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

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U.S. Department of the Interior
U.S. Geological Survey

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By Mahendra K. Verma

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	7,758.4	barrel (bbl)
barrel (bbl; petroleum, 1 barrel=42 gallons)	0.1590	cubic meter (m^3)
stock tank barrel (STB)	0.1590	cubic meter (m^3)

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_{oi}	initial formation volume factor of oil, in reservoir barrel per stock tank barrel (bbl/STB)
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
$So_{start\ of\ CO2\text{-}EOR}$	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
ϕ	porosity, in decimal format

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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 ($So_{start\ of\ CO2\text{-}EOR}$) 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 $So_{start\ of\ CO2\text{-}EOR}$ is another key parameter needed for evaluation of the feasibility of CO_2-EOR, and a material balance approach to determine the $So_{start\ of\ CO2\text{-}EOR}$ 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).

Geologic, reservoir, and oil properties	Production data
Depth	Well spacing
Area	Well count
Net pay (thickness)	Annual oil production
Porosity	Cumulative oil production
Permeability	Known recovery
Lithology	Proved reserves
Initial water saturation	
Initial oil saturation	
Initial formation volume factor	
Original oil in place	
Oil gravity (American Petroleum Institute)	
Viscosity	
Initial pressure	
Temperature	
Gas-to-oil ratio	
Current water saturation	
Current oil saturation	
Current pressure	
Dykstra-Parsons coefficient	

Background

CO_2-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 $So_{start\ of\ CO2\text{-}EOR}$. The $So_{start\ of\ CO2\text{-}EOR}$ has been defined in the following two ways in the literature: (1) the remaining oil saturation after waterflood (*ROS*) and (2) the residual oil saturation after waterflood (S_{orw}). Whereas the *ROS* refers to the oil saturation after waterflood, the S_{orw} refers to the lowest oil saturation during waterflood, at which the relative permeability to oil nears zero. Pathak and others (2012) and Teklu and others (2013) reported their work on the *ROS*. Fertl (1979), Kidwell and Guillory (1980), and Chang and others (1988) presented their work on the S_{orw}.

Teklu and others (2013) defined the *ROS* as the oil saturation after waterflood, which is the oil available at the start of the CO_2-EOR application ($So_{start\ of\ CO2\text{-}EOR}$). The *ROS* is generally higher but may be as low as the S_{orw} (at which the relative permeability to oil nears zero). In a National Petroleum Council (NPC) study (NPC, 1984a; Robl and others, 1986), the *ROS*, which depends on the rock lithology and various reservoir and geologic factors, including the production mechanism and how the 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 $So_{start\ of\ CO2\text{-}EOR}$, 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 $So_{start\ of\ CO2\text{-}EOR}$ 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:

1. Single-well measurements.
   - 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.
3. Material balance.
   - 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_{wi}) and porosity (ϕ) 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 $So_{start\ of\ CO2\text{-}EOR}$ is always lower than the S_{oi} 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 $So_{start\ of\ CO2\text{-}EOR}$, 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 $So_{start\ of\ CO2\text{-}EOR}$ or *ROS* values being higher than the default S_{orw} values is corroborated by $So_{start\ of\ CO2\text{-}EOR}$ data from selected CO_2-EOR projects summarized in table 2 (Koottungal, 2010).

Table 2 presents the results of an analysis of $So_{start\ of\ CO2\text{-}EOR}$ 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 $So_{start\ of\ CO2\text{-}EOR}$ 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).

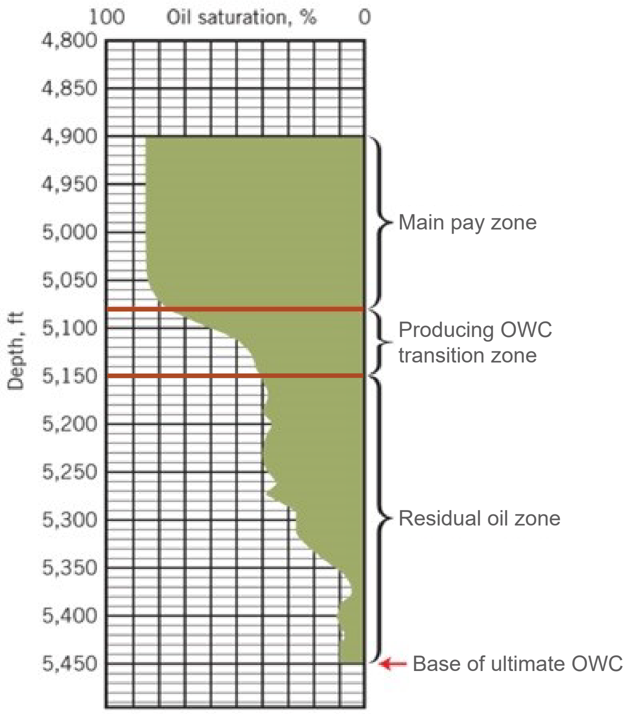

Figure 1. Oil saturation profile across the oil-producing interval in a typical oil well, showing the main pay zone, producing oil-water contact (OWC) transition zone, residual oil zone, and base of the ultimate OWC. ft, feet; %, percent. Modified from Harouaka and others, 2014.

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 Koottungal (2010). NA, not applicable]

Statistic	All data sandstone	All data dolomite	All data dolomite/limestone	Texas sandstone	Mississippi sandstone	Texas dolomite/ limestone
Standard deviation	10.7	9.2	12.4	10.8	12.5	13.1
Average	45.2	47.9	45.3	47.5	47.6	47.3
Mode	37	50	40	NA	55	40
Minimum	24	30	35	26.5	24	38
Maximum	64	75	78	57	64	78
No. of fields	24	26	10	7	8	8

Any of the methods for determining S_{orw} and *ROS* described in the “Background” section can be used to determine the value of $So_{start\ of\ CO2\text{-}EOR}$. Given that each method has limitations in determining the value of S_{orw} or *ROS*, it is helpful to use more than one method to reduce the uncertainty in the $So_{start\ of\ CO2\text{-}EOR}$ 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 $So_{start\ of\ CO2\text{-}EOR}$ 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_{orw} (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 $So_{start\ of\ CO2\text{-}EOR}$ (*ROS* or S_{orw}) 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:

$$\text{cumulative oil produced} = OOIP - \text{remaining oil in place} \tag{1}$$

$$OOIP = \frac{7758.4 \times A \times h \times \phi \times s_{oi}}{B_{oi}} \tag{2}$$

$$\text{remaining oil in place} = \frac{7758.4 \times A \times h \times \phi \times So_{start\ of\ \text{CO2-EOR}}}{B_o} \tag{3}$$

where

cumulative oil produced	is the cumulative oil production, in stock tank barrels (STB);
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);
ϕ	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);
$So_{start\ of\ CO2\text{-}EOR}$	is the oil saturation at the start of CO_2-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 *OOIP* (eq. 2) and remaining oil in place (eq. 3) in equation 1 yields the following:

$$\text{cumulative oil produced} = \frac{7758.4 \times A \times h \times \phi \times S_{oi}}{B_{oi}} - \frac{7758.4 \times A \times h \times \phi \times So_{start\ of\ CO2-EOR}}{B_o} \tag{4}$$

Solving equation 4 for $So_{start\ of\ CO2\text{-}EOR}$ yields equation 5:

$$SO_{start\ of\ CO2-EOR} = \frac{\dfrac{7758.4 \times A \times h \times \phi \times S_{oi}}{B_{oi}}}{\dfrac{7758.4 \times A \times h \times \phi}{B_o}} - \frac{\text{cumulative oil produced}}{\dfrac{7758.4 \times A \times h \times \phi}{B_o}} \tag{5}$$

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

$$So_{start\ of\ CO2-EOR} = \frac{\dfrac{(1 - S_{wi}}{B_{oi}}}{\dfrac{1}{B_o}} - \frac{\text{cumulative oil produced}}{\dfrac{7758.4 \times A \times h \times \phi}{B_o}} = \frac{(1 - S_{wi}) \times B_o}{B_{oi}} - \frac{\text{cumulative oil produced} \times B_o}{7758.4 \times A \times h \times \phi} \tag{6}$$

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 CO_2-EOR, it can be assumed that $B_o = B_{oi}$; therefore, substituting B_{oi} for B_o in equation 6 yields:

$$So_{start\ of\ CO2-EOR} = (1 - S_{wi}) - \frac{\text{cumulative oil produced} \times B_{oi}}{7758.4 \times A \times h \times \phi} \tag{7}$$

For a given reservoir, the variables in equation 7 are known; therefore, the $So_{start\ of\ CO2\text{-}EOR}$ 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 CO_2-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_{oi}), oil saturation after a certain amount of oil production (S_o), oil volume produced, and saturation difference (S_{oi}–S_o) for selected sandstone and carbonate oil fields.

[Reported values of S_{oi} 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_{oi}–S_o) is reported as a percent of the S_{oi} for both the reported and calculated values of S_o]

Oil field	Lithology	Reported S_{oi} (in percent)	Calculated S_o (in percent)	Reported S_o (in percent)	Oil volume produced (in percent)	Saturation difference (S_{oi}–S_o) (in percent)	
						Calculated	Reported
California							
Cat Canyon East	Sandstone	80	75	78	6	6	3
Cat Canyon East	Sandstone	65	60	63	8	8	3
Cat Canyon West	Sandstone	70	53	60	26	25	14
Cat Canyon West	Sandstone	70	57	55	19	18	21
Cat Canyon West	Sandstone	70	55	45	21	21	36
Inglewood	Sandstone	75	50	49	35	33	35
Jasmin	Sandstone	67	59	40	12	11	40
Kern Bluff	Sandstone	61	51	48	17	17	21
Kern Front	Sandstone	68	53	56	23	22	18
Kern River	Sandstone	70	54	50	22	22	29
Midway Sunset	Sandstone	66	50	49	25	24	26
Midway Sunset	Sandstone	76	69	69	9	9	9
Texas							
Cole, West	Sandstone	60	56	52	7	7	13
Seeligson Unit	Sandstone	59	38	46	43	36	22
Seeligson Unit	Sandstone	64	44	38	36	31	40
Seeligson Unit	Sandstone	68	44	33	44	36	52
Seeligson Unit	Sandstone	61	36	32	49	41	48
Spraberry	Sandstone	65	36	62	48	44	5
West Ranch	Sandstone	72	46	32	38	36	55
West Ranch	Sandstone	70	36	34	51	48	51
West Ranch	Sandstone	55	42	37	28	24	32
West Ranch	Sandstone	67	46	48	32	31	28
West Ranch	Sandstone	65	50	48	24	23	27
West Ranch	Sandstone	60	42	57	31	29	4
West Ranch	Sandstone	65	47	27	29	27	58
West Virginia							
Hendershot	Sandstone	80	58	56	31	28	30
Jacksonburg-Stringtown	Sandstone	74	59	57	23	20	23
Mannington	Sandstone	52	45	44	15	14	15
Porto Rico	Sandstone	80	57	54	33	29	33
Salem	Sandstone	80	66	64	20	17	20
Smithfield	Sandstone	60	50	49	18	17	18
Walton (Johnsons & Rock Creeks)	Sandstone	48	37	35	25	23	27
Wolf Summit-Big Isaac	Sandstone	62	52	49	18	16	21
Yellow Creek	Sandstone	73	55	52	28	24	29

Table 3. Values of initial oil saturation (S_{oi}), oil saturation after a certain amount of oil production (S_o), oil volume produced, and saturation difference (S_{oi}–S_o) for selected sandstone and carbonate oil fields.—Continued

[Reported values of S_{oi} 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_{oi}–S_o) is reported as a percent of the S_{oi} for both the reported and calculated values of S_o]

Oil field	Lithology	Reported S_{oi} (in percent)	Calculated S_o (in percent)	Reported S_o (in percent)	Oil volume produced (in percent)	Saturation difference (S_{oi}–S_o) (in percent)	
						Calculated	Reported
Wyoming							
Cole Creek	Sandstone	67	43	56	36	36	16
Cole Creek, South	Sandstone	63	39	26	41	38	59
Elk Basin	Sandstone	94	46	35	52	51	63
Elk Basin	Sandstone	80	66	72	19	17	10
Elk Basin South	Sandstone	84	47	59	44	44	30
Fiddler Creek	Sandstone	71	45	66	37	37	8
Fiddler Creek, West Unit	Sandstone	71	58	67	19	19	6
Lost Soldier	Sandstone	90	61	74	38	32	17
Texas							
Cowden South	Carbonate	65	55	60	21	16	8
Crossett	Carbonate	65	53	44	26	18	32
Dollarhide	Carbonate	55	39	53	30	30	4
Seminole West	Carbonate	82	67	62	20	18	25
Slaughter	Carbonate	80	62	53	25	23	34
Spraberry	Carbonate	70	63	49	12	11	30

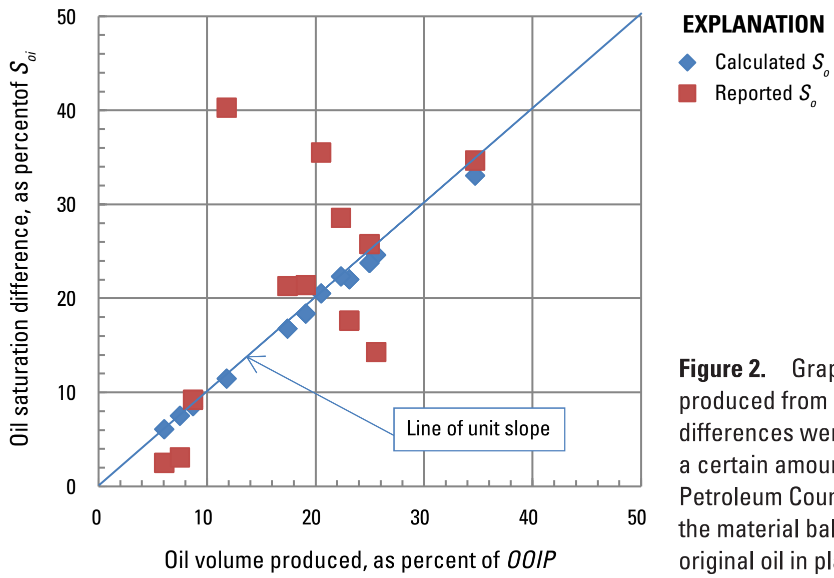

Figure 2. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in California. Saturation differences were determined using values of oil saturation after a certain amount of oil production (S_o) reported in the National Petroleum Council (1984b) database 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.

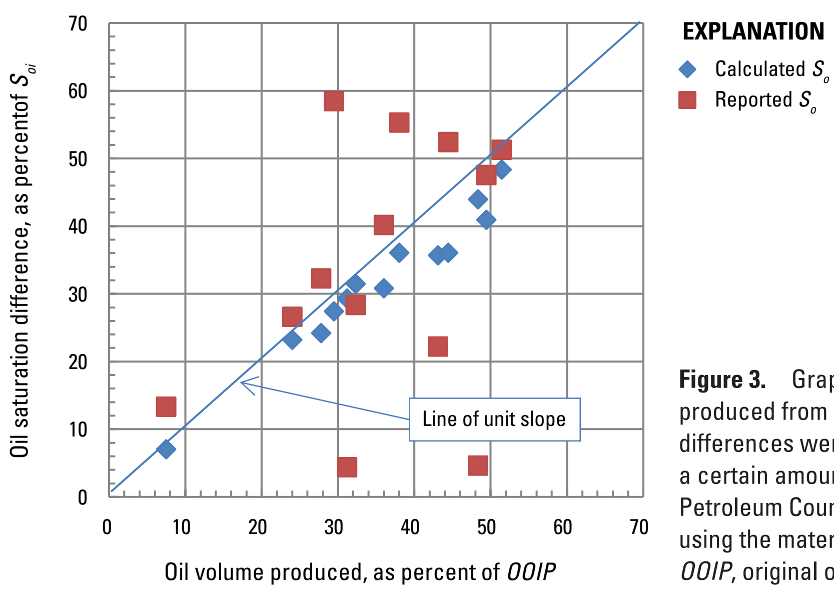

Figure 3. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in Texas. Saturation differences were determined using values of oil saturation after a certain amount of oil production (S_o) reported in the National Petroleum Council (1984b) database and 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.

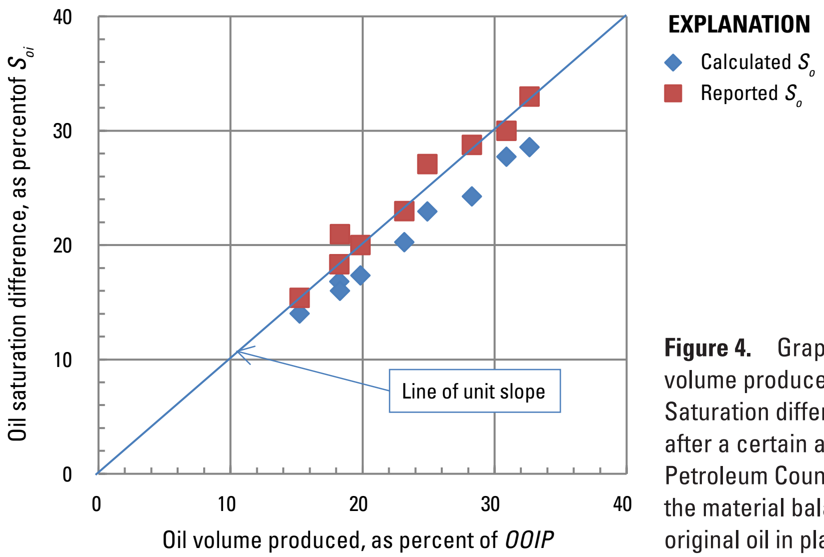

Figure 4. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in West Virginia. Saturation differences were determined using values of oil saturation after a certain amount of oil production (S_o) reported in the National Petroleum Council (1984b) database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

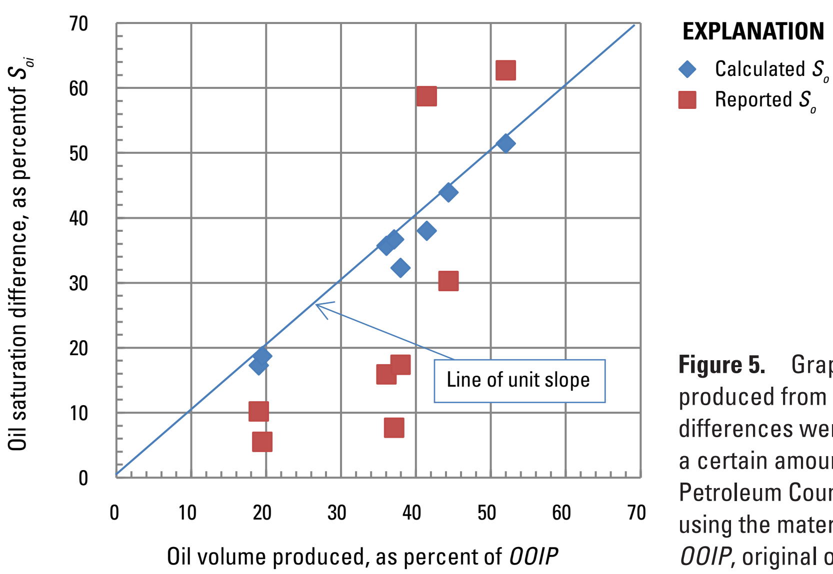

Figure 5. Graph showing oil saturation difference versus oil volume produced from selected sandstone oil fields in Wyoming. Saturation differences were determined using values of oil saturation after a certain amount of oil production (S_o) reported in the National Petroleum Council (1984b) database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

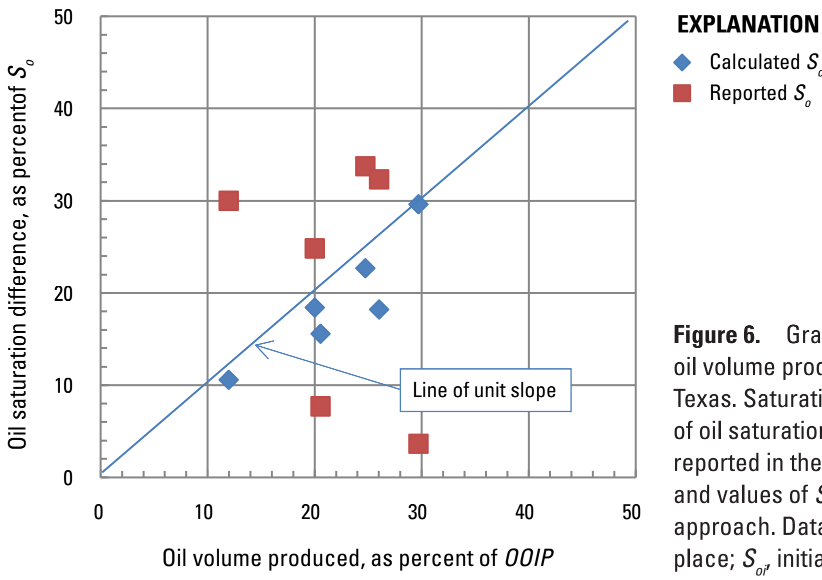

Figure 6. Graph showing oil saturation difference versus oil volume produced from selected carbonate oil fields in Texas. Saturation differences were determined using values of oil saturation after a certain amount of oil production (S_o) reported in the National Petroleum Council (1984b) database and 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.

Conclusions

The value of $So_{start\ of\ CO2\text{-}EOR}$ 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_{orw} or the *ROS* could be used to determine the value of $So_{start\ of\ CO2\text{-}EOR}$ in conjunction with a material balance approach to provide validity. Previous studies indicate that even for the same reservoir the value of $So_{start\ of\ CO2\text{-}EOR}$ 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 $So_{start\ of\ CO2\text{-}EOR}$.

Although material balance has been mentioned in the classification of various methods for estimating the S_{orw} or the *ROS*, only limited use of it has been reported (Verma and others, 1994). Most of the early work on S_{orw} 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 $So_{start\ of\ CO2\text{-}EOR}$ 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 $So_{start\ of\ CO2\text{-}EOR}$, especially when there is a large number of reservoirs to be evaluated.

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