Material Balance Approach for Determining Oil Saturation at the Start of Carbon Dioxide Enhanced Oil Recovery

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By Mahendra K. Verma

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Conversion Factors

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<td>stock tank barrel (STB)</td>
<td></td>
<td>0.1590</td>
<td>cubic meter (m³)</td>
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</tbody>
</table>

Abbreviations, Acronyms, and Symbols

A reservoir area, in acres
acre-ft acre-foot
bbl barrel
bbl/STB reservoir barrel per stock tank barrel
\( B_o \) current formation volume factor of oil, in reservoir barrel per stock tank barrel (bbl/STB)
\( B_w \) initial formation volume factor of oil, in reservoir barrel per stock tank barrel (bbl/STB)
\( \text{CO}_2 \) carbon dioxide
CRD Comprehensive Resource Database
EOR enhanced oil recovery
EPT electromagnetic propagation tool
ft foot
\( h \) formation thickness, in feet (ft)
LIL log-inject-log
MPZ main pay zone
NML nuclear magnetic log
NPC National Petroleum Council
\( OOIP \) original oil in place, in stock tank barrels (STB)
OWC oil-water contact
RF

recovery factor

ROS

remaining oil saturation after waterflood

ROZ

residual oil zone

SCAL

special core analysis

$S_o$

oil saturation after a certain amount of oil production, in decimal format

$S_{oi}$

initial oil saturation, in decimal format

$S_{o\text{start of CO}2-EOR}$

oil saturation at the start of carbon dioxide enhanced oil recovery, in decimal format

$S_{orw}$

residual oil saturation after waterflood

$S_{wi}$

connate water saturation or initial water saturation, in decimal format

STB

stock tank barrel

TDT

thermal decay time

USGS

U.S. Geological Survey

$\phi$

porosity, in decimal format
Material Balance Approach for Determining Oil Saturation at the Start of Carbon Dioxide Enhanced Oil Recovery

By Mahendra K. Verma

Abstract

Oil producers have been using enhanced oil recovery methods, including (1) thermal recovery for heavy oil and (2) carbon dioxide enhanced oil recovery (CO$_2$-EOR) for medium or light oil, to maximize oil recovery from existing reservoirs. The CO$_2$-EOR method is widely used for recovering additional oil after waterflood, which leaves behind a large volume of oil in the reservoir. Completing a CO$_2$-EOR feasibility study requires values of various geologic, petrophysical, and reservoir properties, as well as production data. Most of the required data are available except for two critical parameters: (1) the oil saturation at the start of CO$_2$-EOR and (2) the oil recovery factor. Several methods, including core analysis, open-hole and cased-hole well logging, well-to-well tracer tests, and material balance, have been deployed to determine the residual oil saturation after waterflood (at which the relative permeability to oil nears zero) or remaining oil saturation after waterflood, equal to the oil saturation at the start of CO$_2$-EOR. This report presents the material balance approach, which is less expensive than other approaches and provides reasonably accurate values of oil saturation at the start of CO$_2$-EOR, and therefore is more useful when assessing a large number of reservoirs.

Introduction

Because of the decline in new oil discoveries and the increase in energy demand over the years, oil producers around the world have been looking for ways to recover more oil from existing reservoirs through the application of enhanced oil recovery (EOR) methods. Among those EOR methods, thermal recovery for heavy oil and carbon dioxide (CO$_2$)-EOR for medium and light oil have been widely used, especially during times when oil prices are high. The CO$_2$-EOR method has a much wider application than thermal recovery because CO$_2$-EOR not only helps to recover additional oil but also has the potential to sequester CO$_2$, which is one of the greenhouse gases contributing to global warming.

The application of the CO$_2$-EOR method requires a thorough review of (1) the operational needs, (2) reservoir characteristics, (3) pressure-volume-temperature properties of the oil, and (4) production data. The availability of at least 90-percent pure CO$_2$ for miscible floods (Jarrell and others, 2002) and facilities for injecting CO$_2$ into the reservoir are two of the more critical operational needs. Relevant reservoir characteristics include reservoir pressure and temperature, initial and current oil saturations, reservoir wettability, and reservoir heterogeneity. Oil properties include oil gravity, viscosity, and bubble point pressure. The production data include produced volumes of oil, water, and gas. Table 1 lists geologic, reservoir, and oil properties and production data included in the Comprehensive Resource Database (CRD), which was developed by INTEK Inc., a petroleum engineering consulting company under contract to the U.S. Geological Survey (USGS). The CRD uses data from Nehring Associates Inc. (2012) and IHS Inc. (2012). Data missing from the Nehring Associates Inc. (2012) and IHS Inc. (2012) databases were calculated using established equations and correlations (Carolus and others, 2017).

Most of the data required for evaluating the feasibility of CO$_2$-EOR are available in the CRD, except for the oil saturation at the start of enhanced oil recovery ($S_o^{\text{start of CO}_2\text{-EOR}}$) and the oil recovery factor ($RF$), which is generally true for the availability of such data in the oil industry. Because the $RF$ is one of the most critical parameters in evaluating the feasibility of CO$_2$-EOR, a team of USGS researchers evaluated methods to estimate the $RF$ and proposed three approaches to determine this important parameter, focusing on simulation (Verma, 2017). The $S_o^{\text{start of CO}_2\text{-EOR}}$ is another key parameter needed for evaluation of the feasibility of CO$_2$-EOR, and a material balance approach to determine the $S_o^{\text{start of CO}_2\text{-EOR}}$ is presented in this report.
Table 1. Various geologic, reservoir, and oil properties and production data included in the Comprehensive Resource Database (Carolus and others, 2017).

<table>
<thead>
<tr>
<th>Geologic, reservoir, and oil properties</th>
<th>Production data</th>
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</thead>
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<td>Oil gravity (American Petroleum Institute)</td>
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<tr>
<td>Viscosity</td>
<td></td>
</tr>
<tr>
<td>Initial pressure</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
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</tr>
<tr>
<td>Gas-to-oil ratio</td>
<td></td>
</tr>
<tr>
<td>Current water saturation</td>
<td></td>
</tr>
<tr>
<td>Current oil saturation</td>
<td></td>
</tr>
<tr>
<td>Current pressure</td>
<td></td>
</tr>
<tr>
<td>Dykstra-Parsons coefficient</td>
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Background

CO₂-EOR methods are used after an oil field has gone through primary and secondary production phases. The primary production phase requires drilling of development wells and producing the reservoir under its natural forces, such as the expansion of oil, water encroachment from the associated aquifer, and expansion of the gas cap, if present. Over time, oil production decreases to an economic limit because of a decline in reservoir pressure and a drop in the reservoir’s natural forces. Primary recoveries are generally low, on the order of 5 to 15 percent of the original oil in place (OOIP) (Walsh and Lake, 2003; Tzimas and others, 2005), leaving behind a significant volume of oil in the reservoir. As a common practice, a secondary recovery phase, such as water injection (waterflood) or gas injection, is introduced to restore the reservoir pressure and help recover more oil. However, during waterflood, water-cut rises and field operations become uneconomical because of excessive water production. Total oil recovery at the end of the secondary recovery phase (waterflood) has been observed to range between 30 and 50 percent of the OOIP (Green and Willhite, 1998; Walsh and Lake, 2003) and between 35 and 45 percent of the OOIP (Tzimas and others, 2005). At the end of waterflood, a tertiary recovery method such as thermal, chemical, or miscible displacement EOR is introduced to recover additional oil (Verma, 2015).

Before applying a tertiary recovery or EOR method, it is essential to carry out a feasibility study, for which it is imperative to have an understanding of the $S_{\text{w}}$ (Walsh and Lake, 2003) and other reservoir and geologic factors, including the production mechanism and how the
Background

field has been operated, was defaulted to the $S_{orw}$ values of 25 percent for sandstone reservoirs and 38 percent for carbonate reservoirs. A detailed assessment of the $S_{orw}$ for carbonate reservoirs suggested that the $S_{orw}$ of 38 percent used in the NPC study was too high; therefore, the default value was revised to 30.5 percent after industry and government adjustments (Donald J. Remson, National Energy Technology Laboratory, written communication, as cited in Attanasi, 2017). However, these default $S_{orw}$ values (25 percent for sandstone reservoirs and 30.5 percent for carbonate reservoirs) used in CO$_2$-EOR assessments in the United States are much lower than the ROS values at the start of CO$_2$-EOR projects reported in a 2010 worldwide EOR survey (Koottungal, 2010). The reason for this discrepancy is project economics, which dictate the termination of waterflood operations before the oil saturation reaches the default $S_{orw}$ value. Therefore, the objective of this report is to develop a reliable method to calculate the ROS or $S_{orw, start of CO2-EOR}$ which can help to evaluate the feasibility of the CO$_2$-EOR application in oil reservoirs and to assess the oil recovery potential of a reservoir using CO$_2$-EOR.

A review of the literature revealed that extensive work has been done to determine the ROS and the $S_{orw}$ (Fertl, 1979; Kidwell and Guillory, 1980; Chang and others, 1988; Pathak and others, 2012; Teklu and others, 2013). The ROS or $S_{orw, start of CO2-EOR}$ is critical to evaluating the performance of a waterflood and the feasibility and success of tertiary oil recovery or EOR. The ROS is affected by the reservoir’s geologic complexity in terms of porosity-permeability distribution and rock wettability; fluid properties, such as oil gravity, oil viscosity, and oil-to-water mobility ratio; relative permeability of oil and water; presence of gas; and water salinity. Several methods, described briefly below, have been used to determine the values of ROS and $S_{orw}$, but each method yields different values for the same formation interval because of the effects of reservoir complexities and the limitations of each method. Therefore, it is prudent to use three or four methods to verify the value of ROS and to reduce the degree of uncertainty.

Fertl (1979) used the following four methods to determine the $S_{orw}$: (1) material balance techniques, (2) core analysis, (3) single-well tracer tests, and (4) well-logging techniques with a focus on log-inject-log (LIL) applications. Kidwell and Guillory (1980) attempted to determine the $S_{orw}$ in a deep, high-pressured, Gulf Coast sandstone reservoir primarily by using pulsed neutron logging, but they also deployed other methods, including conventional coring and electric logging, to validate the results because each approach has limitations. The average $S_{orw}$ across the LIL interval was found to be 22.1 percent. Chang and others (1988) discussed various techniques to determine ROS by grouping them into the following three categories:

   A. Core analysis (conventional, pressure, and sponge).
   B. Backflow tracer tests.
   C. Well logs:
      I. Open-hole logs—resistivity logs, nuclear magnetic logs (NML), electromagnetic propagation tool (EPT) logs, and dielectric-constant logs.
      II. Cased-hole logs—pulsed neutron capture logs including LIL, carbon/oxygen logs, gravity logs, and gamma-ray logs.

2. Interwell measurements.
   A. Measurement of the formation resistivity by generating electrical current and measuring potentials among pairs of open holes.
   B. Well-to-well tracer tests.
   C. Injection of fluid into a reservoir to displace both water and oil toward an observation well and measuring the arrival time of the oil/water front by detecting a change in bottomhole pressure.

   A. Estimate of reservoir-wide average ROS by subtracting the oil volume produced from the OOIP.

Verma and others (1994) reported their work on narrowing the range of the $S_{orw}$ in a carbonate reservoir in Qatar, where they used the following four approaches: (1) special core analysis (SCAL), (2) LIL, (3) thermal decay time (TDT) logs, and (4) material balance. The $S_{orw}$ was found to be sensitive to the method used for its determination. The $S_{orw}$ was a function of the connate water saturation ($S_{wc}$) and porosity ($\phi$) and ranged from 23 to 27 percent. In one well where both SCAL and LIL methods were carried out, the data showed an excellent match, with average $S_{orw}$ values of 24.4 and 24.3 percent, respectively, for the two methods.
Teklu and others (2013) reviewed previous work on ROS values in various sandstone and carbonate reservoirs. They discussed several techniques to determine oil saturation after waterflood and summarized the results of work done by others, as listed below.

**Sandstone Reservoirs**

1. $S_{orw} = 24.0$ percent, determined from core analysis and well logs, the field was not defined (Elkins and Poppe, 1973).
2. $S_{orw} = 9.3$ to $31.9$ percent, determined from core analysis and well logs in Main Pass Block 69 field, offshore Louisiana (Thomas and Ausburn, 1979).
3. $S_{orw} = 32.0$ to $33.5$ percent, determined from core analysis and well logs (EPT, NML) in Rangely field, Colorado (Neuman, 1983).
4. $ROS = 32.0$ to $38.0$ percent, determined from single-well chemical tracer tests, higher than $S_{orw}$ values determined from core analysis and well logs (21 to 25 percent) in Cormorant field, North Sea, offshore United Kingdom (van Poelgeest and others, 1991).

**Carbonate Reservoirs**

1. $S_{orw} = 23$ to $27$ percent (average $24.3$ percent), determined from SCAL, LIL, TDT logs, and material balance in Arab D reservoir, Qatar (Verma and others, 1994).
2. $ROS = 34$ to $41$ percent, determined from well logs in Arab D reservoir, Saudi Arabia. The final $S_{orw}$ values determined from core waterflood and centrifuge tests were not reported (Pham and Al-Shahri, 2001).
3. $S_{orw} = 17.3$ to $26.2$ percent (average $22.3$ percent), determined from core waterflood in Arab D reservoir, Abu Safah field, Saudi Arabia; $S_{orw} = 6.5$ to $31.3$ percent (average $18.2$ percent), determined from core waterflood in Shuaiba Reservoir, Shaybah field, Saudi Arabia (Okasha and others, 2005).

As shown by the above results, the value of oil saturation after waterflood ($ROS$ or $S_{orw}$) varies widely from one reservoir to another, and even for the same reservoir, the values may vary depending on the method used. To overcome this drawback, oil producers use several methods to verify the results and narrow down the range of the $ROS$ or the $S_{orw}$.

**Oil Saturation Zones**

Because several terms have been used to define the oil saturation after waterflood, it is useful to look at a typical well log (fig. 1) modified from Harouaka and others (2014), who reported on the $S_{orw}$ in the watered-out sections of the residual oil zone (ROZ) in the Permian basin. Figure 1 shows oil saturation across the entire producing formation, ranging from the lowest value in the ROZ below the base of the producing oil-water contact (OWC) transition zone to the highest value across the main pay zone (MPZ). The plot also shows the base of the true or ultimate OWC, below which water saturation approaches 100 percent. The oil saturation across the ROZ, ranging between 5 and 40 percent (fig. 1), was reached after natural waterflooding over millions of years and represents the true $S_{orw}$. The initial oil saturation ($S_{oi}$) in the MPZ is about 85 percent (fig. 1), which will decline during waterflood. The $ROS$ or $S_{start\ of\ CO2-EOR}$ is always lower than the $S_{orw}$ but is generally higher than the $S_{orw}$, except in some homogeneous, high-permeability reservoirs, where the $ROS$ can reach its lower limit, the $S_{orw}$.

**Oil Saturation After Waterflood**

The $S_{start\ of\ CO2-EOR}$, which is equated to $ROS$ (Teklu and others, 2013), is generally higher than the $S_{orw}$ for the following reasons: (1) waterflood may be terminated before oil saturation reaches the $S_{orw}$ because of economic constraints, and (2) in some cases, the CO$_2$-EOR may be implemented after primary recovery without going through waterflood. This observation of $S_{start\ of\ CO2-EOR}$ or $ROS$ values being higher than the default $S_{orw}$ values is corroborated by $S_{start\ of\ CO2-EOR}$ data from selected CO$_2$-EOR projects summarized in table 2 (Koottungal, 2010).

Table 2 presents the results of an analysis of $S_{start\ of\ CO2-EOR}$ data for CO$_2$-EOR projects reported in the Oil and Gas Journal (Koottungal, 2010). Depending on the reservoir geologic characteristics and the producing strategy used, the $S_{start\ of\ CO2-EOR}$ in the oil zone ranged from minimum values of 24 to 26.5 percent for sandstone reservoirs and 30 to 38 percent for carbonate reservoirs (dolomite or dolomite/limestone) to maximum values of 57 to 64 percent for sandstone reservoirs and 75 to 78 percent for carbonate reservoirs, with average values between 45.2 and 47.6 percent for sandstone reservoirs and 45.3 and 47.9 percent for carbonate reservoirs (table 2).
Oil Saturation After Waterflood

Figure 1. Oil saturation profile across the oil-producing interval in a typical oil well, showing the main pay zone, producing oil-water contact (OWC) transition zone, residual oil zone, and base of the ultimate OWC. ft, feet; %, percent. Modified from Harouaka and others, 2014.

Table 2. Summary statistics for values of oil saturation at the start of enhanced oil recovery (in percent) reported for selected carbon dioxide enhanced oil recovery projects.

[Data from Kootungal (2010). NA, not applicable]

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<th>All data dolomite</th>
<th>All data dolomite/limestone</th>
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Any of the methods for determining $S_{o_{\text{w}}}^\text{start of CO}_2$-EOR and $ROS$ described in the “Background” section can be used to determine the value of $S_{o_{\text{w}}}^\text{start of CO}_2$-EOR. Given that each method has limitations in determining the value of $S_{o_{\text{w}}}^\text{start of CO}_2$-EOR or $ROS$, it is helpful to use more than one method to reduce the uncertainty in the $S_{o_{\text{w}}}^\text{start of CO}_2$-EOR when assessing individual reservoirs for the feasibility of CO$_2$-EOR application, provided the analysis can be economically justified. However, using several methods may not be realistic when assessing a large number of reservoirs, as is the case in a recent undertaking by the USGS, authorized by the Energy Independence and Security Act of 2007 (U.S. Congress, 2007, 121, Stat. 1711), to develop a methodology for assessing the potential oil and gas recoverable by CO$_2$-EOR in oil reservoirs in the United States. When there is a large number of reservoir to assess, the material balance approach has the advantage over other approaches for determining the value of $S_o^\text{start of CO}_2$-EOR because material balance is relatively cheap, accurate, and quick, and it provides an average value for the entire reservoir. However, because of time constraints and the number of reservoirs that need to be assessed, the USGS methodology for assessing potential oil and gas recoverable by CO$_2$-EOR relies on the default values of $S_{o_{\text{w}}}^\text{start of CO}_2$-EOR (25 percent for sandstone and 30.5 percent for carbonate reservoirs) that were used in previous studies (Attanasi, 2017).
Proposed Approach to Determine Oil Saturation

Several methods for measuring the oil saturation at the start of CO2-EOR (ROS or Sorw) have been developed over the years, and each method has advantages and limitations. The material balance approach is an established method (Terry and Rogers, 2014) and offers a reliable alternative to other methods, especially SCAL and logging techniques, which are expensive and time consuming. The material balance method provides accurate results for reservoirs with sufficient geologic and reservoir data and long production history and is based on the concept of conservation of fluid volume within a reservoir, as shown in the following equations:

\[
\text{cumulative oil produced} = \text{OOIP} - \text{remaining oil in place}
\]

\[
\text{OOIP} = \frac{7758.4 \times A \times h \times \phi \times S_{oi}}{B_{oi}}
\]

\[
\text{remaining oil in place} = \frac{7758.4 \times A \times h \times \phi \times S_{\text{start of CO2-EOR}}}{B_o}
\]

where
- cumulative oil produced is the cumulative oil production, in stock tank barrels (STB);
- \(\text{OOIP}\) is the original oil in place, in stock tank barrels (STB);
- remaining oil in place is the remaining oil in place, in stock tank barrels (STB);
- 7758.4 is the conversion factor from acre-foot (acre-ft) to barrel (bbl);
- \(A\) is the reservoir area, in acres;
- \(h\) is the formation thickness, in feet (ft);
- \(\phi\) is the porosity, in decimal format;
- \(S_{oi}\) is the initial oil saturation, in decimal format;
- \(B_{oi}\) is the initial formation volume factor of oil, in barrel per stock tank barrel (bbl/STB);
- \(S_{\text{start of CO2-EOR}}\) is the oil saturation at the start of CO2-EOR, in decimal format; and
- \(B_o\) is the current formation volume factor of oil, in barrel per stock tank barrel (bbl/STB).

Substituting the \(\text{OOIP}\) (eq. 2) and remaining oil in place (eq. 3) in equation 1 yields the following:

\[
\text{cumulative oil produced} = \frac{7758.4 \times A \times h \times \phi \times S_{oi}}{B_{oi}} - \frac{7758.4 \times A \times h \times \phi \times S_{\text{start of CO2-EOR}}}{B_o}
\]

Solving equation 4 for \(S_{\text{start of CO2-EOR}}\) yields equation 5:

\[
S_{\text{start of CO2-EOR}} = \frac{\frac{7758.4 \times A \times h \times \phi \times S_{oi}}{B_{oi}}}{\frac{7758.4 \times A \times h \times \phi}{B_o}} - \frac{\text{cumulative oil produced}}{\frac{7758.4 \times A \times h \times \phi}{B_o}}
\]

Because \(S_{oi} = (1 - S_{wi})\), \((1 - S_{wi})\) can be substituted in equation 5:

\[
S_{\text{start of CO2-EOR}} = \frac{(1 - S_{wi})}{\frac{1}{B_{oi}}} - \frac{\text{cumulative oil produced}}{\frac{7758.4 \times A \times h \times \phi}{B_o}} = \frac{(1 - S_{wi}) \times B_{oi}}{B_o} - \frac{\text{cumulative oil produced} \times B_o}{7758.4 \times A \times h \times \phi}
\]

where
- \(S_{wi}\) is the initial water saturation (connate water saturation), in decimal format.
If the initial reservoir pressure is maintained, as is normally done by water injection before implementing CO₂-EOR, it can be assumed that \( B_o = B_{oi} \); therefore, substituting \( B_{oi} \) for \( B_o \) in equation 6 yields:

\[
S_{O_{start \ of \ CO2-EOR}} = (1 - S_{oi}) - \frac{\text{cumulative oil produced} \times B_{oi}}{7758.4 \times A \times h \times \phi}
\]  

(7)

For a given reservoir, the variables in equation 7 are known; therefore, the \( S_{O_{start \ of \ CO2-EOR}} \) can be calculated.

**Validation Process and Discussion**

Although material balance is a well-established concept, it is beneficial to check the validity of the proposed approach for determining the oil saturation of a reservoir before implementing CO₂-EOR, which could take place after waterflood or directly after primary recovery. Checking the validity of the material balance equation requires the availability of values for the input variables that make up equation 7. Fortunately, the NPC (1984b) database is in the public domain and provides these required values. In addition, the NPC (1984b) database provides the \( S_{oi} \) and the oil saturation after a certain amount of oil production (\( S_o \)). The availability of the \( S_{oi} \) and \( S_o \) data has allowed for direct comparison of the calculated and reported \( S_o \) values, thereby helping to validate the material balance approach.

Table 3 shows the values of two parameters (\( S_{oi} \) and \( S_o \)) taken from the NPC (1984b) database for those sandstone and carbonate oil fields for which all the required data were available. According to the material balance concept, the volume of oil produced is directly proportional to the change in oil saturation in a reservoir. However, to normalize this relationship for a group of fields, the oil volume produced is reported as a percent of the OOIP, and the corresponding oil saturation difference is reported as a percent of the \( S_{oi} \). Table 3 also shows the oil volume produced as a percent of the OOIP and the corresponding oil saturation difference as a percent of the \( S_{oi} \) for both calculated and reported \( S_o \) values.

The two variables (oil volume produced and the corresponding oil saturation difference) correlate well, as can be seen in figures 2 through 6. The saturation differences calculated using values of \( S_o \) determined by the material balance approach plot close to the line of unit slope, whereas the saturation differences calculated using reported \( S_o \) values show good correlation in some cases and scatter in others, illustrating the inherent limitations of the other methods used to determine \( S_o \). The comparison of \( S_o \) values calculated using the material balance approach with reported values determined using other approaches validates the accuracy of the material balance approach.
## Table 3.

Values of initial oil saturation ($S_o$), oil saturation after a certain amount of oil production ($S_o$), oil volume produced, and saturation difference ($S_o - S_o$) for selected sandstone and carbonate oil fields.

[Reported values of $S_o$ and $S_o$ are from the National Petroleum Council (1984b) database, whereas calculated values of $S_o$ were determined using the material balance approach (eq. 7). The “Oil volume produced” column shows the oil volume as a percent of the original oil in place. The saturation difference ($S_o - S_o$) is reported as a percent of the $S_o$ for both the reported and calculated values of $S_o$.]

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Table 3. Values of initial oil saturation ($S_i$), oil saturation after a certain amount of oil production ($S_o$), oil volume produced, and saturation difference ($S_i - S_o$) for selected sandstone and carbonate oil fields.—Continued

[Reported values of $S_i$ and $S_o$ are from the National Petroleum Council (1984b) database, whereas calculated values of $S_o$ were determined using the material balance approach (eq. 7). The “Oil volume produced” column shows the oil volume as a percent of the original oil in place. The saturation difference ($S_i - S_o$) is reported as a percent of the $S_i$ for both the reported and calculated values of $S_o$.]

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Figure 2. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in California. Saturation differences were determined using values of oil saturation after a certain amount of oil production (\(S_o\)) reported in the National Petroleum Council (1984b) database and values of \(S_o\) calculated using the material balance approach. Data are provided in table 3. \(OOIP\), original oil in place; \(S_{oi}\), initial oil saturation.

Figure 3. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in Texas. Saturation differences were determined using values of oil saturation after a certain amount of oil production (\(S_o\)) reported in the National Petroleum Council (1984b) database and values of \(S_o\) calculated using the material balance approach. Data are provided in table 3. \(OOIP\), original oil in place; \(S_{oi}\), initial oil saturation.
Figure 4. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in West Virginia. Saturation differences were determined using values of oil saturation after a certain amount of oil production ($S_o$) reported in the National Petroleum Council (1984b) database and values of $S_o$ calculated using the material balance approach. Data are provided in table 3. \textit{OOIP}, original oil in place; $S_{oi}$ initial oil saturation.

Figure 5. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in Wyoming. Saturation differences were determined using values of oil saturation after a certain amount of oil production ($S_o$) reported in the National Petroleum Council (1984b) database and values of $S_o$ calculated using the material balance approach. Data are provided in table 3. \textit{OOIP}, original oil in place; $S_{oi}$ initial oil saturation.
Conclusions

The value of $S_{o_{\text{start of CO2-EOR}}}$ will vary by reservoir depending on (1) rock properties (lithology, faulting, layering, homogeneity, porosity-permeability distribution, wettability, fluid saturations, and relative permeability of oil and water), (2) reservoir fluid properties (oil gravity, viscosity, solution gas-to-oil ratio, reservoir pressure, and temperature), and (3) production mechanisms and how well the reservoirs have been managed and produced. Some of the methods used for estimating the $S_{w}$ or the $ROS$ could be used to determine the value of $S_{o_{\text{start of CO2-EOR}}}$ in conjunction with a material balance approach to provide validity. Previous studies indicate that even for the same reservoir the value of $S_{o_{\text{start of CO2-EOR}}}$ can vary depending on the method used because each method has advantages and limitations. Therefore, it would be beneficial for oil producers engaged in CO$_2$-EOR to use more than one method to validate the oil saturation values and narrow the range of variability of $S_{o_{\text{start of CO2-EOR}}}$.

Although material balance has been mentioned in the classification of various methods for estimating the $S_{w}$ or the $ROS$, only limited use of it has been reported (Verma and others, 1994). Most of the early work on $S_{w}$ and $ROS$ focused on narrowing the range of oil saturation after waterflood rather than EOR projects. Also, efforts were focused on determining oil saturation around wellbores primarily by using well logging and core analysis. It is also important to keep in mind that whereas all other approaches provide oil saturation values for a localized area around the well, the material balance approach gives an average value of oil saturation across the entire reservoir. Because the $S_{o_{\text{start of CO2-EOR}}}$ calculated by material balance is based on some simplifying assumptions, the value may differ from values obtained from a more sophisticated reservoir simulation. However, material balance is reliable if all variables in equation 7 are available with reasonable accuracy, as evident from the graphs of oil volume produced and corresponding oil saturation difference (figs. 2–6). The material balance approach has the advantages of being inexpensive and easy to use, making it an attractive option for determining the value of $S_{o_{\text{start of CO2-EOR}}}$, especially when there is a large number of reservoirs to be evaluated.

Acknowledgments

The author would like to thank C. Özgen Karacan and Ricardo A. Olea of the U.S. Geological Survey for their in-depth reviews and comments. The author would like to acknowledge the assistance and support received from Peter D. Warwick and other U.S. Geological Survey staff during the preparation of this report.
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Material Balance Approach for Determining Oil Saturation at the Start of Carbon Dioxide Enhanced Oil Recovery


