I submit for approval the following research proposal for my: Thesis

Major: Petroleum Engineering

Tentative Title:

The Analysis and Interpretation of Water-Oil Ratio Performance in Petroleum Reservoirs.

Journal used for Style and Format: Journal of Petroleum Engineering

This research proposal includes 5 attached sheets. (A maximum of ten pages of narration).

Will human or animal subjects be used in this research? No. If Yes, please attach a copy of approved form from the Institutional Review Board for the human subjects or the University Laboratory Animal Care Committee for animal use.

The proposal should contain concise information on the following:
1. Objectives: A clear statement of the results you hope to obtain through the proposed research.
2. Present Status of the Question: Summarize the previous research in your area, identifying particular problems which your study may help to resolve. Include specific citations in your summary.
3. Procedure: Clearly indicate the methods you will use in gathering and analyzing the data to accomplish your objectives.

Approval Recommended:

Name: T.A. Blasingame
(Committee Chair)
Date: 1 Sep 99
PETE
Dept.

Name: W.J. Lee
(Member)
PETE
Dept.

Name: R.R. Berg
(Member)
GEOI
Dept.

Name: (Member)

Name: (Member)

Name: (Graduate Council Representative **)

**For Doctoral Students Only

Name: T.A. Blasingame for
(Department Head)

Student's Signature

BONDAR, Valentina V.
Student's Name

000-03-1109
Student's I.D. Number
401 Harvey Rd. #188
College Station, TX 77840
Mailing Address

Name: Dept.
(Member)

Date of Approval

For the Office of Graduate Studies

Office of Graduate Studies
January 20, 1998
THE ANALYSIS AND INTERPRETATION OF WATER-OIL RATIO PERFORMANCE IN PETROLEUM RESERVOIRS

Valentina Bondar

B.S. Petroleum Engineering (1997)
Moscow State Academy of Oil and Gas (Russia)

Introduction

Natural water drive and/or water injection are two of the most common drive mechanisms in oil production. Detailed analysis of past performance data should be conducted in order to predict future performance and to estimate the volume of movable oil ($N_{p,mov}$). The logarithm of the water-oil ratio ($WOR$) or water cut ($f_w$) functions plotted versus cumulative oil production are commonly used for evaluation and prediction of waterflood performance. This presumed log-linear relationship of $WOR$ (or $f_w$) and oil recovery allows extrapolation of the straight-line to any desired water cut as a mechanism for determining the corresponding oil recovery. Straight-line extrapolation methods assume that the mobility ratio is equal to unity and the plot of log ($k_w/k_o$) versus $S_w$ is a straight line.¹ According to Ershagi and Omorogie¹ this approach is only applicable when $f_w$ is greater than 0.5, and should not be used during the early stages of a waterflood.

Our goal is to develop and test a multivariable equation, which incorporates properties of both phases (oil and water) and does not involve the assumptions of conventional analysis (the mobility ratio is not required to unity, and general relations for relative permeability are assumed). This model is an extension of steady-state model (straight-line extrapolation methods) to the case of the pseudosteady-state flow regime (for both the oil and water phases). The pseudosteady-state model reproduces observed field performance better than the steady-state models previously presented.

Aside from the estimation of $N_{p,mov}$, $WOR$ can be plotted versus time on a log-log plot and used as a diagnostic tool to the dominant mechanism for reservoir performance (uniform displacement, coning or channeling).²
It is our intention to develop a technique that combines the classic techniques with recent methods for the analysis of oil and water performance data. We believe this approach will be a powerful tool for the interpretation of water-oil ratio performance in petroleum reservoirs.

**Objectives**

Our objective is to extend the conventional water-oil ratio analysis based on steady-state flow theory to the case for pseudosteady-state flow.

**Goals and Objectives:**

1. We will estimate and compare values of movable oil using various methods for the analysis of oil and water production data.

2. A new method for estimating $N_{p,mov}$ will be introduced. We suggest that $1/q_o$ versus the oil material balance time ($t_o=N_p/q_o$) plot can be used to evaluate $N_{p,mov}$ since a linear trend was observed for all cases considered. In addition, the values of $N_{p,mov}$ obtained correspond to those determined by the conventional techniques (decline curves, EUR plots, etc.).

3. We provide the development of pseudosteady-state WOR equation, which uses pseudosteady-state models for oil and water flow. We believe that this combined model gives the best representation for the actual production performance behavior.

4. Our objective is to investigate and analyze WOR and WOR derivative behavior as a function of material balance and production time trends ($t_o$ and $t_p$). Further, we also consider the WOR integral and WOR integral-derivative functions as well.

**Present Status of the Question**

In 1978 Ershagi and Omoregie,⁴ and then later (1984) Ershagi and Abdassah⁵ presented a technique for the extrapolation of water-cut versus recovery curves for the waterflood process. The proposed method is based on the concepts of fractional flow and the frontal
advance theory proposed by Buckley and Leverett. This approach provides the estimation of a field relative permeability ratio curve that includes reservoir properties as well as operational conditions of the field. This approach also provides an estimate oil recovery.

In 1989, Lijek\textsuperscript{4} investigated various WOR analysis techniques and presented analytical methods by which the oil rate can be modeled as a function of time. It was shown that predictions were possible for either the constant rate or constant producing pressure cases if the logarithm of water relative permeability versus \( S_w \) could be approximated by one or more linear relationships. In such cases the gross rate (water + oil) can be represented by a power function of WOR, or the logarithm of the gross rate can be represented as a function of cumulative oil production.

In 1995, Chan\textsuperscript{2} presented a new technique for the diagnosis and evaluation of the production mechanisms (reservoir water coning or channeling). It was suggested that log-log plots of WOR and WOR derivative functions versus time showed different characteristic trends for different performance mechanisms.

In 1997, Yortsos, et al\textsuperscript{5} conducted analytical and numerical studies of WOR trends under a variety of conditions. They analyzed the behavior of WOR versus time curve for different periods of time (following breakthrough or at late times) and developed a methodology to interpret the observed behavior. Yortsos, et al\textsuperscript{5} indicated that this relation contains two effects — one due to relative permeability (and mobility) and another due to the production scenario.

\textbf{Procedure}

Our primary goal is to demonstrate the analysis of oil and water rate data using a variety of techniques to predict movable oil volumes at current conditions. Our approach will include: single-phase analogs (analyzing the oil and water data separately), as well as empirical and semi-analytical methods for analyzing the oil and water data simultaneously.

To achieve the objectives of this research, we propose the following tasks:
1. Review the conventional approaches for WOR analysis:
   - \( \log(\text{WOR}) \) versus \( N_p \) approach.
   - Ershagi and Omori\(^1\) model.
   - Yortsos, \textit{et al}\(^5\) model.
   - Chan\(^2\) approach — \( \text{WOR} \) and \( \text{WOR} \) derivative diagnostic plot.

2. The pseudosteady-state model for the water-oil ratio function (\( \text{WOR} \)) is given by:
   - General pseudosteady-state flow model for a closed reservoir system, single-phase liquid case:
     \[
     q_o = \frac{1}{b_o + m_o (N_p / q_o)} \Delta p \tag{1}
     \]
   - The combined pseudosteady-state flow model for a closed reservoir system, two-phase liquid (water/oil) case:
     \[
     \text{WOR} = \frac{b_o + m_o (N_p / q_o)}{b_w + m_w (W_p / q_w)} \tag{2}
     \]

3. Analysis of \( \text{WOR} \) data: Estimation of \( N_{p, \text{mov}} \) (movable oil at current conditions)
   - Conventional analysis of oil and water rate performance data
     - \( \log(q_o) \) and \( \log(q_w) \) versus production time.
     - \( q_o \) versus cumulative oil production, \( N_p \).
   - Two-phase pseudosteady-state flow model.
     - Fractional flow of oil, \( f_o \), versus cumulative oil production, \( N_p \).
     - Reciprocal fractional flow of water, \( f_w \), versus cumulative oil production, \( N_p \).
   - \( \log(\text{WOR}) \) versus \( N_p \) approach
     - \( \log(f_w) \) \( (f_w=\text{fractional flow of water}) \) versus cumulative oil production, \( N_p \).
     - \( \log(\text{WOR}) \) versus cumulative oil production, \( N_p \).
   - Single-phase pseudosteady-state flow model (separate analysis for oil and water).
     - Reciprocal oil rate \((1/q_o)\) versus oil material balance time \((N_p/q_o)\).
• Reciprocal water rate ($1/q_w$) versus water material balance time ($W_p/q_w$).

• Extended Chan$^2$ approach — diagnostic plots:
  • $WOR$ and $WOR$ derivative functions versus oil material balance time ($N_p/q_o$).
  • $WOR$ integral and $WOR$ integral-derivative functions versus oil material balance time ($N_p/q_o$).
  • $WOR$ and $WOR$ derivative functions versus production time.
  • $WOR$ integral and $WOR$ integral-derivative functions versus production time.

4. Decline Type Curve Analysis:

• Conventional single-phase analysis of oil and water rate performance data:
  • ($q_o/\Delta p$) versus oil material balance time ($N_p/q_o$).
  • ($q_w/\Delta p$) versus water material balance time ($W_p/q_w$).
  • ($f_o/\Delta p$) versus oil material balance time ($N_p/q_o$).

References


APPENDIX

In this Appendix we provide plots of well performance data and WOR data analysis for North Robertson Unit (West Texas) and White Lake Field (South Louisiana). These plots are used to orient the reader as to characteristic behavior for a reservoir system undergoing a waterflood.
$q_o$ and $q_w$ Versus Production Time: NRU Well 3107

![Graph of Oil and Water Rates - Well NRU 3107]

Fig. A.1.a – Oil and Water Production Rate History, NRU Well 3107.

$q_o$ Versus $N_p$: NRU Well 3107

![Graph of Oil Production Rate Versus Cumulative Oil Production, NRU Well 3107]

Fig. A.1.b – Oil Production Rate Versus Cumulative Oil Production, NRU Well 3107.
$f_o$ Versus $N_p$: NRU Well 3107

![Graph showing the relationship between $f_o$ and $N_p$]

Legend:
- $f_o$ Function
- $f_o$ Linear $N_p$ Model
- $f_o$ pss Model

Pseudosteady-State Model:

$$f_o = \frac{1}{1 + (1.9422 + 1.1108 \times 10^{-3} t_o)(62.451 + 4.1516 \times 10^{-2} t_w)}$$

Variables:

$t_o = N_p/q_o$, $t_w = W_p/q_w$

$N_{p,mov} = 164,500$ STB

Cumulative Oil Production, $N_p$, STB

---

$1/f_w$ Versus $N_p$: NRU Well 3107

![Graph showing the relationship between $1/f_w$ and $N_p$]

Legend:
- $1/f_w$ Function
- $1/f_w$ Linear $N_p$ Model
- $1/f_w$ pss Model

Pseudosteady-State Model:

$$1/f_w = 1 + (62.451 + 4.1516 \times 10^{-2} t_w)(1.9422 + 1.1108 \times 10^{-1} t_o)$$

Variables:

$t_o = N_p/q_o$, $t_w = W_p/q_w$

$1/f_w = 1.7464 - 4.53739 \times 10^{-4} N_p$

$N_{p,mov} = 164,500$ STB

Cumulative Oil Production, $N_p$, STB

---

Fig. A.1.c – Fractional Flow of Oil Versus Cumulative Oil Production, NRU Well 3107.

Fig. A.1.d – Reciprocal of Fractional Flow of Water Versus Cumulative Oil Production, NRU Well 3107.
**f_w Versus N_p**: NRU Well 3107

![Graph showing fractional flow of water versus cumulative oil production with a line equation and data points.]

\[ f_w = 0.54 \exp(3.74581 \times 10^{-5} N_p) \]

**Legend:** NRU 3107
- \( f_w \) Function
- \( f_w \) Exponential \( N_p \) Model
- \( f_w \) pss Model

**Fig. A.1.e** — Fractional Flow of Water Versus Cumulative Oil Production, NRU Well 3107.

**WOR Versus N_p**: NRU Well 3107

![Graph showing water-oil ratio versus cumulative oil production with a line equation and data points.]

\[ WOR = \exp(1.24 \times 10^{-5} N_p) \]

**Legend:** NRU 3107
- WOR Function
- WOR Exponential \( N_p \) Model
- WOR pss Model

**Fig. A.1.f** — Water-Oil-Ratio Versus Cumulative Oil Production, NRU Well 3107.
$1/q_o$ Versus Oil Material Balance Time: NRU Well 3107

![Graph showing the relationship between $1/q_o$ and Oil Material Balance Time. The graph includes a line equation and a point marked with its corresponding NRU Well 3107 values.]

**Fig. A.1.g** – Reciprocal of Oil Rate Versus Oil Material Balance Time, NRU Well 3107.

$1/q_w$ Versus Water Material Balance Time: NRU Well 3107

![Graph showing the relationship between $1/q_w$ and Water Material Balance Time. The graph includes a line equation and a point marked with its corresponding NRU Well 3107 values.]

**Fig. A.1.h** – Reciprocal of Water Rate Versus Water Material Balance Time, NRU Well 3107.
**WOR and WOR Derivative Versus Oil Material Balance Time: NRU Well 3107**

![Graph showing WOR and WOR derivative functions versus oil material balance time.](image)

**Legend:** NRU 3107
- **WOR Function**
- **WOR\(_d\) Function**
- **WOR\(_{pss}\) Model**
- **WOR\(_d\) pss Model**

**Fig. A.1.i** — Water-Oil Ratio and Water-Oil Ratio Derivative Versus Oil Material Balance Time, NRU Well 3107.

**WOR Integral and Integral-Derivative Versus Oil Material Balance Time: NRU Well 3107**

![Graph showing WOR integral and integral-derivative functions versus oil material balance time.](image)

**Legend:** NRU 3107
- **WOR\(_I\) Function**
- **WOR\(_{I\_d}\) Function**
- **WOR\(_I\) pss Model**
- **WOR\(_{I\_d}\) pss Model**

**Fig. A.1.j** — Water-Oil Ratio Integral and Integral-Derivative Versus Oil Material Balance Time, NRU Well 3107.
Fig. A.1.k  – Water-Oil Ratio and Water-Oil Ratio Derivative Versus Production Time, NRU Well 3107.

**WOR Integral and Integral-Derivative Versus Production Time : NRU Well 3107**

Fig. A.1.l  – Water-Oil Ratio Integral and Integral-Derivative Versus Production Time, NRU Well 3107.
$q_o$ and $q_w$ Versus Production Time: WWL Well 41

![Graph showing $q_o$ and $q_w$ versus production time.]

Fig. A.2.a — Oil and Water Production Rate History, WWL Well 41.

$q_o$ Versus $N_p$: WWL Well 41

![Graph showing $q_o$ versus cumulative oil production.]

Fig. A.2.b — Oil Production Rate Versus Cumulative Oil Production, WWL Well 41.
$f_o \text{ Versus } N_p$: WWL Well 41

**Pseudosteady-State Model:**

$$f_o = 1/(1 - 0.2178x10^2 + 2.1064t_o/(1.3617x10^3 - 3.5275x10^2 t_o))$$

Variables:

$$t_o = N_p/q_o \quad t_w = W_p/q_w$$

$N_{p, mov} = 360,000 \text{ STB}$

Fig. A.2.c – Fractional Flow of Oil Versus Cumulative Oil Production, WWL Well 41.

$1/f_w \text{ Versus } N_p$: WWL Well 41

**Pseudosteady-State Model:**

$$1/f_w = 1 + (1.3617x10^3 - 3.5275x10^2 t_w)/( - 2.178x10^2 + 2.1064t_o)$$

Variables:

$$t_o = N_p/q_o \quad t_w = W_p/q_w$$

$N_{p, mov} = 360,000 \text{ STB}$

Fig. A.2.d – Reciprocal of Fractional Flow of Water Versus Cumulative Oil Production, WWL Well 41.
$f_w$ Versus $N_p$: WWL Well 41

\[ f_w = 0.4 \exp(2.54525 \times 10^{-4} N_p) \]

$N_{p,mov} = 360,000$ STB

Fig. A.2.e - Fractional Flow of Water Versus Cumulative Oil Production, WWL Well 41.

**WOR** Versus $N_p$: WWL Well 41

\[ WOR = 4.0 \times 10^{-2} \exp(1.74525 \times 10^{-5} N_p) \]

Fig. A.2.f - Water-Oil-Ratio Versus Cumulative Oil Production, WWL Well 41.
$1/q_o$ Versus Oil Material Balance Time: WWL Well 41

\begin{align*}
1/q_o &= 3.4 \times 10^{-2} + 2.12766 \times 10^{-4} (N_p/q_o) \\
N_{p,mov} &= 47,000 \text{ STB}
\end{align*}

\textbf{Fig. A.2.g} – Reciprocal of Oil Rate Versus Oil Material Balance Time, WWL Well 41.

$1/q_w$ Versus Water Material Balance Time: WWL Well 41

\begin{align*}
q_w &= 2.3 \times 10^{-3}
\end{align*}

\textbf{Fig. A.2.h} – Reciprocal of Water Rate Versus Water Material Balance Time, WWL Well 41.
Fig. A.2.i – Water-Oil Ratio and Water-Oil Ratio Derivative Versus Oil Material Balance Time, WWL Well 41.

Fig. A.2.j – Water-Oil Ratio Integral and Integral-Derivative Versus Oil Material Balance Time, WWL Well 41.
**WOR and WOR Derivative Versus Production Time**: WWL Well 41

![Graph of WOR and WOR Derivative Versus Production Time]

*Fig. A.2.k* – Water-Oil Ratio and Water-Oil Ratio Derivative Versus Production Time, WWL Well 41.

**WOR Integral and Integral-Derivative Versus Production Time**: WWL Well 41

![Graph of WOR Integral and Integral-Derivative Versus Production Time]

*Fig. A.2.i* – Water-Oil Ratio Integral and Integral-Derivative Versus Production Time, WWL Well 41.