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RESERVOIR MANAGEMENT FOR WATERFLOODS

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Reservoir Management for Waterfloods

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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.

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Abstract

Waterflood projects account for over half the current Canadian and U.S. oil production, so the reservoir management of waterfloods is a key issue. There are numerous published textbooks and simulation methods for the design of waterfloods, however the literature has to a great extent been silent on reservoir surveillance to help monitor and improve existing waterfloods. Often the "operating" engineer has a rate and reserve forecast that often over estimates performance. When comparing actual to predicted waterflood performance, the typical conclusion is that the forecast input data is based on averaged data and is therefore too homogeneous. Consequently, the forecast can be of limited use to the reservoir management team.

The methods presented here emphasize practical uses and their ties to field data and geology. Production and pressure surveillance data can implicitly account for a useful scale of heterogeneity. Therefore this data can be extremely useful, if used properly, in developing changes in operational strategy that can maximize recovery.

This paper describes a simple, direct approach to the reservoir management and analysis of waterfloods. This approach is used in preparation for simulation studies, to quantify the factors limiting recovery and determine if the oil recovery can be improved.

Typical Objectives for Analytical Work

In general the questions that need to be addressed in order are:

1. What is the OOIP?
2. Where is the current OIP?
3. What are the factors limiting recovery?
4. Can we improve oil recovery economically?
5. How do we improve recovery?

There has been a tendency for engineers to proceed with points four and five first and bypass points one to three. This is a major mistake.

Most often, reservoir or simulation studies can have non-unique solutions. For example, it is easy to interpret a waterflood failure as being due to poor displacement efficiency when actually poor volumetric sweep efficiency may be the primary reason for the problems. Therefore, to reduce the chances of misinterpretation it is important to understand the amount and distribution of original and current oil in place. The understanding of flow patterns and the distribution of movable oil saturations are key to limiting the chances of misinterpretation.

A fundamental geological/petrophysical analysis is a cornerstone of good reservoir engineering analysis. However, geological studies alone do not conclusively quantify the reserve and oil rate increases that can be achieved by optimizing the existing waterfloods. While this paper concentrates on the engineering criteria, it is implicitly assumed that a thorough geological/petrophysical study is either done or being done concurrently. A geological/petrophysical study is key in understanding the initial question: What is the OOIP?

It is absolutely critical that the engineer develops an understanding of the reservoir geology as they proceed. In particular the engineer should concentrate on megascopic permeability and porosity trends, as well as reservoir continuity. In other words the engineer should concentrate on hydraulic flow units.

Surveillance Level

This level of analysis should start from the large scale and proceed to the smaller scale. The methodology will probably identify general opportunities and/or problems first and then, as the analysis proceeds, it will become less general and more specific with respect to the scale of specific wells and how to correct problems.

There is an observed tendency for inexperienced engineers to jump from the field level of surveillance to the well level, bypassing pod and pattern levels, in order to speed up the study to develop well specific recommendations. I believe this is a major oversight because most waterfloods display macroscopic inter-pattern

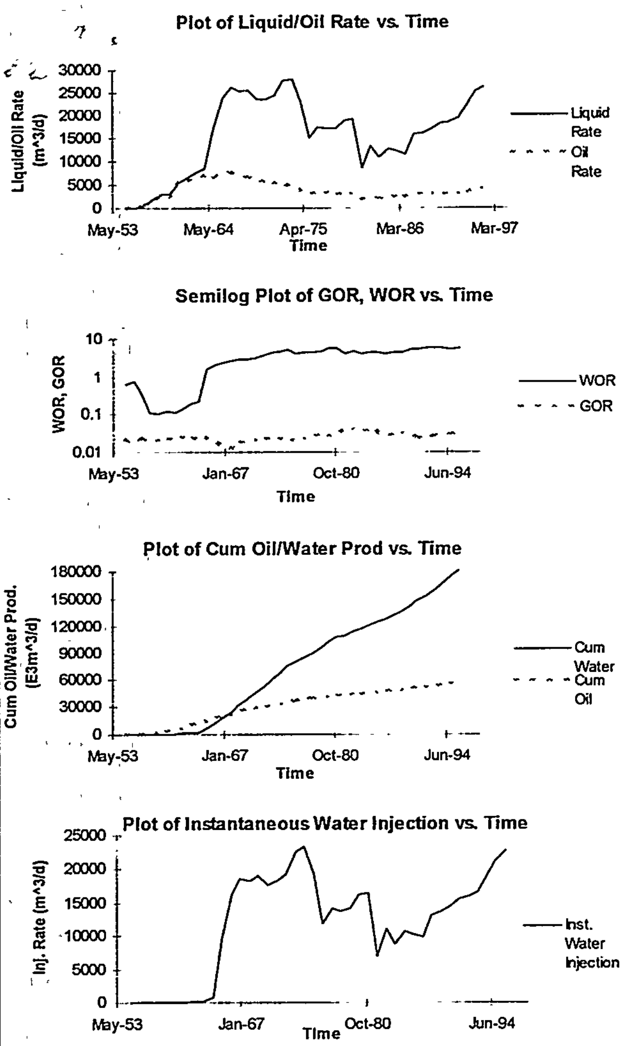

FIGURE 1: Composite reservoir performance chart.

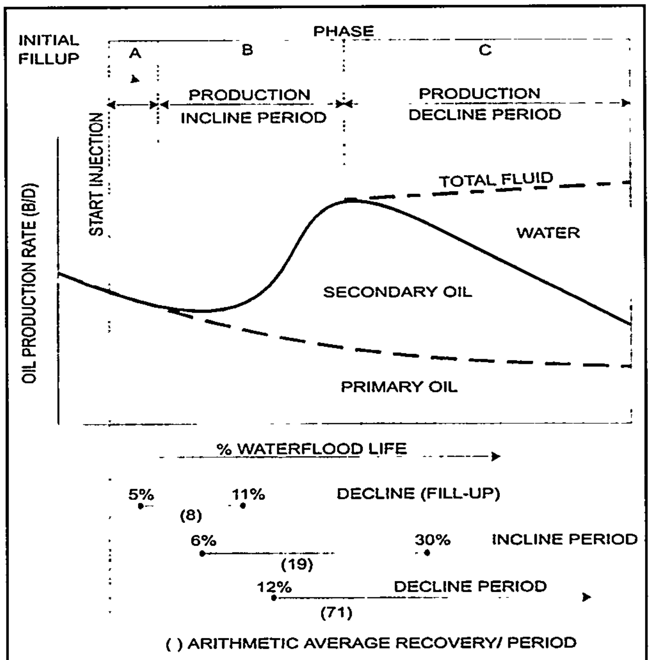

FIGURE 2: Typical successful waterflood performance.[2]

flows and non-uniform volumetric sweep efficiencies. It is important to know these flows to determine the current OIP and its distribution. Neglecting injector/producer flow patterns means that recommended well workovers can be very hit and miss due to the fact that current saturation distribution is not understood. Starting at the field level for surveillance provides a baseline so that engineers can differentiate between poor and good performance. Surveillance on an individual well basis is excellent to get very well specific recommendations after the reservoir flow patterns are understood.

Discussion of Methods

A single technique in isolation is not generally indicative because different parameters can cause similar plot signatures. Combining surveillance plots/techniques is recommended so that a better understanding of the reservoir performance is obtained. This methodology of combining plots and analysis techniques reduces the non-uniqueness problems.

We recommend evaluating the following performance plots/techniques initially for the field, then for patterns, and finally, for individual wells.

1. Composite reservoir performance chart [fluid rate, oil rate, WOR, GOR, cumulative oil and water, and well count vs. time] with clearly annotated changes in operational strategy. (Figure 1)
2. Log of oil rate vs. cumulative oil production.
3. Oil recovery (% OOIP) vs. cumulative net water injected/movable pore volume (conformance plot).
4. Oil recovery (% OOIP) vs. cumulative water injected/hydrocarbon pore volumes (RF vs. HCPVI).
5. Calculation of current and ultimate Volumetric Sweep Efficiency using $N_p = E_{vol} \mid E_d \mid N$
6. Calculation of average throughput rate.

Discussion of Techniques

It is important to generate a composite reservoir performance chart so that the engineer can look for large step changes in fluid production rates, oil rates, and GOR or WOR to see if operational changes correspond to changes in performance. At this stage we are looking at: What are the factors that limit recovery?

Oil Rate Plots and Analysis

Note that a simple Cartesian plot of oil rate vs. time can be very useful in diagnosing field response and is usually a starting point. In analyzing the response it is important to break the response into various periods. In cases where the waterflood is started after significant primary depletion, the common periods are the fillup, incline, peak and decline period. In a case where there has not been much primary depletion, there is usually a plateau period followed by a decline period.

Initial period (fillup): This period begins with the initial water injection and lasts until the first response to injection, represented by a production increase. During this period, the space occupied by gas is being filled, free gas is being brought into solution, and reservoir pressure is being restored (Figure 2). The production rate may continue to decline or may remain steady. As a rule of thumb, the first increase in oil rates usually occurs after a volume of two thirds of the initial voided pore volume of the reservoir has been injected[1]. For some fields in Oklahoma, this period, on the average, ranges from 5% to 11% of the total flood life, depending on the heterogeneity of the reservoir sand, the flood pattern, well spacing, and the volume of void space[2]. In general the more heterogeneous and layered the system, the faster the gas collapse occurs.

Short fillup periods and low peak oil rates during production incline period may be indicative of channeling, bypassing and possibly low levels of pressure depletion. These hypotheses can be confirmed by further examining GOR and WOR trends vs. time.

Production Incline Period: This period occurs when oil production begins to increase through to the peak of the production rate. During this period, the production rate is steadily increasing, and

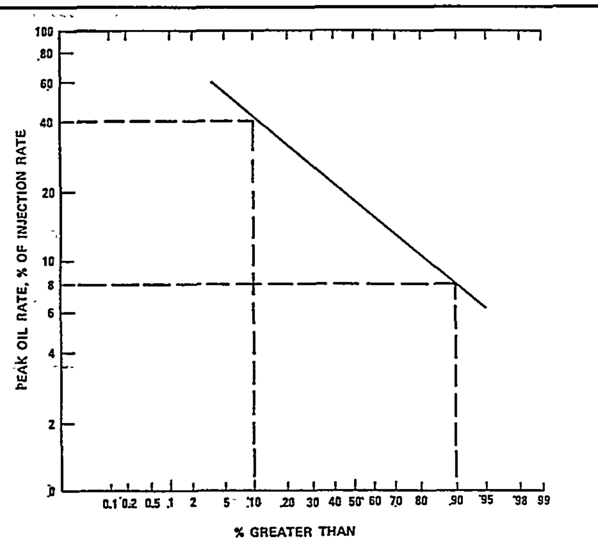

FIGURE 3: Probability distribution of peak oil rates as percent of injection rate during waterflooding.

the water cut is not increasing substantially. The length of time required in this period varies substantially, but, on the average, it is about 20% of the total flood life[2].

Peak Period: In general a higher peak oil rate response in comparison to the primary depletion baseline will occur with:

1. more homogeneous reservoirs
2. more favourable mobility ratios
3. high continuity reservoirs
4. reservoirs with higher primary depletion or pressure depletion
5. reservoirs with better injection support and confinement due to patterns or no flow boundaries
6. fields that have high injection rates

In the case where there is little or no primary depletion and the waterflood is started before significant pressure depletion, the above points with the exception of point four lead to longer plateau periods. Lower mobility ratio waterfloods tend to have better viscous crossflow mechanisms and, in an areal sense, streamline arrival times are similar, resulting in peak oil rates that are higher.

Felsenthal developed Figure 3, that shows peak oil rate to percentage of injection rate[3]. This figure can be used as a rough guide to approximate what the peak oil rates might be. For Felsenthal's data, the median peak oil rate response occurs at 18% of the total injection rate.

If the peak oil rate response is weak or nonexistent, reservoir continuity may be at issue. Usually lack of water production at later times combined with poor gas collapse (high GOR) will confirm this.

Production Decline Period: This period begins after the peak rate has occurred and production rate begins to decline, and continues until the limiting economic rate is reached. In most cases, the production rate decreases as the water cut increases. This period constitutes the largest percentage of the total flood life.

From their study which involved 86 successful Oklahoma waterfloods[2], Bush and Helander showed that the production decline period, is, on average about 70% of the total waterflood life. The cumulative production during the decline period is also about 70% of the total reserves, with an average decline rate of 41%. They observed that two-thirds of the floods declined at 20 to 55% per year, with most curves flattening after the first year.

Although early water breakthrough and lack of oil banking can cause some disappointment, substantial reserves can be recovered after water breakthrough and during the decline period. It is important to carefully examine the decline period. If a decline rate is low (<10%) reservoir crossflow may be very effective in providing additional volumetric sweep. Many reservoirs can have early water breakthrough yet yield very high ultimate recoveries. This is especially true for some fractured, heterogeneous, layered or thick reservoirs with gravity segregation. In these situations, viscous, capillary or gravity forces can result in a large amount of reservoir crossflow, which can recover substantial reserves after breakthrough. In these situations, expect the water cut to initially rise quickly and then increase very gradually over a long period of time. In these cases, it is important to examine logs and core data to get an indication of vertical continuity.

Finally, in analysing oil rate plots remember that additional infill wells generating increased fluid rates may distort the picture somewhat, along with pipeline and facility capacities and government regulations. When analysing individual well response it is critical to note when offset producers are drilled. Well interference between newly drilled producers and old producers is indicative of good reservoir continuity. However, newly drilled producers, especially high rate horizontal wells, will distort flow patterns and cause offset wells to decline much more rapidly.

Decline Analysis

Simple decline plots can give a rough estimate of total recovery and potential incremental recovery due to operational changes. It is important that we do not neglect these plots. There is a balance between over using decline analysis and neglecting the type of analysis. Note the following considerations:

- Reservoir energy and drive mechanism are mainly responsible for the behaviour of decline curves, but well efficiency should not be neglected.
- Gradual buildup of skin or decrease in lifting efficiency may cause similar declines as typical in loss of reservoir energy.
- Relative permeability and fluid saturation play key roles.

Decline curve analysis is powerful for well developed mature fields where flow patterns are established and fluid rates are constant.

Arps showed that for his study area 90% of his fields were hyperbolic decline and no harmonic declines were observed[4]. Bush's Oklahoma study showed mainly harmonic/hyperbolic decline types[2]. Ramsay and Guerrero showed that hyperbolic and harmonic decline was typical[5]. Schuldt et al. indicated that waterflooded oil reservoirs are generally expected to follow hyperbolic decline behaviour. In Canada, Wong showed that most decline types were hyperbolic[6]. In conclusion, the most typical decline types for waterfloods are harmonic or hyperbolic. Lijek showed that there are strong theoretical derivations that tie straight line behaviour on a WOR vs. N_p plot to harmonic or hyperbolic decline types[7]. Often, varying injection/fluid production rates may distort decline rates.

It must be remembered that decline analysis is useful for forecasting expected recovery but it does not tell you how to improve recovery. It is risky to extrapolate historical trends without understanding the factors contributing to the decline or anticipating new factors that come into play[8]. The majority of waterfloods are managed by only looking at oil rate analysis and the wealth of information available by examining pressure and gas/water rates is left out. For proper reservoir management this data should also not be neglected.

Conformance Plot

Another technique that we use heavily is the conformance plot, (Figures 4 and 6) whose primary use is to identify pattern flows and losses to non pay zones. In an ideal case where pressure was constant, there is no initial gas saturation and there was no efflux or influx into the area, the graph should be a straight line with net water volume plotted on the x-axis and oil withdrawals plotted on the y-axis. Changes in slope in the conformance plot may be indicative of:

- influx or efflux out of the control volume
- losses of water to a non-oil pay zone (i.e., gas cap)
- collapsing gas saturation
- pressurization or de-pressurization of pay

Normally for a summary conformance plot of a large number of wells the conformance plot is quite linear. The plot in Figure 4 shows data for an actual waterflood. With losses to non pay zones,

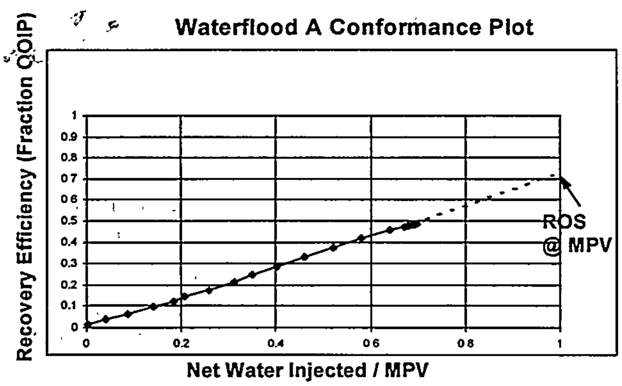

FIGURE 4: Conformance plot.

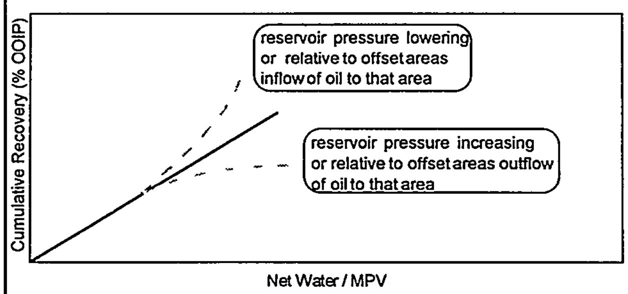

FIGURE 5: Conformance plot; effect of efflux/influx into area.

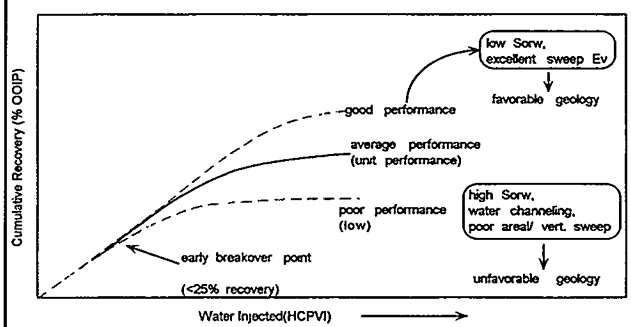

FIGURE 6: RF vs. cum. water injected (HCPVI).

gas caps or initial free gas in the reservoir at the start of waterflooding, the conformance plot will no longer be a straight line. The deviation from straight line behaviour can be used to estimate oil migration volumes.

A theoretical line should first be calculated as a reference point. The end point of the graph should be equal to the displacement efficiency after injecting one movable pore volume of water while the zero recovery and MPV should be the other end point. The displacement efficiency at one movable pore volume can be calculated by:

$$E_d = \frac{(S_{oi} - ROS)}{S_{oi}} \quad \text{......(1)}$$

E_d = displacement efficiency

S_{oi} = initial oil saturation

ROS = the remaining average oil saturation after one movable pore volume has been injected Note this is not the same as S_{orw}. Residual oil saturation (S_{orw}) measurements are taken after multiple pore volumes have been injected into a core, whereas in the field most rock may see less than a pore volume of throughput.

If there is already a well established conformance plot trend then extrapolate the line to one movable pore volume (MPV) injected and estimate an economic displacement efficiency. Using this technique, displacement efficiencies are commonly in the 40-60% range. This usually results in (ROS) being 5 to 10% higher than S_{orw}. The justification for this is small scale by-passings of oil and limited pore volume throughput.

When we look at conformance plots for individual well patterns or pods, we often see significant non linear trends. These trends indicate interpattern flow and/or gas collapse (Figure 6). The conformance plot is an important tool to get rough indications of flow in the reservoir and to determine areal allocation factors for the patterns and pods. If there are significant deviations from the trend line in a pattern or pod conformance plot, the injected water and displaceable volume may be correct, but we may need to adjust the areal allocation factors.

Flow of fluids from or into a pattern from an adjacent pattern will cause the actual performance to be different than the theoretical line. In this case changing the areal allocation factors should be applied to bring the performance back to the trend line (Figure 5). Material balance and reservoir drift maps are extremely useful for confirming allocation factors as well.

Oil Recovery vs. Cumulative Water Injected Plot

The Cumulative Oil recovery (% OOIP) vs. Cumulative water injected/hydrocarbon pore volumes HCPVI (Figure 6) plot is very useful to determine how individual patterns/pods compare to the field average or even other fields. Again the trends are what is important not the absolute numbers. The key question that this plot addresses is: Is recovery low because of low injected volumes (low throughput) or is it low because the reservoir is near to residual oil saturations[9]? The main issue is again: What are the factors limiting recovery?

The waterflood recovery plot break over point occurs at the time when substantial bypassing begins. Normally, for good performing waterfloods, we see break points occur at ~20% total oil recovery for a favourable mobility ratio. Early break over points may be indicative of heterogeneity or unfavourable mobility ratio. According to Sloat, "projects suffer from early water breakthrough owing to extreme permeability variation generally wind up in the 20% recovery efficiency category"[10].

Rapid decreases in slope of the RF vs. HCPVI plot may be indicative of either:

- excessive channeling due to heterogeneity, or:
- fracturing out of zone and water losses to non pay zones

It is important to plot pods with a consistent geology and compare performance to the average trend for the field. We should then compare and group individual patterns in to type high, medium, and poor performance as well as compare performance to the average trend for field.

Often, for mature waterfloods, we can "French curve" these graphs and get an estimate of the oil recovery. A decline analysis should be compared to the extrapolated recovery from the RF vs. HCPVI plot. If the decline analysis shows a much lower recovery than the RF vs. HCPVI plot, this would indicate that recovery is low because water injection throughput rates are low. If decline analysis shows a higher recovery than the RF vs. HCPVI plot, this may indicate that recovery is being supplemented by other drive mechanisms such as gas cap, solution gas or water drive.

Under normal conditions the RF vs. HCPVI plot should have a constant, monotonically decreasing slope. If individual patterns show sudden upward trends and increasing slopes, this may indicate changes in inter-pattern flows. This can be confirmed by examining conformance plots.

As a reference endpoint, normal West Texas and Canadian waterfloods recovery statistics show ultimate recoveries ranging from 25 to 35% with 40 acre spacing averaging ~30% and 20 acre spacing averaging in the upper 30%. For Canadian waterfloods alone, the average recovery is 30% and the range is 16 to 45%[11]. To give an "average" end point, for typical "floods," to the RF vs. HCPVI plot use 30% recovery at 1.25 HCPVI[2].

Estimation of Volumetric Sweep

It is important to get an estimate of current and final volumetric sweep efficiency at this stage using:

$$RF = E_{vol} \xi E_d \quad \text{.........(2)}$$

Displacement efficiency can be estimated by equation 1 or from flood pot tests. Therefore at this stage with a good recovery number and good lab data we can estimate a global volumetric sweep efficiency. This is useful for determining: Where is the current OIP? If volumetric sweep efficiency is low, then infill drilling may be warranted. This equation should be used for both ultimate and current recovery. Estimates of ultimate recovery can come from decline analysis or from extrapolation of RF vs. HCPVI plot. According to Willhite, volumetric sweep efficiency ranges from 0.1 for heterogeneous reservoir to greater than 0.7 for homogeneous reservoirs[12].

Throughput Rate

Another number to calculate is the average throughput rate per year, which is simply:

$$ThroughputRate = \frac{W_I B_W}{V_P(Years)} \quad \text{.........(3)}$$

where:

W_I = cumulative injected volumes

B_w = water formation volume factor

V_P = pore volume

Years = Number of Years Waterflooded

Typical Canadian waterfloods have throughput rates of 2 – 5% pore volume per year. Bush et al. shows the average Oklahoma waterflood had throughput rates of 10% pore volume per year[2]. According to Willhite, a review of waterfloods shows that waterfloods typically require one to two pore volumes of water to recover the majority of mobile oil[12].

Mapping Trends

Often when examining geological trends, it is better to examine bubble plot or contour map displays of water cut, cumulative oil, current oil rate, current reservoir pressure etc. The engineer/geologist should lay the horizontal permeability, porosity, net to gross, net pay, reservoir quality maps out beside the production maps to see if any trends exist.

In some cases, no obvious trend may appear because the geological data is strongly influenced by point source data whereas cumulative oil is not only influenced by well permeability (point source data) but also by injection support. At this point, a combined geological/engineering team is needed to benefit from the major synergistic effect between the geology maps and the production data maps.

Conclusions

In the first part of this two part article, we examined oil, gas, and water production response from waterfloods as a management tool. The second part further investigates gas and water production response as well as injection analysis and reservoir pressure responses. The conclusions derived from the article are as follows:

1. A methodology was proposed for waterflood management. The methods were based on simple surveillance techniques that allow various methods and plots to extract valuable information on reservoir heterogeneity and flow mechanisms.
2. It is critical to understand reservoir flow pattern for successful reservoir management.
3. Implementing a multilevel surveillance effort is critical to understanding reservoir flows and reducing non uniqueness in interpretation.
4. Typical waterflood recoveries and production profiles were presented to act as a reference point for waterfloods.
5. Surveillance techniques should always be a precursor to in-depth studies, including numerical simulation.

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 efficiency
G = initial reservoir gas
K = permeability
N = initial reservoir oil
N_p = cumulative produced oil
P_b = bubble point pressure
P_i = initial reservoir pressure
q_o = oil rate
q_w = water rate
Q_o = cumulative oil
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

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