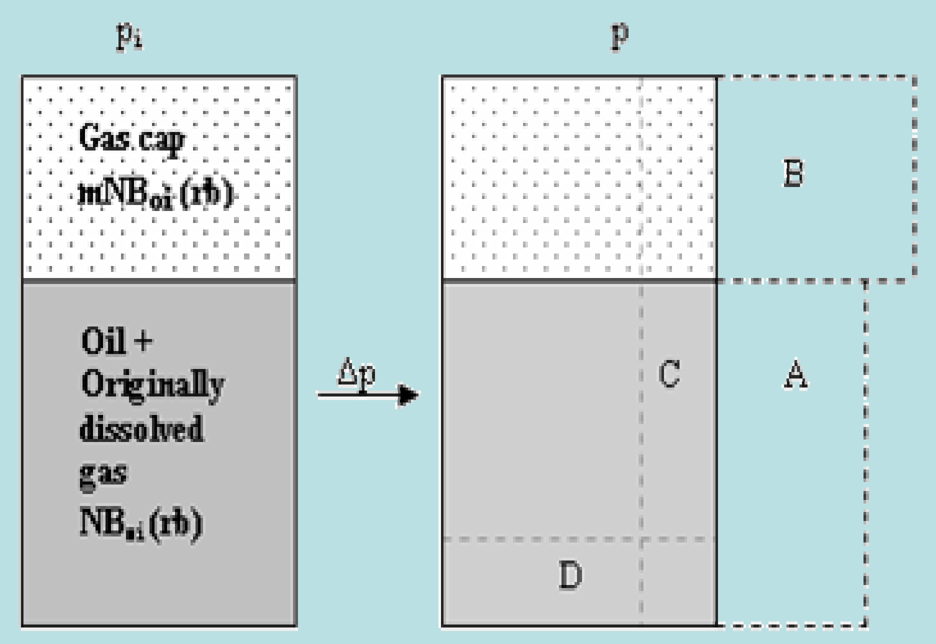
1. Volumetric Method
    - Early stage of reservoir development
    - Geology, Geophysics, Rock and Fluid properties
    - Recovery Factor (RF) assigned arbitrarily
    - No time dependency, No Production data
2. Material Balance
    - Later stage of development (after 20% of initial oil/gas is produced, or 10% of initial reservoir pressure has declined)
    - Geological data, Rock and Fluid properties, Production data
    - RF is calculated
    - Time dependant

Introduction (contd.)

3. Decline Curve Analysis
    - Later stage of development, when production rate undergoes natural decline
    - Mostly Production data
    - RF is calculated
    - Time dependant
4. Reservoir Simulation
    - Can be applied at any stage but more useful and reliable for matured reservoirs
    - Geological data, Rock and Fluid properties, Production data
    - More useful as reservoir management tool

- Uncertainties associated with each method
- More than one method should be used when applicable

Material Balance Method- Basic Principle



Volume changes in the reservoir associated with a finite pressure drop *Δp*;(a) volumes at initial pressure *pi* (b) at the reduced pressure *p*.

- **A** = Increase in HCPV due to the expansion of the oil phase (oil + dissolved gas).
- **B** = Increase in HCPV due to the expansion of the gas phase (free gas in the gas cap).
- **C** = decrease in HCPV due to the combined effects of the expansion of the connate water and the reduction in reservoir pore volume.
- **D** = decrease in HCPV due to water encroachment (from aquifer)

Underground withdrawal (oil + gas + water) = Expansion of oil + dissolved gas (A) + Expansion of gas-cap gas (B) + Reduction in HCPV (C) + Cumulative water influx (D) (1)

Material Balance Equation (MBE)

$$N_p [B_o + (R_p - R_s) B_g] + W_p B_w = N\left[\left(B_o - B_{oi}\right) + \left(R_{si} - R_s\right)B_g\right] + m\, N\, B_{oi} \left(B_g / B_{gi} - 1\right) + \frac{(1+m)NB_{oi}}{\left(1-S_{wc}\right)}\left(c_w S_{wc} + c_f\right)\Delta p + W_e B_w \quad (15)$$

N = oil originally in place (STOIIP), (stb)

G = Initial free gas in place in the gas cap (GIIP), (scf)

We = Cumulative water influx into the reservoir (stb)

HCPV = total hydrocarbon pore volume (oil zone + gas cap) (rb)

m = Initial gas cap ratio

$$m = \frac{\text{Initial hydrocarbon volume of the gas-cap}}{\text{Initial hydrocarbon volume of the oil}} = \frac{GB_{gi}}{NB_{oi}}$$

MBE- Definitions of Variables

Production data

- N_p = Cumulative oil produced (stb)
- G_p = cumulative gas produced (scf)
- W_p = Cumulative water produced (stb)
- $R_p = G_p/N_p$ = Cumulative produced gas-oil ratio (scf/stb)

Reservoir Data

- p_i = Initial mean pressure in the reservoir (psi)
- p = current mean pressure in the reservoir, (psi)
- S_{wc} = connate water saturation, (fraction)
- c_f = Compressibility of formation (psi-1)

Fluid PVT Data

- B_{gi} = Initial gas volume factor at pi (ft3/scf)
- B_g = Gas volume factor at current pressure p (ft3/scf)
- B_{oi} = Initial oil volume factor at pi (rb/stb)
- B_o = Oil volume factor at current pressure p (rb/stb)
- c_w = Compressibility of water (psi-1)
- B_w = Formation volume factor of water at current pressure p (rb/stb)
- R_{si} = solution gas-oil ratio at initial pressure pi (scf/stb)
- R_s = solution gas-oil ratio at current pressure p (scf/stb)

MBE in Linear Form

F = summation of production terms — $Np\ [Bo + (Rp – Rs)\ Bg] + Wp\ Bw$ (rb)

E_o = Oil and Dissolved gas expansion terms — $\left[(B_o - B_{oi}) + (R_{si} - R_s)B_g\right]$

E_g = Gas cap expansion term — $= Boi\ (Bg / Bgi – 1)$ (rb/stb)

$E_{f,w}$ = rock and water compression/expansion terms — $\dfrac{(1+m)B_{oi}}{(1-S_{wc})}\left(c_w S_{wc} + c_f\right)\Delta p$

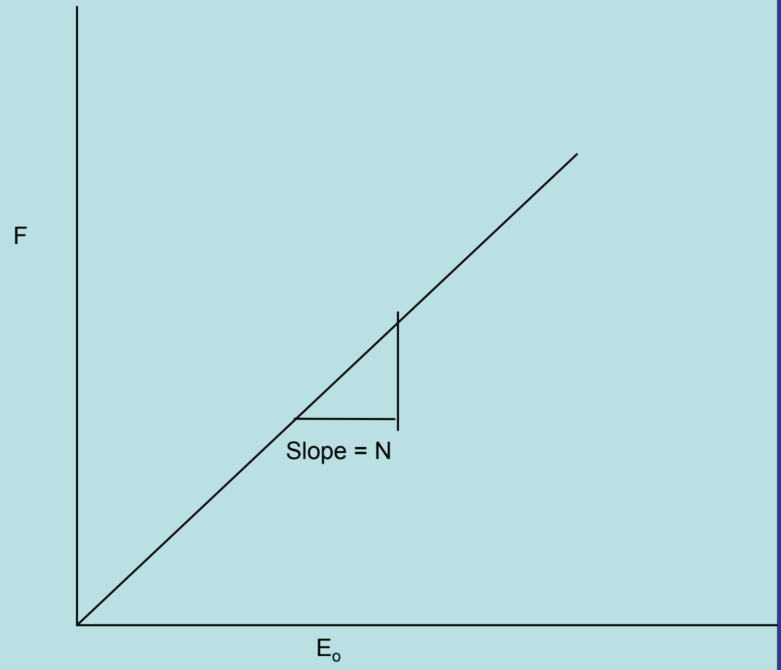
The complete material balance equation (MBE)

$F = N\ (Eo + m\ Eg + Ef,w) + We\ Bw$ (16)

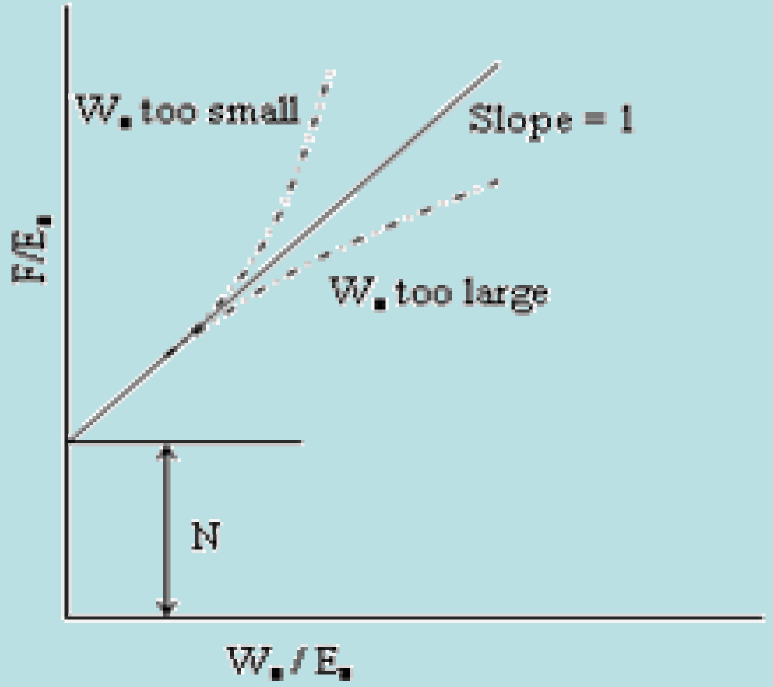
Equation 16 can be modified as equations of straight lines, which can be applied to different types of reservoirs.

Some of the applications are illustrated next.

MBE Applications: Saturated Oil Reservoirs



Case 1 MBE for under saturated volumetric oil reservoirs



Case 2 MBE for under saturated oil reservoirs with strong water drive

Volumetric depletion, $W_e = 0$

No Gas Cap, m = 0

E_{fw} = negligible

F = N Eo

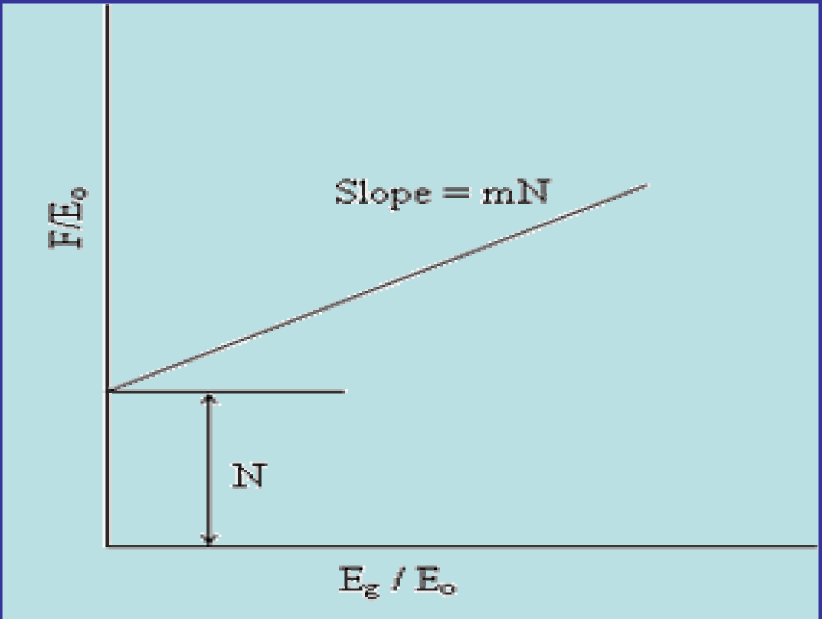
Strong water drive, $W_e \neq 0$

No Gas Cap, m = 0

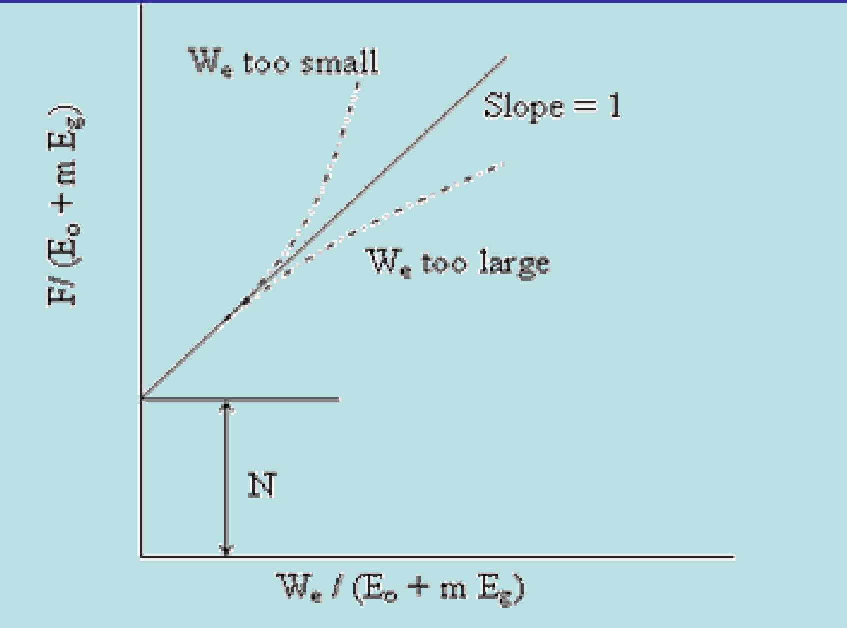
E_{fw} = negligible

F/Eo = N + We / Eo

MBE Applications: Under-saturated Oil Reservoirs



Case 3 Volumetric under saturated oil Reservoir



Case 4 under saturated oil reservoirs with strong water drive

Volumetric depletion, $W_e = 0$

Gas Cap present, $m \neq 0$

E_{fw} = negligible

F/Eo = N + m N Eg /Eo

Strong water drive, $W_e \neq 0$

Gas Cap present, $m \neq 0$

E_{fw} = negligible

$$\frac{F}{(E_o + m \cdot E_g)} = N + \frac{W_e}{(E_o + m \cdot E_g)}$$

MBE for Gas Reservoirs

For GAS RESERVOIRS- MBE (equation 15) can be reduced to:

Gp Bg + Wp Bw = G(Bg – Bgi) + We Bw (19)

For volumetric gas reservoir, We = 0

Assuming water production is negligible, Wp = 0

Equation 19 becomes:

Gp Bg = G(Bg – Bgi) (20)

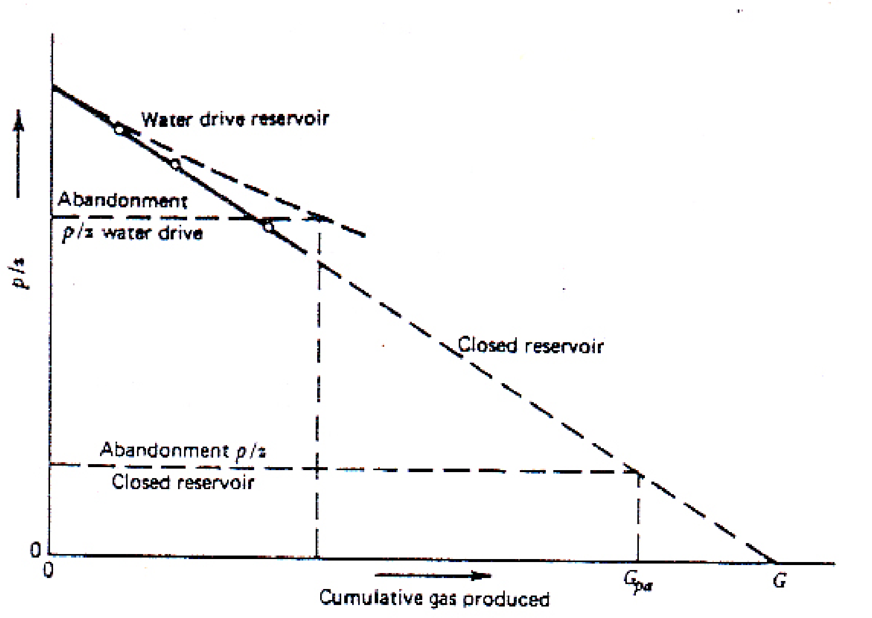
Applying the definitions of gas volume factor

$$G\left(\frac{z\ p_{sc}\ T}{p\ T_{sc}}\right) - G\left(\frac{z_i\ p_{sc}\ T_i}{p_i\ T_{sc}}\right) = G_p\left(\frac{z\ p_{sc}\ T}{p\ T_{sc}}\right)$$

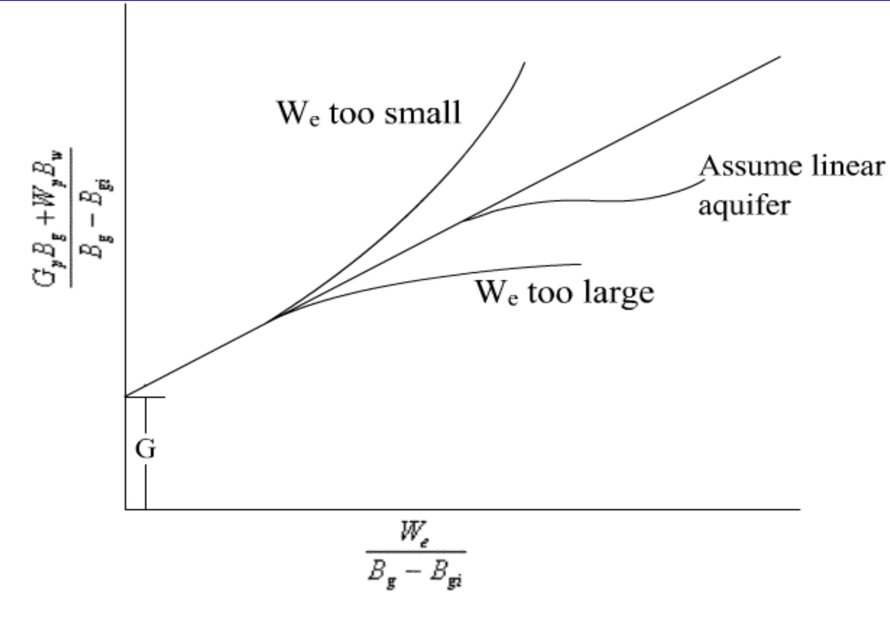
Assuming Isothermal changes in the reservoir (T = Ti)

$$\frac{p}{z} = -\frac{p_i}{z_i G} G_p + \frac{p_i}{z_i} \qquad (22)$$

MBE Applications: Gas Reservoirs



Case 5 MBE for Volumetric Gas reservoirs



Case 6 MBE for Gas reservoirs with water influx

Volumetric depletion, We = 0
Efw = negligible

$$\frac{p}{z} = -\frac{p_i}{z_i G} G_p + \frac{p_i}{z_i}$$

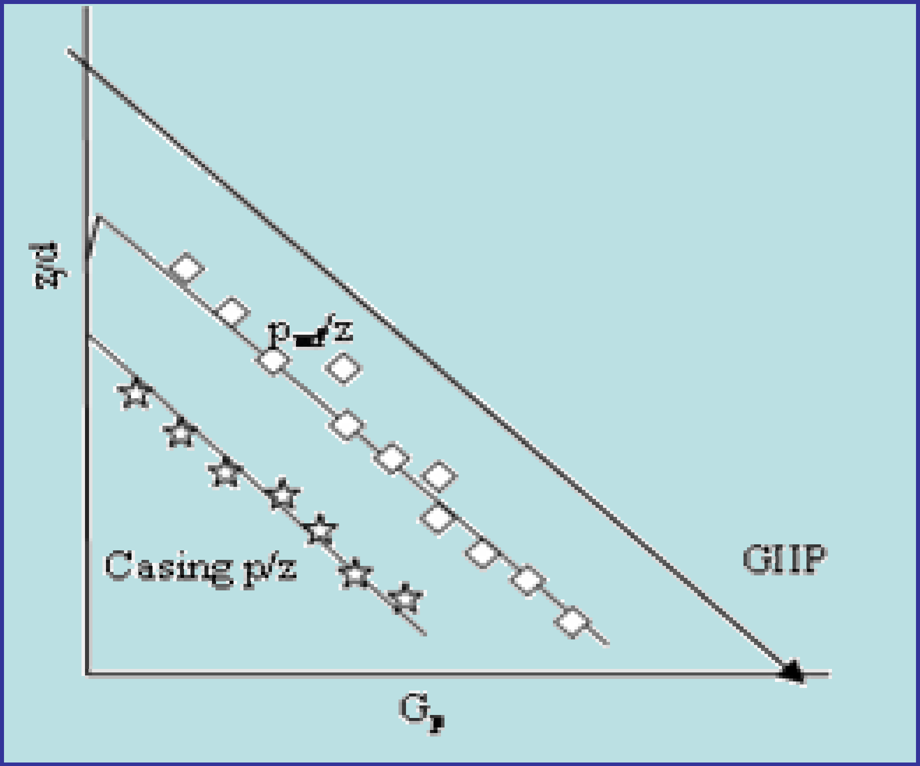
Strong water drive, $W_e \neq 0$
E_{fw} = negligible

$$G + \frac{W_e}{B_g - B_{gi}} = \frac{G_p B_g + W_p B_w}{B_g - B_{gi}}$$

Flowing Material Balance

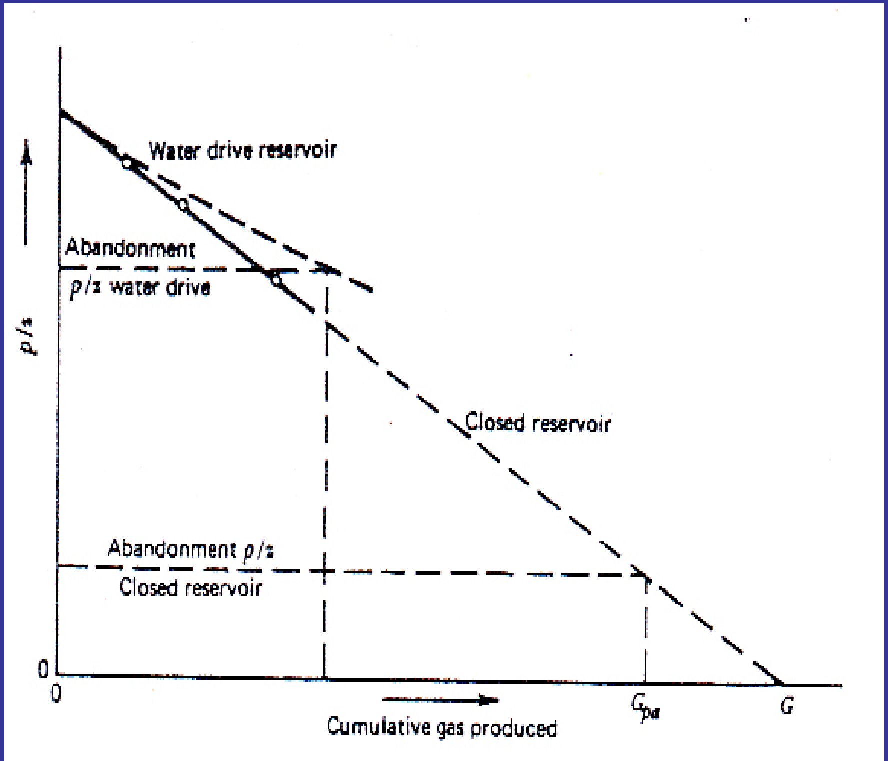
- Developed for Gas reservoir – later extended for oil reservoirs
- Does not account for water drive
- Requires pseudo-steady state flow regime:
  - Reservoir boundaries are ‘felt’
  - pressures at all locations in the reservoir declines at the same rate
- Requires constant flow rate- later extended for variable rate

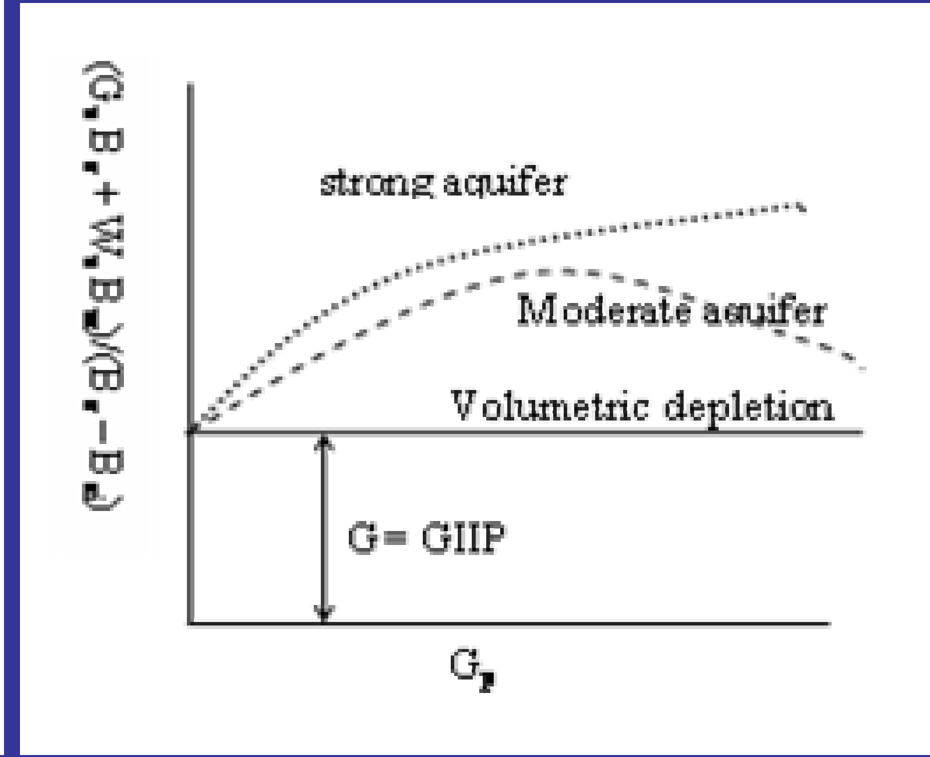
Flowing Material Balance (contd.)



- Classical MBE
  - p/z plot requires average reservoir pressure
  - Requires lengthy shut in tests to determine average reservoir pressure
- Flowing MBE
  - Flowing bottom hole pressures is used
  - pwf/z vs G_p is plotted
  - Well head pressures can also be used

MBE Plotting Technique – Detecting Water Drive





For some water drive gas reservoirs, deviation from p/z plot is not detected until much later

Error in GIIP- large difference between volumetric and MB estimates

Error in Drive mechanism – wrongly assumed depletion type

Alternative plotting technique is more sensitive

Drive Mechanisms & Drive Indices

- A reservoir can have a predominant drive mechanism, or can have a combination of mechanisms.

- Identifying the drive mechanism is important for development strategy and ultimate recovery.

- The drive indices show the relative magnitude of each drive mechanism contributing to total production.

Drive Mechanisms & Drive Indices (contd.)

Dividing through equation 15 by LHS:

Depletion Drive Index (DDI)

$$\frac{N\cdot\left[(B_o-B_{oi})+(R_{si}-R_s)\cdot B_g\right]}{N_p(B_o+(R_p-R_s)\cdot B_g)}$$

Segregation Drive Index (SDI)

$$\frac{N\cdot B_{oi}\cdot m\cdot\left(\frac{B_g}{B_{gi}}-1\right)}{N_p(B_o+(R_p-R_s)\cdot B_g)}$$

Compaction Drive Index (CDI)

$$\frac{\frac{(1+m)NB_{oi}}{(1-S_{wc})}\left(c_w S_{wc}+c_f\right)\Delta p}{N_p(B_o+(R_p-R_s)B_g)}$$

Water Drive Index (WDI)

$$\frac{(W_e-W_p)\cdot B_w}{N_p(B_o+(R_p-R_s)\cdot B_g)}$$

DDI + SDI + CDI + WDI = 1

MBE: Conditions for Application

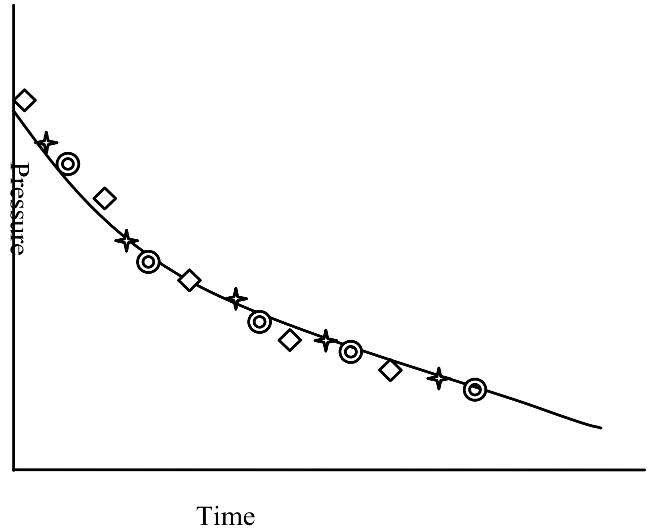


Figure 10: Individual well pressure declines displaying equilibrium in the reservoir

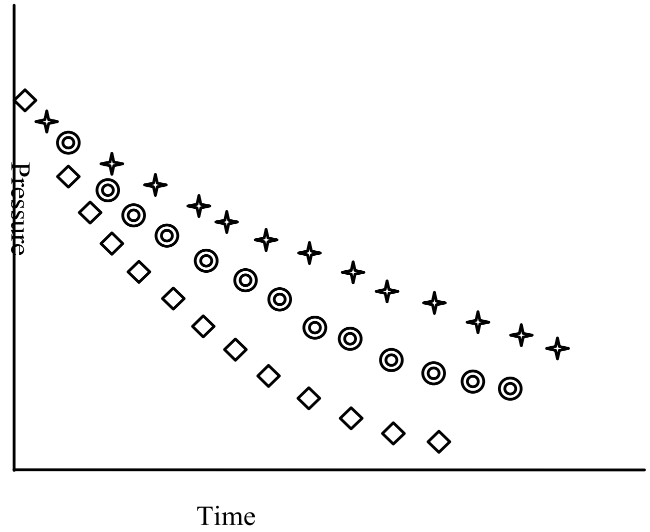


Figure 11: Non-equilibrium pressure decline in a reservoir

1. There should be adequate data collection on production, pressure and PVT properties.
2. It must be possible to define an average pressure decline trend for the system under study.

MBE: Conditions for Application (contd.)

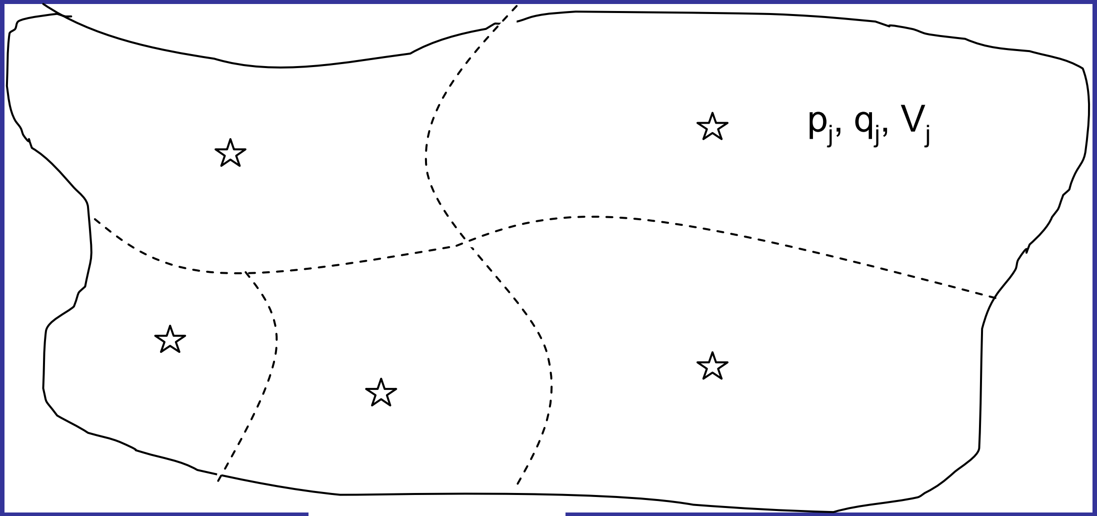


figure 12

The average pressure decline can be determined by the volume weighting of pressures within drainage area of each well

p (avg) = Σ pj Vj / Σ Vj

- It is possible to verify the 2nd condition by plotting the individual well pressures as a function of time (figure 10). It is not really necessary to have rapid pressure equilibrium across the reservoir.
- Average pressure decline trend can be defined even if there are large pressure differences across the reservoir under normal producing conditions.
- Figure 11 shows such a reservoir, where each well has a distinct drainage area and pressure decline (figure 12).

Conclusions

- Volumetric method is applied at early stage of a reservoir, with mostly geological and fluid properties data. No production or time dependency is incorporated in volumetric estimates. As production continues, other methods become applicable.

- Material balance can be applied when about 20% of the initial estimated reserve is produced, or when 10% of initial reservoir pressure has declined.

- MBE is a powerful tool that helps determine the reserves, recovery factor, and drive mechanism.

- MBE can be applied to a variety of reservoirs, either with or without water influx.

Conclusions (contd.)

- Unlike volumetric method, RF can actually be calculated by MBE.
- Volumetric method generally gives the absolute, theoretically maximum possible hydrocarbon in place. MBE gives an indication about the volumes that will actually flow.
- Flowing material balance technique can provide reasonably good approximation of GIIP.
- Flowing material balance technique method removes the need for determining static average reservoir pressure by long and expensive shut in tests.

THANK YOU!

Questions?