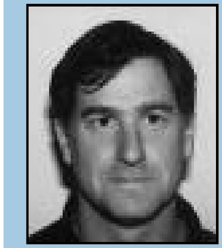
◀ INDEX

DISTINGUISHED AUTHORS SERIES

Reservoir Management for Waterfloods—Part II



Richard Baker has worked on a number of reservoir characterization/reservoir simulation projects world wide in Russia, Indonesia, South America, Middle East and North America. He is currently president of Epic Consulting Services. He has taught courses in reservoir characterization and reservoir simulation both in Canada and internationally. He previously was a senior reservoir engineer at Shell and Husky Oil.

He has interests in reservoir management, naturally fractured reservoirs, reservoir characterization, horizontal wells, EOR and reservoir simulation. He is specifically interested in the use of horizontal wells for improving reservoir characterization and sweep improvement for EOR floods. And is currently working on:

- use of horizontal wells characterize a naturally fractured reservoir and designing a CO_2 flood in West Texas,
- integrating seismic data, fracture data and horizontal wells to improve liquid recovery from a naturally fractured gas condensate reservoir in Canada,
- geostatistics, simulation history matching and history matching pressure transient to characterize a tight gas lenticular reservoir and then understand current horizontal well performance,
- the use of a horizontal well and reservoir characterization to improve vertical sweep efficiency in a waterfloods and hydrocarbon miscible floods in Canada.

He obtained a M.Sc. degree in chemical engineering from University of Calgary and B.Sc. in mechanical engineering from University of Alberta.

Forward

This paper is the second part of a two-part article (part one published April 1997). Waterflood management is critical, particularly for poor quality or geologically complex reservoirs. In part one, we examined oil production response to a waterflood. In the second part, we investigate gas and water production response as well as injection analysis and reservoir pressure response.

Gas-oil Ratio and Water-oil Ratio

An indicator of bypassing is a premature drop in gas-oil ratio; i.e., earlier than expected collapse of gas saturation. Early gas collapse (water fillup) may indicate that channeling has occurred. In layered reservoirs with no or little vertical crossflow, water injection in an initially depressurized layer will cause GOR to drop rapidly. Often naturally fractured reservoirs exhibit fast gas collapse because water fills up the fracture system and does not initially invade the matrix, the desired target for waterflooding. Figure 1 shows an example of a pattern where channeling has occurred. This type of pattern should be reviewed geologically to attempt to identify the thief zones/natural fractures.

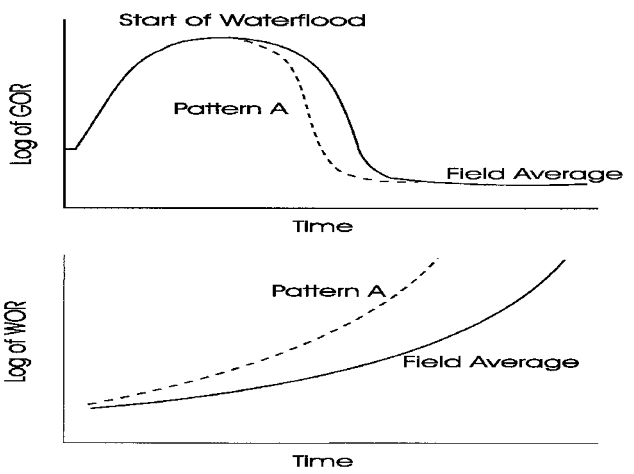


FIGURE 1: Log of GOR and WOR vs. Time for Pattern A and Field Average.

Other key performance indicators are water breakthrough times and subsequent WOR trends, which also can be indicative of channeling and bypassing problems. However, since wells or patterns showing high WOR rise or quick gas collapse may simply be due to high injection rates, one should plot WOR and GOR versus hydrocarbon pore volume injected (HCPVI). In general, if water breakthrough occurs before 20% hydrocarbon pore volume injected (HCPVI), channeling or bypassing due to heterogeneity is likely occurring.

Like the WOR or GOR versus time plots, the log of WOR versus cumulative oil produced (N_p) is used as an indication of channeling and heterogeneity (Figures 2 – 4).(1,2) In an unfavourable mobility ratio situation (M >1), the late time slope of the graph is primarily controlled by the oil water relative permeability curves; therefore, volumetric sweep efficiency can be derived from this plot.(2) In a favourable mobility ratio situation (M (1), the late time slope of the graph is controlled primarily by permeability heterogeneity or fluid segregation. In layered systems, the WOR versus N_p plot may have a stair-type profile as various layers breakthrough (Figure 4). Plotting WOR versus N_p and comparing individual patterns against a group average (e.g., for an entire unit operation) gives a qualitative indicator of volumetric sweep efficiency. This should be evaluated in the context of known or suspected geological trends. Stylized representations of waterflood performance in simplistic geological cross sections are depicted in the companion insets to Figures 3 and 4.

Extrapolation of the WOR versus N_p plot and changes in its slope can indicate incremental oil recovery. Therefore, an examination of the log of WOR versus N_p plot is useful in determining the incremental recovery due to infill drilling or operational changes, as shown in Figure 5. The changing slope of the curve indicates increased reserves after infill drilling. In our experience, successful additional recovery efforts (including recompletions or treatments to suppress water as well as infill drilling) can make

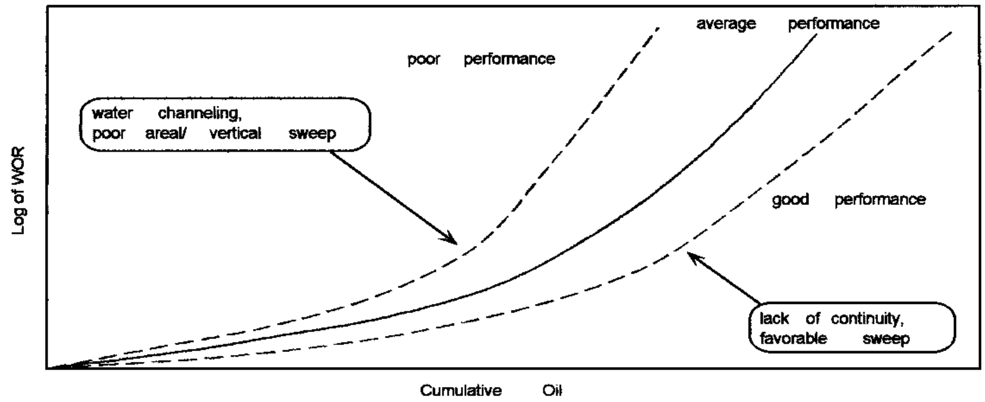


FIGURE 2: Generalized WOR vs. N_p plot.

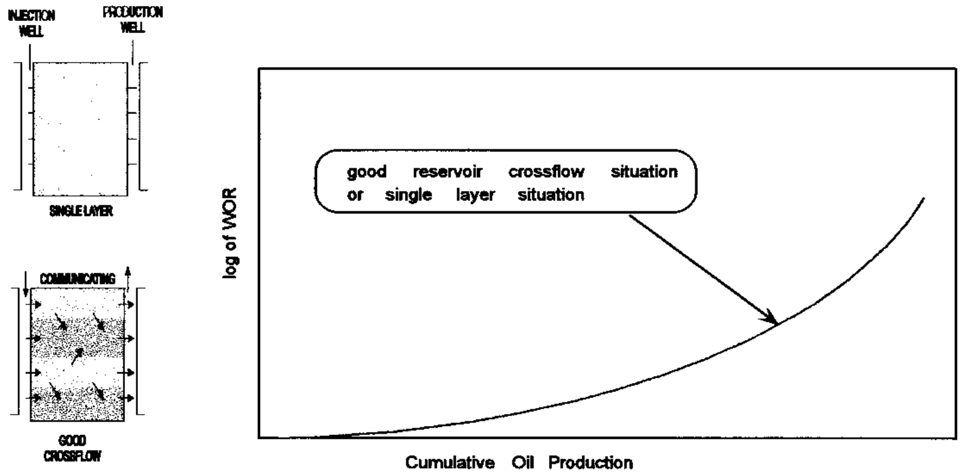


FIGURE 3: WOR vs. N_p for single layered reservoir, or multi-layered reservoir with good crossflow.

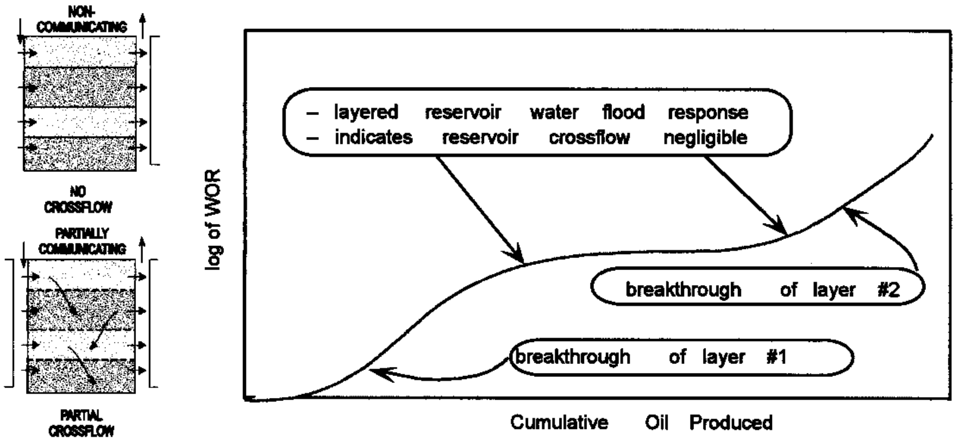


FIGURE 4: WOR vs. N_p for a Layered reservoir with negligible crossflow.

substantial, noticeable changes in the WOR versus N_p relationship.

Calculation of Mobility Ratio, Gravity-viscous Number and Capillary-viscous Number

"Waterdrive in macroscopic reservoir sections occurs on the scale of flooding in hillsides rather than core plugs. At this level, there are three factors which govern the oil recovery efficiency: mobility ratio, heterogeneity and gravity. Precisely how they interact requires careful consideration and, as demonstrated, can sometimes provide surprising results in enhancing or downgrading oil recovery by waterdrive. Correct evaluation of the influence of the three factors amounts to paying rigorous attention to detail in determining the vertical sweep efficiency across sand sections…"(7)

Simple dimensionless ratios(4) can be used to determine the flow regimes expected between wells. This allows the engineer to quickly relate flow regimes to production response signatures, thereby suggesting what factors are the key determinants to oil recovery.

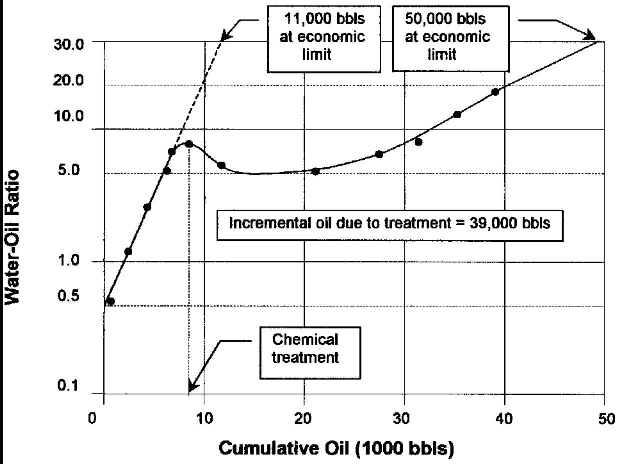


FIGURE 5: Producing well response after a near-wellbore blocking/diverting treatment.

TABLE 2: Indications of watercut performance.

	Homogeneous Reservoir	Heterogeneous Reservoir
$M \leq 1$	Late water breakthrough, rapid watering out of producers	Early water breakthrough, watercut performance depends upon crossflow and permeability contrast ratios
$M > 1$	Early water breakthrough, high but slowly rising watercut	Early breakthrough, generally poor performance

Mobility Ratio

The mobility of a fluid is the effective relative permeability of that fluid divided by its viscosity. For an injection scheme, the mobility ratio (M) is the ratio of the mobility of the displacing fluid behind the flood front to that of the displaced fluid ahead of the flood front.

The most common mobility ratio definition used for an oil water system is(3):

$$M = \frac{M_{rw}}{M_{ro}} = \frac{k^{\Upsilon}_{rw}}{k^{\Upsilon}_{ro}} \mid \frac{\mu_o}{\mu_w} \qquad \text{...(1)}$$

where:

μ_o = oil viscosity

μ_w = displacing fluid (water)

k_{ro} = end point relative permeability to oil

k_{rw} = end point relative permeability to water

The mobility ratio along with the water cut performance profile can be used to identify heterogeneity in the reservoir as indicated by Table 1.

Vertical Equilibrium and Effect of Gravity Forces

The distribution of fluids is dictated by gravity/capillary equilibrium for a waterflood. When a reservoir is produced at low rates and there is a large density difference between injected and produced fluids, gravity forces dominate over viscous forces. As displacement rates increase, viscous forces become stronger, causing fluids to flow preferentially through the more highly permeable layers. This implies the creation of a vertical fluid distribution that is not in gravity equilibrium. The importance of gravity segregation of fluids can be determined by the viscous-gravity time ratio,(4) shown by:

$$N_{gv} = \frac{\text{time required for horizontal flow movement due to viscous forces}}{\text{time required for vertical fluid movements due to gravity forces}} \qquad \text{.....(2)}$$

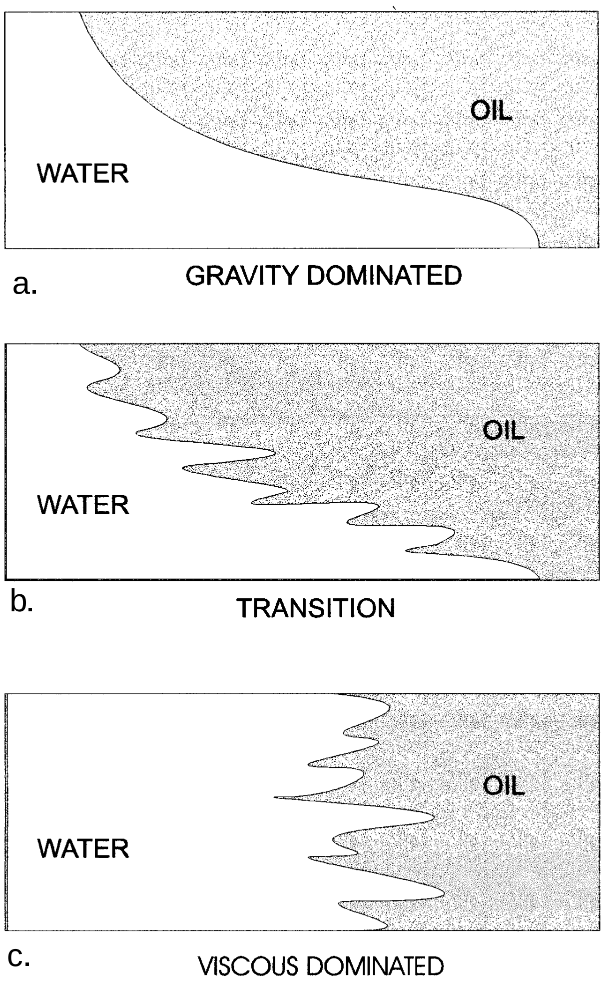


FIGURE 6a: Gravity dominated flow regimes for waterflood displacement in a vertical cross section.
FIGURE 6b: Transition flow regimes for waterflood displacement in a vertical cross section.
FIGURE 6c: Viscous dominated flow regimes for waterflood displacement in a vertical cross section.

In practical field units, the gravity-viscous number becomes:

$$N_{gv} = \frac{K_v\ \Delta\rho\ g\ \cos(\alpha)\ L}{K_h\ \Delta(P_h)}\ \frac{L}{h} \quad \left\langle \textit{field units} \right\rangle \qquad \text{...............(3)}$$

In terms of flow rate and field units:

$$N_{gv} = \frac{K_v\ k_{rw}\ \Delta\rho\ g'\ \cos(\alpha)\ A}{887.2\, q\, \mu_w}\ \frac{L}{h} \quad \left\langle \textit{field units} \right\rangle \qquad \text{.....(4)}$$

$$\text{and } g' = 1/144 \frac{lb_f\ ft^2}{lb_m in^2} = \frac{g}{g_c} \qquad \text{...(5)}$$

where:

$\Delta(P_h)$ = effective pressure difference between injector and producer neglecting near wellbore pressure drop

α = angle of dip

This number is referred to by Baker,(4) Wellington and Vinegar,(7) and Crump.(8) For a reservoir where $N_{gv} < 0.1$, the flow regime is viscous dominated (Figure 6c); when $N_{gv} > 10.0$, the

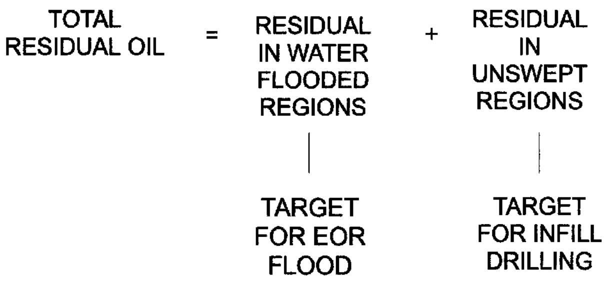


FIGURE 7: Target oil.

flow regime is gravity dominated (Figure 6a). The gravity-viscous number gives an indication of both the importance of gravity forces in a displacement process as well as when gravity equilibrium is re-established. It is important to note that the number does not indicate what the fluid distribution will be.

In general, one would expect a gravity dominated flood to have early water breakthrough, as seen on the WOR versus N_p plot, and that this plot would have a gradual slope indicative of coning behaviour (i.e., substantial post-breakthrough oil production). On the RF versus HCPVI plot, one would expect an early breakpoint but a substantial slope after water breakthrough (again, indicative of substantial post-breakthrough oil production). In other words, peak oil rates are generally modest but oil decline rates are gradual.

Vertical Equilibrium and Effect of Capillary Forces

When water is injected into a layered reservoir, movement of the flood front is more rapid in the more permeable layers. The different flood front positions create sharp saturation gradients between layers. However, for a water-wet system, water is imbibed into the lower permeability layers from the higher permeability layers. This process, called capillary crossflow, is a result of the tendency for tighter rock, with its more tortuous and complex pore structure, to retain the wetting fluid on its greater wetting surface area.

The capillary-viscous number is an indication of the importance of capillary forces in the displacement process and whether capillary equilibrium can be reached. To determine the effect of capillary crossflow, a ratio of viscous redistribution time to capillary redistribution time is computed as:

$$N_{cv} = \frac{K_v\,\Delta(P_c)\,L}{K_h\,\Delta(P_h)\,h}\left(\frac{L}{h}\right) \quad \left\langle consistent\ units \right\rangle \qquad \text{.................(6)}$$

where:

L = reservoir length

A = cross-sectional area

K_v = vertical permeability

K_h = horizontal permeability

h = thickness of reservoir

$\Delta(P_c)$ = capillary pressure difference between leading and lagging layers (use capillary pressure at S_w = 50%)

$\Delta(P_h)$ = pressure difference between injectors and producers neglecting near wellbore pressure losses

In field units:

$$N_{cv} = \frac{K_v\,A\,L\,\Delta(P_c)}{887.2\,q\,\mu\,h^2}$$

$$\left\langle field\ units;\ cp,\ md,\ Rbbl/d,\ ft \right\rangle \qquad \text{.......................................(7)}$$

The capillary-viscous number increases as capillary forces become more important than viscous forces (e.g., when rates decrease, when K_v/K_h increases, when interwell spacing increases or when reservoir thickness decreases). More specifically, when a horizontal waterflood is conducted at low rates, or if vertical permeability is high (i.e., N_{cv} is large on the order of >10), capillary forces dominate the waterflood displacement, causing fluids to travel in the direction transverse to flow. The balance between capillary and viscous forces in such a situation is therefore rate dependent. If capillary numbers are high (N_{cv}>10), we would expect a uniform waterflood front, a late breakover point on the RF versus HCPVI plot and a rapid watering-out of wells once water breakthrough has occurred.(4)

The capillary-viscous number is useful in that it indicates how sharp or diffuse the flood front will be and how much viscous fingering may occur. It is also critical in understanding if capillary forces are a dominant force. The greatest uncertainty in both the N_{gv} and N_{cv} numbers is the vertical permeability and the cross sectional area to flow.

Voidage Replacement Ratio versus Time

Voidage Replacement Ratios on both a field basis as well as a pattern basis should be calculated in the following manner:

$$VRR = \frac{injected\ reservoir\ volumes}{produced\ reservoir\ volumes}$$

$$= \frac{B_w(i_w)}{(B_O q_O) + (B_w q_w) + q_O(GOR - R_S)B_g} \qquad \text{........................(8)}$$

These computations should be done cumulatively as well as

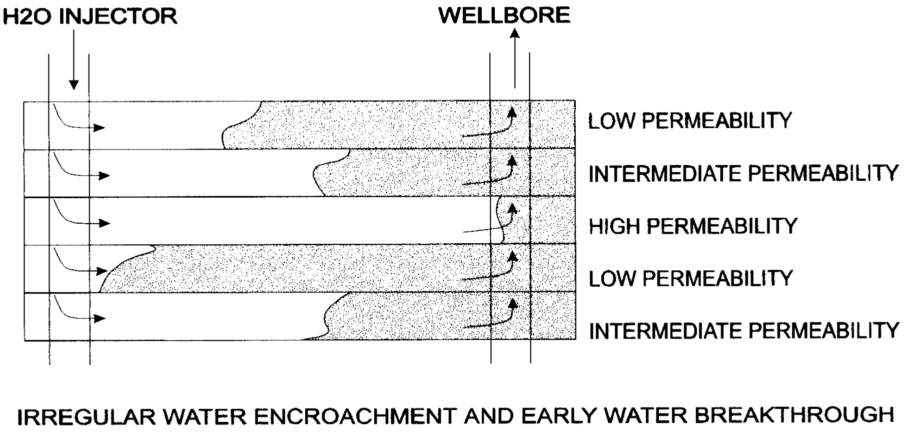


FIGURE 8: Stratified reservoir.

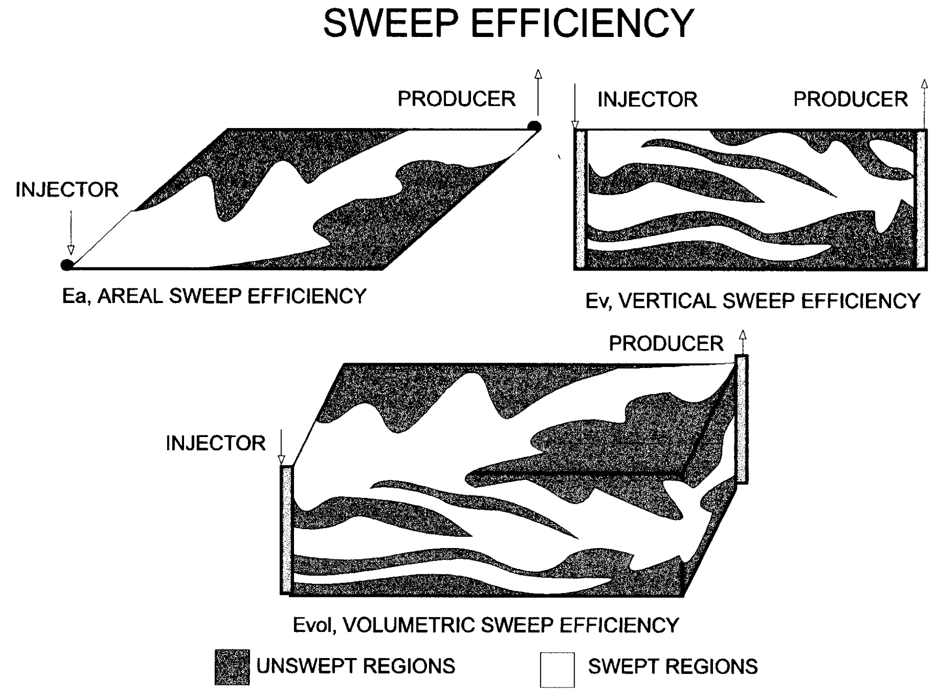


FIGURE 9: Areal, vertical and volumetric sweep efficiencies in a reservoir block.

instantaneously (e.g., monthly) and plotted versus time, providing another tool for monitoring waterflood performance.

Often an engineer may question the need to be concerned about reservoir pressure and material balance analysis when the VRR is essentially unity (i.e., voidage replacement is being maintained). However, there are often water injection losses to non-pay intervals which will result in decreasing reservoir pressure even when VRR appears to be unity (or greater). Periods of depressurization and/or repressurization during waterflood or on primary depletion therefore can be very useful in understanding OOIP and geology. Also note that, although the overall reservoir VRR may in fact be unity, certain areal and/or zonal regions may significantly deviate from this. Finally, geological trends typically do not coincide with patterns; and, where there are heterogeneities and/or communication with active regional systems (e.g., an aquifer), reservoir "drift" (i.e., a velocity field typically caused by a regional system) and/or interpattern flow can be substantial even if a well-balanced pressure-maintenance scheme is in place. Therefore, the generally arbitrary reservoir engineering patterns and VRR calculations should not be assumed to correspond to actual pattern flows. So, in conjunction with VRR calculations, the conformance plot and material balance calculations are recommended; such an analysis is usually successful in identifying interpattern flows.

Voidage replacement ratio versus time plots are used to indicate if pressure has been maintained by water injection. It is important to compare reservoir pressure versus time with voidage replacement ratio versus time plots (we recommend comparing plots of cumulative VRR versus time and average reservoir pressure versus time). Normally, these plots will correlate; anomalies are indicated if they do not. For example, if VRR > 1 and reservoir pressure is not increasing, out of zone injection loss or efflux of fluids from the control area is indicated. If VRR < 1 and reservoir pressure is not decreasing, influx of fluids into the control area is indicated.

Problem Identification

In the final section of this discussion, we will re-cap briefly the critical problem areas in waterflood management. In each of these problem areas, we will provide a list of indicators that may facilitate the identification of the problem.

Volumetric Sweep Efficiency vs. Displacement Efficiency

One of the critical applications of surveillance is to identify the amount and distribution of oil (Figure 7). This is where surveillance adds the most economic value. Channeling through high permeability layers and gravity segregation of injected water below the target oil may result in oil being bypassed (Figures 6, 8 and 9). Throughout the analysis, the surveillance engineer must determine the relative importance of volumetric sweep efficiency (i.e., getting the injected water into the right areal and/or zonal regions of the reservoir) or displacement efficiency (i.e., getting the injected water to efficiently displace oil within the microscopic pores). Jackson,(6) in a study of failed waterfloods, found that 45% of them were due to poor volumetric sweep efficiency; displacement efficiency was found not to be as important as volumetric sweep efficiency in waterflood success. He found poor volumetric sweep efficiency to be twice as likely to cause poor waterflood recovery as poor displacement efficiency. Further, as pointed out by Dake,(3) waterflooding is conducted on "hillsides," not at a pore scale level. In the past the industry has concentrated on easier-to-measure laboratory data to evaluate waterfloods. While laboratory data is important for narrowing the range of displacement efficiency, geological information (particularly the degree of heterogeneity) should be pre-eminent.

Channeling/Gravity Segregation

The indications of channeling, due to heterogeneity, are:

1. low peak oil rate response
2. low total recovery
3. high slope on the WOR versus Np curve
4. early breakover point in the % recovery versus pore volume injected curve
5. high Dykstra-Parsons coefficient (> 0.7) {not applicable to gravity segregation}
6. fast gas collapse (< 0.05 HCPVI of water)
7. increasing WOR versus time derivative for individual wells(9).

Water cut maps will indicate that some producers will have had rapid water breakthrough. The engineering and geological team should try to correlate geological trends with water cut behaviour.

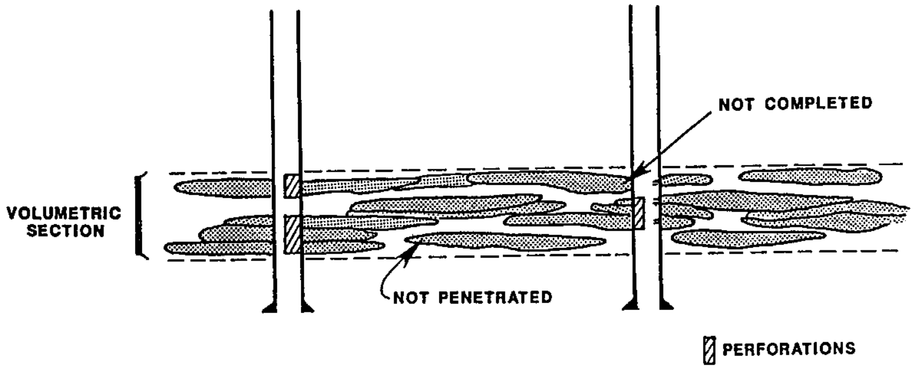


FIGURE 10: The difficulty of correlating thin beds over cross sections.

Poor Continuity

In many tight, lenticular-type reservoirs and/or reservoirs from fluvial environments, continuity may be a major problem. Early identification is important for spacing considerations. Poor reservoir continuity will be indicated by:

1. the OOIP determined by material balance will be much less than the OOIP determined by volumetrics
2. very poor peak oil rate response
3. little or no gas collapse; GOR remains high
4. very large differences in build up pressures between wells, especially between injectors and producers
5. little or no water production seen on either trend maps and WOR versus N_p plots even after >25% HCPVI of water
6. poor injectivity
7. low net to gross pay ratio; often it will be difficult to correlate thin, good permeability beds over cross sections (see Figure 10).

Poor Displacement Efficiency

Some high initial water saturation/low permeability reservoirs may have poor displacement efficiency. This low efficiency may be indicated by:

1. low peak oil rate response
2. low total recovery
3. rapid decline in oil rates
4. high and early water production
5. rapid breakover on RF versus HCPVI plots.

In this case, getting good lab waterflood test data is critical in evaluating performance.

Nomenclature

B_{ob} = Formation volume factor of oil at bubble point
B_{oi} = Formation volume factor of oil at initial reservoir conditions
B_w = Formation volume factor of water
E_d = Displacement efficiency
E_{vol} = Volumetric sweep efficiency
G = Initial reservoir gas in place (also denoted OGIP)
K = Absolute permeability
N = Initial reservoir oil in place (also denoted OOIP)
N_p = Cumulative produced oil (also denoted Q_o)
P_b = Bubble point pressure
P_i = Initial reservoir pressure
q_o = Oil rate
q_w = Water rate
Q_o = Cumulative oil (also denoted N_p)
Q_w = Cumulative water
S_{oi} = Initial oil saturation
RF = Recovery Factor
ROS = Remaining average oil saturation after one pore volume has been injected
S_w = Water saturation
W_I = Cumulative water injected
V_p = Pore volume
ϕ = Porosity
μ_{ob} = Viscosity of oil at bubble point
μ_{oi} = Viscosity of oil at initial reservoir conditions
MPV = Movable Pore Volume

REFERENCES

1. LIJEK S.J., Simple Performance Plots Used in Rate Time Determination and Waterflood Analysis; *SPE 19847, San Antonio Texas, October 1989.*
2. CURRIER, H., SINDELAR, S.T., Performance Analysis in an Immature Waterflood: The Kuparuk River Field; *Society of Petroleum Engineers, 20775, 1990.*
3. DAKE, L.P., Fundamentals of Reservoir Engineering; *Elsevier Science Publishers B.V., 1978.*
4. BAKER, R.O., Effect of Reservoir Heterogeneities and Flow Mechanisms on Numerical Simulation Requirements—A Thesis Paper Submitted to the University of Calgary, Faculty of Graduate Studies; *July 1993.*
5. LAKE, L.W., Enhanced Oil Recovery; *Prentice-Hall, Inc. New Jersey, 1989.*
6. JACKSON, R.W., Why Some Waterfloods Fail; *World Oil.*
7. WELLINGTON, S.L., and VINEGAR, H.J., CT Studies of Surfactant Induced CO_2 Mobility Control; *Society of Petroleum Engineers, 14393, 1985.*
8. CRUMP, J.G., Detailed Simulations of the Effects of Process Parameters on Adverse Mobility Ratio Displacements; *Society of Petroleum Engineers, 17337, 1988.*
9. CHAN, K.S., Water Control Diagnostic Plots; *Society of Petroleum Engineers, 755, 1995.*

Canada Assists Pakistan's Oil and Gas Sector
Continued from page 6

Although workshop participants identified many obstacles for women working in the sector, they also made several positive suggestions for supporting women already in the sector, and for encouraging others to join. A major obstacle for women in the petroleum sector all over the world is work conditions at field sites, which are usually in remote and isolated areas. This is particularly difficult in Pakistan, where women often face opposition to entering the work force at all. One of the conclusions from the workshops was to concentrate on employment in urban areas in Pakistan, rather than field positions at this time.

Many opportunities to offer technical assistance in conjunction with the OGSP will emerge through the next four years. Additional opportunities within specific niches of the sector are likely to increase as Pakistan continues to create incentives and concessions for exploration companies, privatize the companies presently controlling its extensive gas transmission and distribution network, and ultimately develop a market-driven indigenous petroleum industry.

Female and male professionals interested in being considered as a technical advisor in conjunction with the Oil and Gas Sector Programme Pakistan in the short or longer term, please contact Dianne Keenan at Coopers & Lybrand in Calgary at (403) 260-2241, or fax, (403) 260-2114 for further information.