Carbon Dioxide Enhanced Oil Recovery Performance According to the Literature

By Ricardo A. Olea

Chapter D of

Three Approaches for Estimating Recovery Factors in Carbon Dioxide Enhanced Oil Recovery

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Chapter D. Carbon Dioxide Enhanced Oil Recovery Performance According to the Literature

By Ricardo A. Olea[1]

Introduction

The need to increase the efficiency of oil recovery and environmental concerns are bringing to prominence the use of carbon dioxide (CO_2) as a tertiary recovery agent. Assessment of the impact of flooding with CO_2 all eligible reservoirs in the United States not yet undergoing enhanced oil recovery (EOR) requires making the best possible use of the experience gained in 40 years of applications. Review of the publicly available literature has located relevant CO_2-EOR information for 53 units (fields, reservoirs, pilot areas) in the United States and 17 abroad.

As the world simultaneously faces an increasing concentration of CO_2 in the atmosphere and a higher demand for fossil fuels, the CO_2-EOR process continues to gain popularity for its efficiency as a tertiary recovery agent and for the potential for having some CO_2 trapped in the subsurface as an unintended consequence of the enhanced production (Advanced Resources International and Melzer Consulting, 2009). More extensive application of CO_2-EOR worldwide, however, is not making it significantly easier to predict the exact outcome of the CO_2 flooding in new reservoirs. The standard approach to examine and manage risks is to analyze the intended target by conducting laboratory work, running simulation models, and, finally, gaining field experience with a pilot test. This approach, though, is not always possible. For example, assessment of the potential of CO_2-EOR at the national level in a vast country such as the United States requires making forecasts based on information already available.

Although many studies are proprietary, the published literature has provided reviews of CO_2-EOR projects. Yet, there is always interest in updating reports and analyzing the information under new perspectives. Brock and Bryan (1989) described results obtained during the earlier days of CO_2-EOR from 1972 to 1987. Most of the recovery predictions, however, were based on intended injections of 30 percent the size of the reservoir's hydrocarbon pore volume (HCPV), and the predictions in most cases badly missed the actual recoveries because of the embryonic state of tertiary recovery in general and CO_2 flooding in particular at the time. Brock and Bryan (1989), for example, reported for the Weber Sandstone in the Rangely oil field in Colorado, an expected recovery of 7.5 percent of the original oil in place (OOIP) after injecting a volume of CO_2 equivalent to 30 percent of the HCPV, but Clark (2012) reported that after injecting a volume of CO_2 equivalent to 46 percent of the HCPV, the actual recovery was 4.8 percent of the OOIP. Decades later, the numbers by Brock and Bryan (1989) continue to be cited as part of expanded reviews, such as the one by Kuuskraa and Koperna (2006). Other comprehensive reviews including recovery factors are those of Christensen and others (2001) and Lake and Walsh (2008). The Oil and Gas Journal (O&GJ) periodically reports on active CO_2-EOR operations worldwide, but those releases do not include recovery factors. The monograph by Jarrell and others (2002) remains the most technically comprehensive publication on CO_2 flooding, but it does not cover recovery factors either.

This chapter is a review of the literature found in a search for information about CO_2-EOR. It has been prepared as part of a project by the U.S. Geological Survey (USGS) to assess the incremental oil production that would be technically feasible by CO_2 flooding of all suitable oil reservoirs in the country not yet undergoing tertiary recovery.

Data Acquisition and Normalization

The method of choice for predicting the effectiveness of CO_2-EOR has been to assess the tertiary recovery, *EOR*, as the product of the recovery factor (*RF*) and the original oil in place (*OOIP*) in each reservoir:

$$EOR = RF \cdot OOIP \qquad \text{(D1)}$$

Although equation D1 is simple in form, the dependence of both variables on several other factors leads to complexity and makes the modeling and displaying of results difficult. In order to obtain more accurate predictions, it is customary to differentiate recovery factors by lithology and prepare two-dimensional graphs as a function of cumulative CO_2 injected.

[1]U.S. Geological Survey.

To express *RF* in percent, convert equation D1 by dividing *EOR* by *OOIP* (that is, normalize *EOR*) and multiply by 100:

$$RF = 100 \cdot \frac{EOR}{OOIP} \qquad \text{(D2)}$$

The CO_2 injected is also normalized as a fraction of the *OOIP*, except that here the conversion is more elaborate because we are dealing with two different fluids, which in the U.S. system of units are measured in different units (Olea, 2015). The normalized variable is *HCPV,* which is measured as a percentage of the *OOIP*:

$$HCPV = 100 \cdot \frac{inj_{CO2}}{e \cdot OOIP} \qquad \text{(D3)}$$
$$e = 48.156 \cdot B_o \cdot \rho_{CO2res}$$

where

- inj_{CO2} is the cumulative injected CO_2, in standard cubic feet (SCF);
- *OOIP* is the original oil in place, in stock tank barrels (STB);
- B_o is the oil formation volume factor, in reservoir barrel per stock tank barrel;
- ρ_{CO2res} is the density of CO_2 at reservoir conditions, in pounds per cubic foot (lb/cf); and
- e is the conversion factor from *OOIP* to CO_2 volume.

The literature search was done primarily with three engines: OnePetro, Google Search, and Scopus. The results are summarized in table D1 (which follows the “References Cited” for this chapter). The table has 70 entries, of which 76 percent are for operations in the United States. Of the floodings, 73 percent have been clearly identified as operating under miscible conditions, 16 percent operated under immiscible conditions, and the remainder operated in unspecified conditions. Uneven reports of facts were a general problem in the research; it was impossible to collect 100 percent of the information of interest for any of the 70 units.

The minimum requirement for a unit to be included in the table was to have information on recovery after undergoing CO_2 flooding. As much as possible, entries were restricted to actual results from field operations. The table was completed with information about other variables commonly associated with CO_2 flooding recovery.

It was considered convenient to have two entries for recovery: latest reported figure and ultimate recovery. Because most CO_2 floods are still in operation, most of the ultimate recovery values are extrapolated predictions. Field values for ultimate recoveries and associated injection volumes are notoriously scarce. Conversely, most of the other values are actual results. Some of the “last reports” are from several years ago because analysts commonly stop publishing about a reservoir after the initial excitement is over. Numerous fields have never been the subject of a publication, making their inclusion impossible in any review.

The table was completed starting backwards from the most recent reference. When older references did not contribute with information already reported in newer ones, the older references were ignored. For example, eight publications have information on the Lost Soldier Tensleep field in Wyoming, but information relevant to table D1 was covered by only three of the most recent five publications. The Lockhart Crossing field in Louisiana, on the contrary, was only mentioned in the presentation by Wood (2010). As a result, 45 percent of the consulted references are not cited in the table because they have been superseded by more recent data, they are not the original source, or they did not contain information valuable for this compilation.

Analysis of the Information about CO_2-EOR Recovery

An analysis of the values in table D1 allows detecting outliers and providing some perspective. Figures D1 and D2 cover the variations of recovery with HCPV injected for the two main lithologies: clastic and carbonate. For convenience in the display, volumes of CO_2 injections were limited to 150 percent of the HCPV despite availability of three larger values at 320 percent, 242 percent, and 160 percent. The values at 150 percent were interpolated from the original curves. Recoveries for the North Coles Levee field in California were ignored systematically in all figures because they are significantly different from the rest of the reported values.

Instead of mathematically fitting a curve to the cloud of points, actual recovery curves (among the few in the literature) were included to summarize general trends. For the miscible operations in clastic reservoirs (fig. D1), such a curve was a composite of two curves from two fields in Wyoming (Eves and Nevarez, 2009): Wertz Tensleep from 0 to 45 percent of the HCPV and Lost Soldier Tensleep from 50 percent of the HCPV and up. In the immiscible case, the selected curves are from Trinidad and Tobago (Mohammed-Singh and Singhal, 2005): from Forrest Reserve pilot EOR 26 up to 70 percent of the HCPV and from Forrest Reserve pilot EOR 33 above 95 percent of the HCPV. For miscible flooding in carbonate reservoirs (fig. D2), the summary recovery curve is an average between the recoveries for two fields in the Permian Basin of Texas: the Seminole field and the Denver unit of the Wasson field (Stell, 2005). Information was insufficient to investigate a trend in immiscible flooding in carbonate reservoirs.

For clastic reservoirs (fig. D1), except for the abnormal values for the Quarantine Bay pilot in Louisiana and the Oropouche pilot in Trinidad and Tobago (about 14 percent), reported values are roughly within 4 percentage points from the summary recovery curve. Dispersion of data for the carbonate reservoirs follows a different style (fig. D2). Except for four data points with deviations larger than 4 percentage

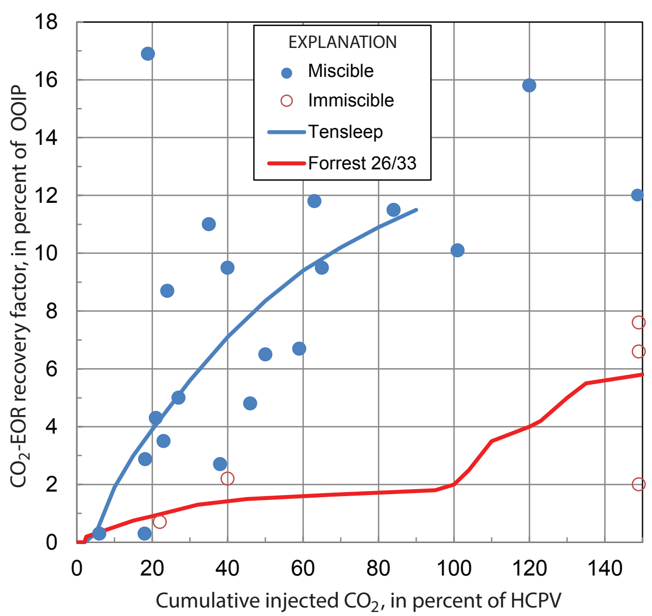

Figure D1. Graph showing recovery factors versus cumulative injected carbon dioxide for clastic reservoirs. Dots denote reported point values summarized in table D1, and the continuous curves are regarded as representative summaries of the general trends. The sources of the composite curves of actual data (Tensleep and Forrest 26/33) are explained in the text. CO_2-EOR, carbon dioxide enhanced oil recovery; HCPV, hydrocarbon pore volume; OOIP, original oil in place.

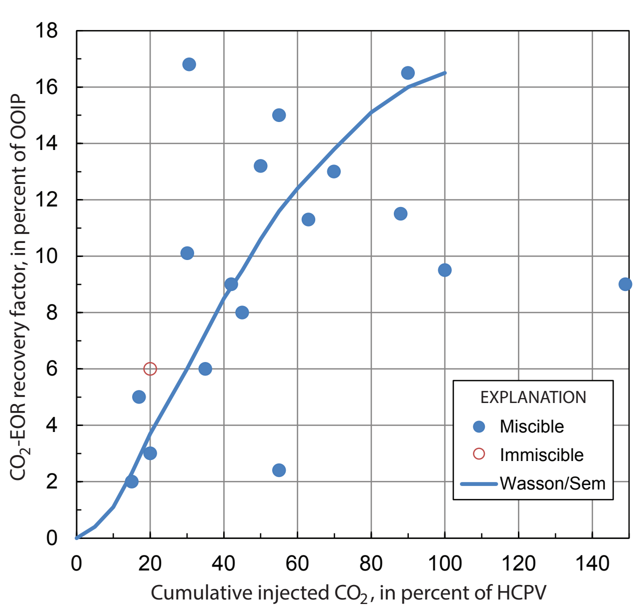

Figure D2. Graph showing recovery factors versus cumulative injected carbon dioxide for carbonate reservoirs. Dots denote reported point values summarized in table D1, and the continuous curve is regarded as a representative summary of the general trend; see details in the text. CO_2-EOR, carbon dioxide enhanced oil recovery; HCPV, hydrocarbon pore volume; OOIP, original oil in place.

points, the remaining points are closer to the type curve. The two most anomalous points, closest to the lower right corner of figure D2, are for the Beaver Creek field in Wyoming. They follow a different trend, which most likely is the result of the highly fractured nature of the reservoir (Peterson and others, 2012).

According to this compilation, there is little difference in recovery below 20 percent of HCPV for CO_2 injection. Above that value, however, the greater the injection, the larger the margin in favor of the carbonate reservoirs. For example, on average, a volume of CO_2 equivalent to 90 percent of the HCPV recovers 16 percent of the original oil in place (OOIP) when injected in a carbonate reservoir, but only 11.5 percent of the OOIP when injected into a clastic reservoir; these results are in close agreement with the 12 percent for clastic reservoirs and 17 percent for carbonate reservoirs reported by van't Veld and Phillips (2010) as ultimate recoveries based on 115 CO_2 floods worldwide.

Analysis of Other Attributes of Interest

Oil density determines to a large extent the feasibility of a reservoir being a candidate for miscible CO_2 flooding. It is often reported in terms of American Petroleum Institute (API) gravity, a dimensionless number comparing the relative density of oil to water, which has a gravity of 10 degrees API (°API). API gravity is loosely and inversely related to viscosity. Unlike geologic characteristics, such as porosity, oil density at standard conditions is a fluid property without significant spatial variation across a reservoir. Consequently, one number is sufficient to characterize exactly a reservoir. In addition, because it is easy to measure, it is one of the variables related to CO_2-EOR most widely reported in the literature, often as degrees of API gravity. The findings are summarized in table D1 and figure D3. There has been a tendency to CO_2-flood reservoirs containing light oils. The average API gravity for clastic and carbonate reservoirs differs by a fraction of one percentage point, not a significant difference. Each histogram in figures D3–D7 includes a list of statistics. For definitions of these terms, see, for example, Olea (2010).

As we have seen, the number of immiscible CO_2 floodings reported in the literature is small. Miscibility is prevented mainly by two factors: (1) oil gravity is too low to have a miscible flood, say, below 25 °API, and (2) gravity is medium to high, but miscibility of CO_2 in oil is not possible because the reservoir is too shallow. The literature reports five reservoirs in the first category, all clastic reservoirs, and three in the second category, with two being carbonate reservoirs.

All other factors being the same, the larger the remaining (or residual) oil saturation of a reservoir, the higher is its CO_2-EOR recovery factor. Oil saturation monotonically declines during production. Thus, the oil saturation at the start of CO_2 flooding will be different depending on the initial conditions and the production history. In the modeling of

CO_2-EOR recovery factors, it is customary to assume that the CO_2 flooding is always preceded by waterflooding. One of the attributes of critical importance in reservoir simulations is the remaining oil saturation in those portions of the reservoir thoroughly flushed by the waterflooding, often denoted as *Sorw* (Verma and others, 1994). In table D1, the similar variable *ResSo* refers to the oil saturation before CO_2 flooding whether or not it was preceded by waterflooding. In other parts of the reservoir, the saturation is higher, closer to the initial oil saturation. Values of *Sorw* imply nothing about the reservoir's volumetric extension. Reported values of *Sorw* are few despite its importance in CO_2-EOR simulation. They are even scarcer when the analysis requires additional evidence that the CO_2 flooding was preceded by waterflooding. The values behind figures D4 and D5 are those listed in table D1. The mean values follow closely the default values of 25 percent for clastic reservoirs and 38 percent for carbonate reservoirs used by the National Petroleum Council (NPC, 1984) and are within the interval of 20 to 35 percent postulated by Tzimas and others (2005). Neither of the numbers published in those two sources, however, is supported with data or references.

Biennially, the Oil and Gas Journal reports results of EOR operations after contacting operators, the latest one being that of Koottungal (2014). The saturation information requested by the journal has been done in terms of "Satur. start" and "Satur. end." Although not reported in the journal version, the saturations are clearly specified as oil saturations in the form distributed by the O&GJ to the operators (Lake and others, 2014). Less clear is the process to which the saturations apply, for which there are discrepancies even among the O&GJ staff (Jacqueline Roueche, Lynxnet LLC, written communications, 2015). Are the data for the start and end of the present recovery process or of the previous one? Even though the most valuable information to have is the starting oil saturation for the current EOR process at those places previously reached by waterflooding (*Sorw*), some of the reported values are so high that they seem to be starting oil saturations before waterflooding. Given this state of confusion, table D1 and the histograms for *Sorw* in figure D4 were prepared by ignoring all the values reported by the O&GJ as well as those from Jarrell and others (2002), who do not disclose sources and also report starting and ending saturations with some quite high values most likely taken from the O&GJ. Nonetheless, it is interesting to note that selected values of "Satur. end" from Koottungal (2014) can produce similar values to those in figure D4, suggesting that some operators interpret "Satur. end" as *Sorw* regardless of the intent of the O&GJ questionnaires. For example, for clastic reservoirs, when four values from Koottungal (2014) are considered in addition to those in figure D4, the mean is 26.8 percent. For carbonate reservoirs, the sample size can significantly increase to 21 by taking 13 of the values from Koottungal (2014) for a mean *Sorw* of 33.5 percent for the sample of size 21.

Bootstrapping is a method to numerically model uncertainty in the calculation of a sample parameter, say, the mean. The method is quite straightforward; it is based on resampling the data, with replacement, multiple times. Given a sample, the bootstrap method allows numerical modeling of any statistics (Efron and Tibshirani, 1993; Pyrcz and Deutsch, 2014), such as the mean. Figure D5 shows the results for the data in figure D4.

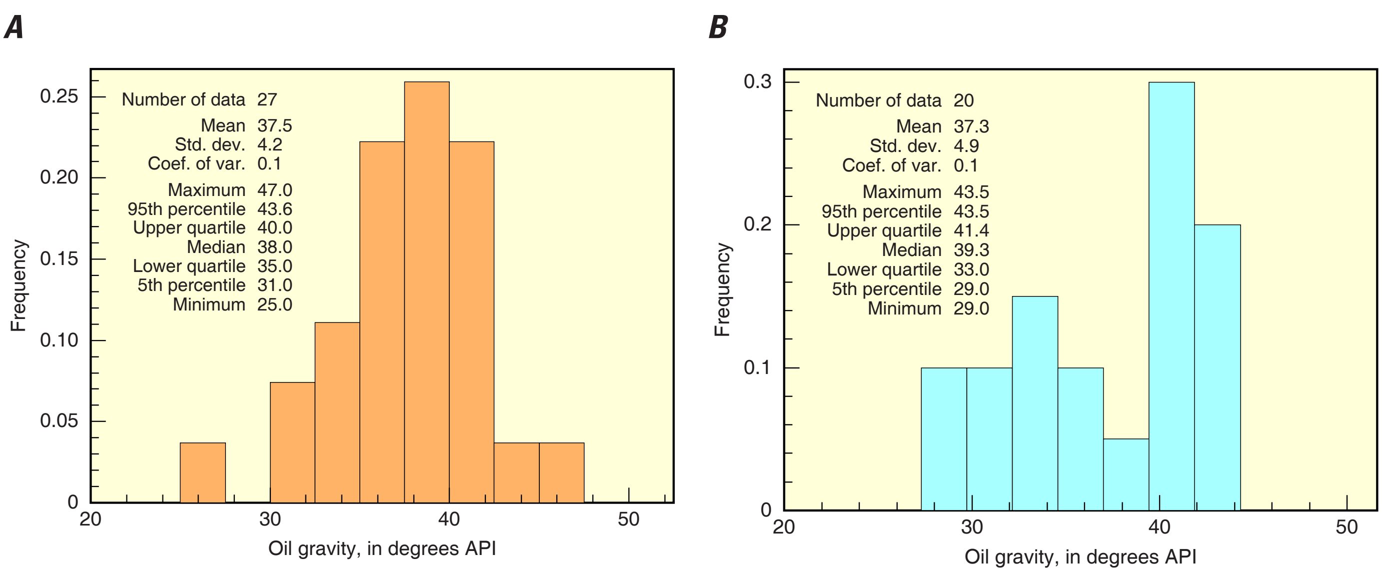

Figure D3. Histograms showing frequency of oil gravity at standard conditions for units under miscible CO_2 flooding for (*A*) clastic reservoirs and (*B*) carbonate reservoirs. Data are from table D1. API, American Petroleum Institute; Coef. of var., coefficient of variation; Std. dev., standard deviation.

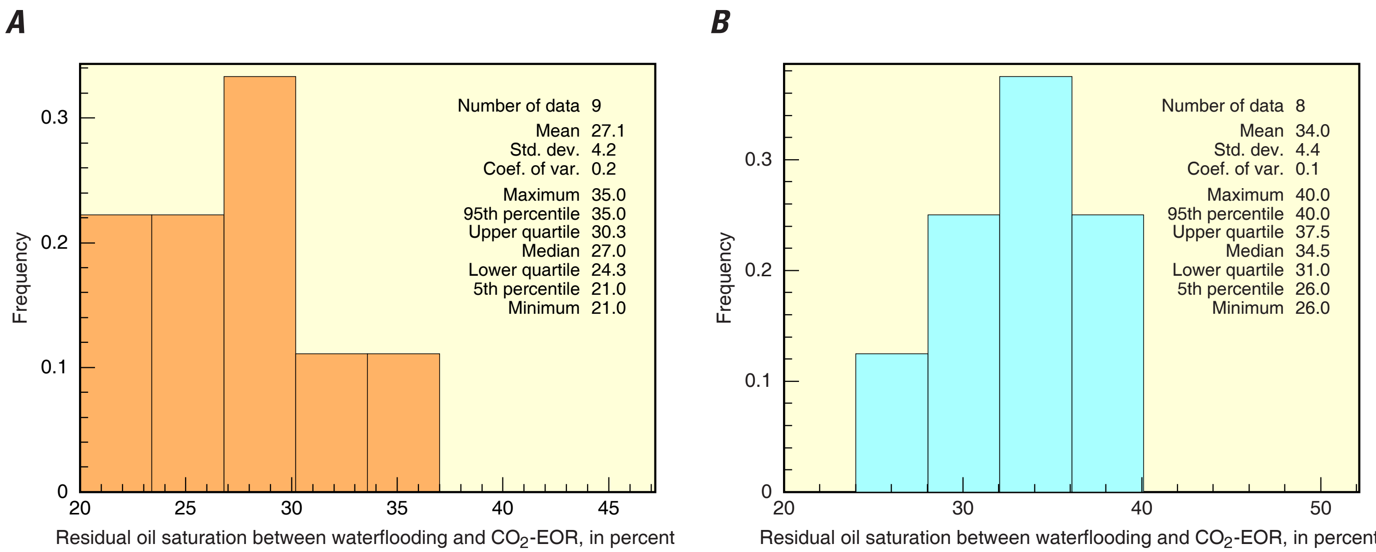

Figure D4. Histograms showng the frequency of residual oil saturation at the beginning of carbon dioxide enhanced oil recovery (CO_2-EOR) when preceded by waterflooding (*Sorw*) for (*A*) clastic reservoirs and (*B*) carbonate reservoirs. Data are from table D1. Coef. of var., coefficient of variation; Std. dev., standard deviation.

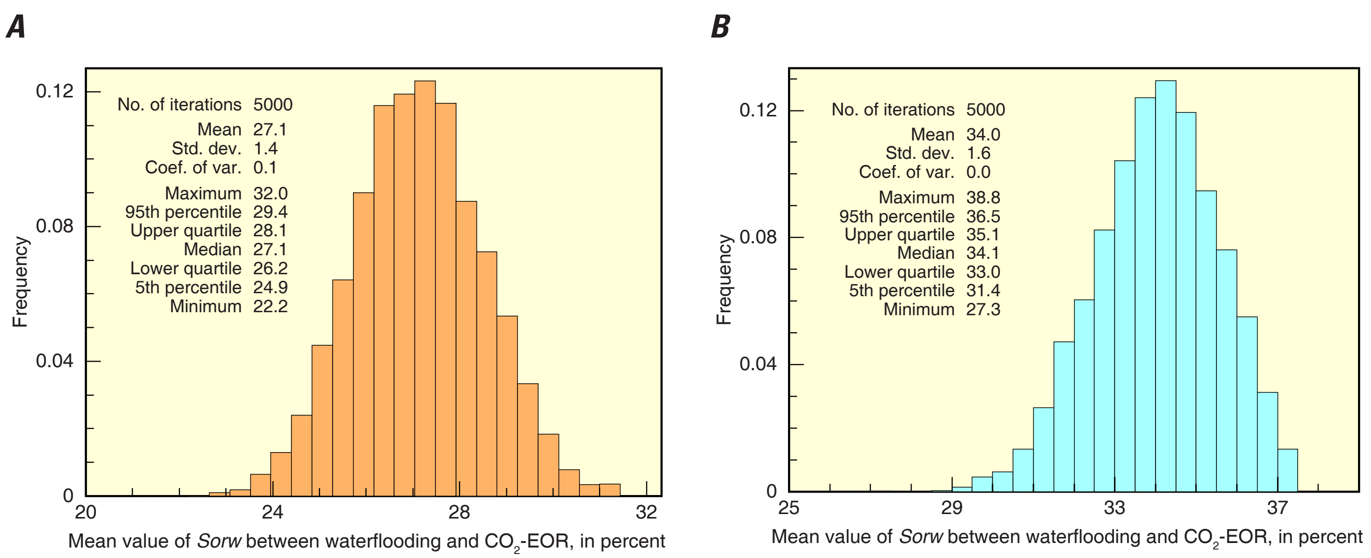

Figure D5. Histograms showing the distribution of the mean value of residual oil saturation (*Sorw*) for the data in figure D4 for (*A*) clastic reservoirs and (*B*) carbonate reservoirs. The distribution shows the proportion of data in each class (frequency). CO_2-EOR, carbon dioxide enhanced oil recovery; Coef. of var., coefficient of variation; No., number; Std. dev., standard deviation.

In reservoir simulation, the value of *Sorw* used ought to be the average value over the field or reservoir. However, the Seminole San Andres unit is the only unit with enough disaggregated information (table D2) to attempt inferring a field average value (fig. D6). It is worth noting that the levels of uncertainty in the national averages and the Seminole average as measured by the interval from the 5th percentile to the 95th percentile are within 1 percentage point (4.5–5.5).

Another variable of the highest importance in CO_2-EOR simulation is the Dykstra-Parsons coefficient (Tiab and Donaldson, 2012). Unfortunately, the information in the literature is minimal and primarily for miscible processes in clastic reservoirs. As reported in table D1, no values were found for the Dykstra-Parsons coefficient of vertical permeability variation (V_{DP}) for any form of CO_2-EOR in carbonates; all the 11 values were for clastic reservoirs, of which 1 was for the immiscible category, and the remaining 10 were for the miscible category. Figure D7 summarizes the findings for clastic reservoirs under miscible CO_2-EOR; the three values for the Katz Strawn unit were averaged so that figure D7 could show one value for each of eight reservoirs. The values closely follow those graphically summarized by Willhite (1986).

Table D2. Residual oil saturation values for flow units within the Seminole San Andres unit, Texas.

[Source: Wang and others (1998). *Sorw*, residual oil saturation after waterflooding; %, percent]

Flow unit	*Sorw* (%)
Wackestone	40
Packstone I	35
Packstone II	35
Packstone III	35
Moldic grainstone I	40
Moldic grainstone II	40
Highly moldic grainstone	40
Grainstone I	35
Grainstone II	25
Grainstone III	25

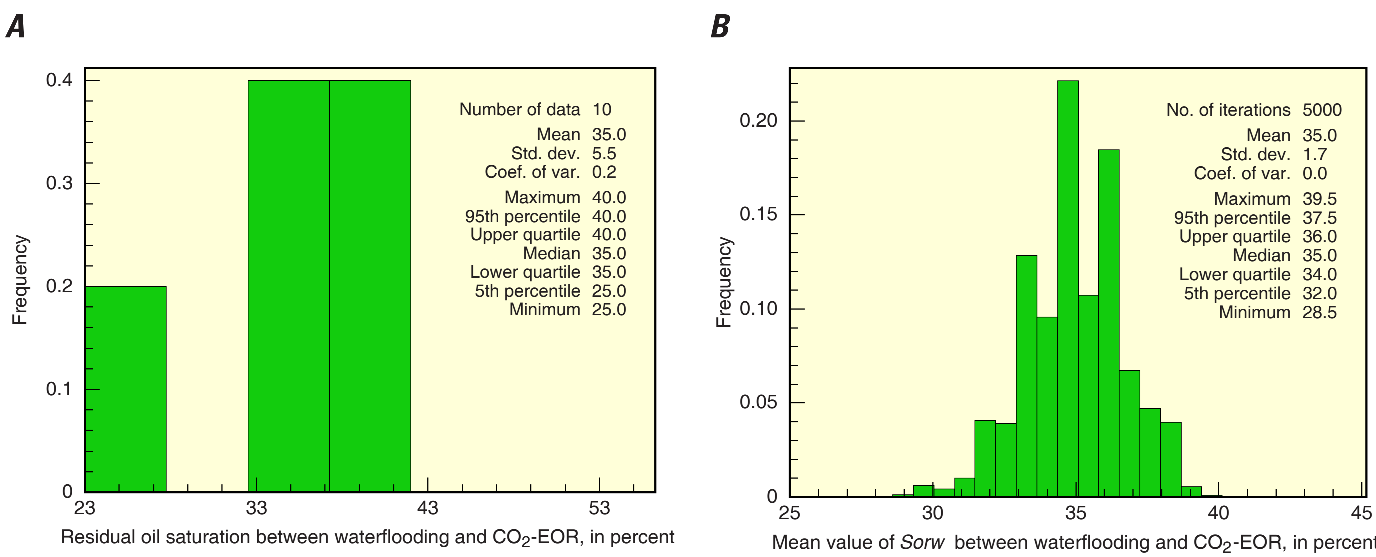

Figure D6. Histograms for residual oil saturation after waterflooding (*Sorw*) for the Seminole San Andres (carbonate) unit showing (*A*) frequency distribution of the data and (*B*) distribution of the mean. CO_2-EOR, carbon dioxide enhanced oil recovery; Coef. of var., coefficient of variation; No., number; Std. dev., standard deviation.

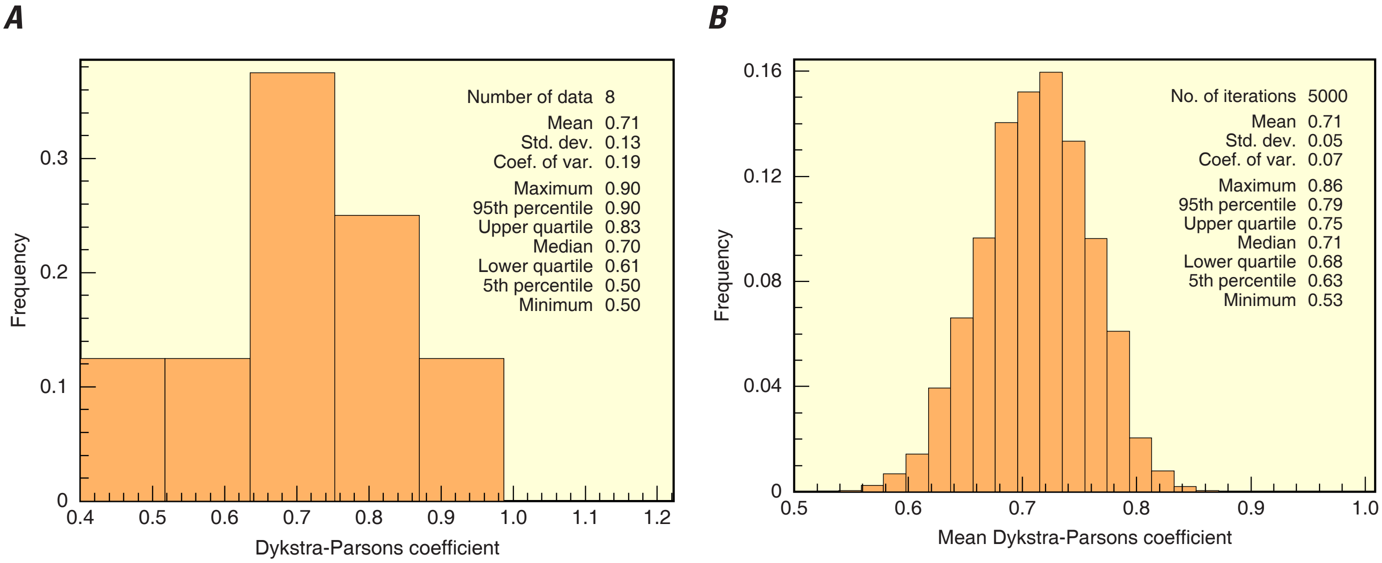

Figure D7. Histograms summarizing reported values for the Dykstra-Parsons coefficient in miscible carbon dioxide (CO_2) flooding of clastic reservoirs and showing (*A*) frequency of 8 values found in the literature (table D1) and (*B*) distribution for the mean obtained by bootstrapping. Coef. of var., coefficient of variation; No., number; Std. dev., standard deviation.

Conclusions

A search of the literature has provided CO_2-EOR data for 70 units (table D1). Recovery-factor values in the dataset and additional values that may be obtained from decline curve analysis should allow calibration against ground truth of hypothetical oil recoveries generated by computer modeling.

Analysis beyond the mere collection of recovery values has provided some results that have been used to formulate generalizations for the national assessment. Lack of complete records reduced the number of units possible to consider in the analyses, compromising the significance of the findings because of the small sample sizes. The main findings are summarized below:

- On average, for large injected CO_2 volumes under miscible conditions, the recovery factors for carbonate reservoirs are larger than those for clastic reservoirs.

- In general, immiscible flooding is significantly less efficient than miscible flooding.

- Despite the dependence of the CO_2-EOR recovery factor on several other attributes than injected volume, there is a general trend in the dependence to injected volume that roughly can be captured by summary recovery curves.

- Of 60 units with both gravity and miscibility information in table D1, 49 are miscible, of which 26 units are clastic reservoirs (ss, sandstone) and 18 are carbonate reservoirs (dl, dolomite; ls, limestone; f.ls, fractured limestone). Independent of the lithology, in the case of miscible flooding, the tendency has been to use CO_2 to flood reservoirs producing light oils that have an average gravity of about 37 °API.

- The mean value of residual oil saturation after waterflooding (*Sorw*) is 27.1 percent for clastic reservoirs and 34.0 percent for carbonate reservoirs. The confidence interval from the 5th to 95th percent for the Seminole San Andres unit in Texas is 5.5 percent, while the same confidence interval from the 5th to 95th percent is remarkably similar for all clastic reservoirs in the literature (4.5 percent) and for all carbonate reservoirs (5.1 percent).

- For the Dykstra-Parsons coefficient of vertical permeability variation, there was enough information to summarize values related to miscible floods in clastic reservoirs. The values are in the range of 0.50–0.90 and have a mean of 0.71.

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Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America

Definitions of terms in table D1 are given below by column from left to right.

Column 1: Petroleum-producing units in column 1 include fields, reservoirs, and pilot areas.

Column 2: Loc.=location by ISO (International Organization for Standardization) 3166 code; data for U.S. States come first and their codes have omitted the prefix "US" (AR, Arkansas; CA, California; CO, Colorado; LA, Louisiana; MS, Mississippi; ND, North Dakota; NM, New Mexico; OK, Oklahoma; TX, Texas; UT, Utah; WY, Wyoming); data for Canada follow, and their codes have omitted the prefix "CA" (AB, Alberta; SK, Saskatchewan); and data for countries outside North America complete the table (BR, Brazil; CN, China; HU, Hungary; IT, Italy; NO, Norway; TR, Turkey; TT, Trinidad and Tobago; UK, United Kingdom; VN, Vietnam).

Column 3: Grav.=American Petroleum Institute oil gravity, in degrees (°API).

Column 4: Conditions: M=miscible or I=immiscible or M/I=miscible and immiscible.

Column 5: Injection method: c→WAG=continuous followed by water alternating with gas; Contin.=continuous; TWAG=tapered water alternating with gas; WAG=water alternating with gas.

Column 6: Lithology (Lith.) terms: chalk, cht=chert, dl=dolomite, f.=fractured, grn=granite, ls=limestone, ss=sandstone.

Column 7: V_{DP}=Dykstra-Parsons coefficient of vertical permeability variation.

Column 8: *OOIP*=original oil in place, in millions of stock tank barrels (MMstb).

Column 9: Pr. + Sec.=primary plus secondary recovery, in percent (%); a single number denotes an aggregated value.

Column 10: *ResSo*=residual oil saturation before starting the CO_2 flooding, in percent.

Column 11: CO_2 start=initial year of CO_2 flooding.

Columns 12, 13, and 14: Last report=last mention in the literature of CO_2 flooding results.

Column 12: *RFco2*=recovery factor for CO_2 flooding (in percent of OOIP) at the date specified in column 13.

Column 13: Year=date reported in the literature.

Column 14: $HCPV_i$=hydrocarbon injected, in percent of pore volume. An asterisk (*) denotes a value estimated for this report using equation D3.

Columns 15 and 16: Ultimate recov.=predicted results at the end of the CO_2 injection.

Column 15: *Ult.RF*=final recovery factor for the CO_2-EOR, in percent of OOIP.

Column 16: $HCPV_i$=CO_2 volume necessary to inject to obtain the ultimate recovery, in percent of pore volume.

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.

[—, no data. Other terms are defined on p. D15]

General information										
Unit	**Loc.**	**Grav. (°API)**	**M/I**	**Method**	**Lith.**	V_{DP}	***OOIP*** **(MMstb)**	**Pr. + Sec. (%)**	***ResSo*** **(%)**	CO_2 **start**
United States										
Lick Creek pilot	AR	17	I	WAG	ss	—	15.8	31.9 + 11.1	—	1976
North Coles Levee pilot CLA 487.	CA	36	M	TWAG	ss	—	—	—	34	1981
North Coles Levee pilot CLA 488.	CA	36	M	TWAG	ss	—	—	—	34	1981
North Coles Levee pilot 5 spot	CA	36	M	TWAG	ss	—	—	—	34	1981
Wilmington field	CA	14	I	WAG	ss	—	69.5	—	—	1982
Rangely Weber field	CO	34	M	TWAG	ss	—	1,810	21 + 21	25	1986
Delhi field	LA	—	M	WAG	ss	—	357	57	—	—
Lockhart Crossing field	LA	42	M	—	ss	—	56	12 + 20	—	2007
Paradis pilot	LA	39	M	Contin.	ss	—	—	—	20	1984
Quarantine Bay pilot	LA	32	M	WAG	ss	—	—	—	38	1981
Timbalier Bay pilot RS-1BSU	LA	39	M	Contin.	ss	—	20.6	44 + none	29	1984
Weeks Island B reservoir	LA	32	M	Contin.	ss	—	3.3	24 + 54	22	1978
Little Creek field	MS	39	M	—	ss	0.5–0.89	102	25 + 22	21	1985
West Mallalieu	MS	38	M	—	ss	—	—	—	15	1986
Little Knife field, minitest	ND	41	M	WAG	dl	—	195	—	40	1980
East Vacuum	NM	38	M	WAG	ss/dl	—	296	25 + 15	30	1985
Maljamar 6th Zone pilot	NM	36	M	Contin.	dl	—	107	21 + 23	30	1981
Maljamar 9th Zone pilot	NM	36	M	Contin.	dl	—	26	21 + 23	40	1981
Garber field pilot	OK	47	M	Contin.	ss	—	—	—	25.3	1981
Northeast Purdy unit	OK	34.9	M	WAG	ss	—	225	16 + 22	—	1983
Postle Morrow unit	OK	42	M	TWAG	ss	—	300	34.7	—	1995
Sho-Vel-Tum	OK	25	M	—	ss	—	210	—	59	1982
Cogdell Canyon Reef unit	TX	40	M	WAG	ls	—	117	—	—	2001
Dollarhide	TX	40	M	WAG	cht	—	145.6	13.4 + 29.6	25	1985
East Ford	TX	40	M	—	ss	0.52	18.4	16 + none	49	1995
Ford Geraldine unit	TX	40	M	Contin.	ss	—	99	18 + 4.5	31	1981
Hanford San Andres field	TX	32	M	WAG	dl	—	17	17.9 + 14.2	—	1986
Hansford Marmaton field	TX	38	I	WAG	ss	0.92	12.5	13 + none	43	1980
Katz Strawn unit	TX	38	M	c→WAG	ss	0.82 0.67 0.64	206	14 + 19	—	2010

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.—Continued

[—, no data. Other terms are defined on p. D15]

Last report			Ultimate recov.		References
RFco2 (%)	Year	*$HCPV_i$* (%)	*Ult.RF* (%)	*$HCPV_i$* (%)	
United States—Continued					
11.1	1990	242	—	—	Moffitt and Zornes (1992); Jarrell and others (2002).
25.8	1984	38	—	—	MacAllister (1989): Jarrell and others (2002).
21.8	1984	61	—	—	MacAllister (1989); Jarrell and others (2002).
15.6	1984	38	—	—	MacAllister (1989): Jarrell and others (2002).
0.7	1986	22*	—	—	Spivak and others (1990); Merchant (2010).
4.8	2011	46	—	—	Hervey and Iakovakis (1991); Masoner and Wackowski (1995); Advanced Resources International (2006); Clark (2012).
—	—	—	17	—	Evolution Petroleum Corporation (2013); Chen and others (2014).
2.7	2010	38	—	—	Wood (2010).
14.5	1985	—	—	—	Holtz (2009).
16.9	1987	18.9	—	—	Hsie and Moore (1988); Holtz (2009).
—	—	30	23	—	Moore (1986); Kuuskraa and Koperna (2006); Holtz (2009).
8.7	1987	24	—	—	Jarrell and others (2002); Kuuskraa and Koperna (2006); Holtz (2009).
18.4	2007	—	—	—	Jarrell and others (2002); Senocak (2008); Senocak and others (2008).
—	—	—	18.5	—	Martin and Taber (1992); Jarrell and others (2002).
—	1981	—	8	—	Desch and others (1984); Thakur and others (1984).
2	1996	16	10	—	Brownlee and Sugg (1987); Martin and others (1995); Harpole and Hallenbeck (1996); Jarrell and others (2002).
16.8	1986	30.6	—	—	Pittaway and others (1987); Moore and Clark (1988); Plumb and Ferrell (1989).
10.1	1986	30.1	—	—	Pittaway and others (1987); Moore and Clark (1988); Plumb and Ferrell (1989).
11	1984	35	14	—	Kumar and Eibeck (1984).
2.8	1985	18	7.5	—	Fox and others (1988); Electric Power Research Institute (1999); Jarrell and others (2002).
6.7	2009	59	10.1	101	Jarrell and others (2002); Wehner (2009).
—	—	—	4.8	—	Electric Power Research Institute (1999); Jarrell and others (2002).
11	—	—	17	—	Oil & Gas Journal (12 April 2004); Meyer (2010).
11	1996	11.2	14	—	Lin and Poole (1991); Bellavance (1996).
1	2002	—	—	—	Jarrell and others (2002); Dutton and others (2003).
3.5	1989	24	13	—	Lee and El-Saleh (1990); Pittaway and Rosato (1991); Dutton and others (2003).
14	1989	—	—	—	Merrit and Groce (1992); Jarrell and others (2002).
9	1988	—	—	—	Flanders and others (1990); Jarrell and others (2002).
0.3	2011	18	15.8	120	Smith and others (2012).

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.—Continued

[—, no data. Other terms are defined on p. D15]

General information										
Unit	Loc.	Grav. (°API)	M/I	Method	Lith.	V_{DP}	*OOIP* (MMstb)	Pr. + Sec. (%)	*ResSo* (%)	CO_2 start
United States—Continued										
Means San Andres unit	TX	29	M	TWAG	dl	—	230	35	34	1983
North Cross unit	TX	44	M	Contin.	cht	—	53	13 + none	49	1972
North Ward Estes	TX	37	M	WAG	ss	0.85	1,100	13 + 28.5	25	1989
Port Neches pilot	TX	35	M	WAG	ss	0.7	10.4	40 + 14	30	1993
Reinecke field	TX	42	M	c→WAG	ls	—	180	50	32	1998
SACROC modern pilot	TX	41.8	M	—	ls	—	144	—	26.1	2008
Salt Creek field	TX	39	M	WAG	ls	—	700	48	—	1993
Seminole field, San Andres unit	TX	35	M	WAG	dl	—	1,100	13 + 22.3	35	1983
Sharon Ridge Canyon unit	TX	43	M	WAG	ls	—	398	50	—	1999
Slaughter Estate unit	TX	33	M	Contin.	dl	—	646	50.5	26	1984
South Welch unit	TX	34.4	M	WAG	dl	—	67	—	50	1993
Spraberry pilot	TX	—	—	—	f.ss	—	10,000	10 + 15	—	2001
Twofreds	TX	36.4	M	WAG	ss	0.5	51	12.9 + 4	—	1974
Wasson field, Denver unit	TX	33	M	WAG	dl	—	2,000	17.2 + 30.1	40	1983
Wellman unit	TX	43.5	M	Contin.	ls	—	127	33 + 11	35	1983
Aneth unit	UT	41	—	WAG	ls	—	534	—	—	1998
McElmo Creek unit	UT	40	—	WAG	ls	—	487	—	—	1985
Beaver Creek	WY	39.5	M	c→WAG	ls/dl	—	109	43.6	—	2008
Hartzog Draw field	WY	36	—	—	ss	—	370	34	—	2016
Lost Soldier Tensleep	WY	34	M	WAG	ss	—	240	19.9 + 24.4	—	1989
Monell unit	WY	43	—	—	ss	—	115	20 + 14	—	2003
Salt Creek	WY	39	M	WAG	ss	—	1,700	40	—	2004
Wertz Tensleep	WY	35	M	—	ss	0.8	172	45.1	—	1986
West Sussex pilot	WY	39	M	Contin.	ss	0.9	33.2	18.1 + 24.1	28	1982
Canada										
Caroline field	AB	42	M	WAG	ss	—	34.6	8.7 + none	—	1984
Joffre Viking pool	AB	40.5	M	WAG	ss	—	30	42	35	1984
Midale field pilot	SK	29	M	—	f.ls	—	500	—	50	1986
Weyburn field	SK	30	M	c→WAG	dl/ls	—	1,400	24	—	2000

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.—Continued

[—, no data. Other terms are defined on p. D15]

Last report			Ultimate recov.		References
RFco2 (%)	Year	*HCPV$_i$* (%)	*Ult.RF* (%)	*HCPV$_i$* (%)	
United States—Continued					
15	2012	55	—	—	Magruder and others (1990); Kuuskraa (2008); SPE International (2013).
23	1994	84	—	—	Mizenko (1992); Jarrell and others (2002); Kinder Morgan (2013).
4.3	1995	21	—	—	Winzinger and others (1991); Ring and Smith (1995).
—	—	—	9–15	150	Davis (1994); Holtz (2009).
4	2012	—	—	—	Jarrell and others (2002); Saller and others (2006); Zhou and others (2012).
—	—	—	9	42	Xiao and others (2011).
6	2004	35	9.5	100	Bishop and others (2004); Wilkinson and others (2004); Kuuskraa (2008).
13.7	1998	58	16.5	90	Wang and others (1998); Stell (2005); Meyer (2010).
—	—	—	13	70	Brinkman and others (1998); Yuan and others (2001).
11.5	2005	88	—	—	Stein and others (1992); Folger and Guillot (1996); Stell (2005).
—	—	—	13.2	50	Keeling (1984); Hill and others (1994); Jarrell and others (2002).
—	—	—	6.5	—	Knight and others (2004); Kuuskraa and Koperna (2006).
5	1985	27*	12	—	Kirkpatrick and others (1985); Flanders and DePauw (1993); Dutton and others (2003).
11.3	2003	63	19.5	—	Tanner and others (1992); Garcia Quijada (2005); Stell (2005); Kuuskraa (2012).
5.7	1998	—	16.7	—	Nagai and Redmond (1983); Schechter and others (1998); Rojas (2002); Kuuskraa and Koperna (2006); Howard (2013).
3	2012	20	—	—	Jarrell and others (2002); Chidsey and others (2006); Resolute Energy Corporation (2012).
8	—	45	11.9	—	Jarrell and others (2002); Stell (2005); Resolute Energy Corporation (2013).
2.4	2011	55	12	320	Peterson and others (2012).
—	—	—	7	—	Hunt and Hearn (1982); Wo (2007); van't Veld and Phillips (2010); Denbury Resources (2012).
11.5	2004	84	—	—	Wo (2007); Lake and Walsh (2008); Cook (2012).
2.6	2008	14	—	—	Gaines (2008).
0.3	2008	6	10	—	Gaines (2008); Page (2009); Bailey (2010); Meyer (2010); Mukherjee and others (2014).
9.5	2004	65	—	—	Kleinstelber (1990); Lake and Walsh (2008); Eves and Nevarez (2009).
9.5	1985	40	—	—	Hoiland and others (1986); Lake and Walsh (2008).
Canada—Continued					
5.3	1987	—	—	—	Birarda and others (1990).
11.8	2003	63	16.3	—	Pyo and others (2003).
14	1988	—	17	—	Beliveau and others (1993); Jarrell and others (2002).
2	2004	15	9	—	Wilson and Monea (2004); Schlumberger Excellence in Education Development (2014).

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.—Continued

[—, no data. Other terms are defined on p. D15]

General information										
Unit	**Loc.**	**Grav. (°API)**	**M/I**	**Method**	**Lith.**	V_{DP}	***OOIP* (MMstb)**	**Pr. + Sec. (%)**	***ResSo* (%)**	**CO_2 start**
Countries Outside North America										
Buracica field	BR	35	I	Contin.	ss	—	60.4	36.8	—	1991
Daqing pilot	CN	—	I	WAG	ss	—	—	—	—	1991
PF-A-I reservoir	HU	30.2	M/I	c→WAG	ss	—	—	27.6 + 4.6	—	1973
Armatella	IT	10.4	I	WAG	dl/ls	—	82	—	—	2015
Giaurone	IT	—	—	—	—	—	—	—	—	2015
Ekofisk field	NO	37	M	WAG	chalk	—	6,600	—	—	—
Bati Raman	TR	12	I	c→WAG	f.ls	—	1,850	2 + none	—	1986
Forrest Reserve pilot EOR 4	TT	25	I	Contin.	ss	—	36.4	41.7	—	1986
Forrest Reserve pilot EOR 26	TT	17	I	Contin.	ss	—	1.9	4.9 + none	—	1974
Forrest Reserve pilot EOR 33	TT	19	I	Contin.	ss	—	16.2	17.4	—	1976
Oropouche, pilot EOR 44	TT	29	I	Contin.	ss	—	8.7	17.9 + none	53	1990
Forties field	UK	37	—	WAG	ss	—	4,200	59	27	—
White Tiger field	VN	—	M	—	f.grn	—	3,300	—	—	—

Table D1. Carbon dioxide (CO_2) recovery factors and other related information for petroleum-producing units in the United States, Canada, and countries outside North America.—Continued

[—, no data. Other terms are defined on p. D15]

Last report			Ultimate recov.		References
RFco2 (%)	Year	*HCPV$_i$* (%)	*Ult.RF* (%)	*HCPV$_i$* (%)	
Countries Outside North America—Continued					
—	—	—	4.4	—	Lino (2005); Rocha and others (2007); Estublier and others (2011).
4.7	1993	—	—	—	Jingcun and others (1997).
6.5	2010	50	—	—	Uj and Fekete (2011).
—	—	—	5.4	—	Andrei and others (2010).
—	—	—	4	—	Andrei and others (2010).
—	—	—	5.6	—	Mathiassen (2003).
6	2011	20	10	—	Sahin and others (2008, 2012, 2014).
2.2	2003	40	4.7	—	Mohammed-Singh and Singhal (2005).
1.5	—	50	7.6	270	Mohammed-Singh and Singhal (2005).
5.8	2003	150	9.0	—	Mohammed-Singh and Singhal (2005).
3.1	2003	160	3.9	—	Jarrell and others (2002); Mohammed-Singh and Singhal (2005).
—	—	—	4.7	—	Mathiassen (2003).
—	—	—	20	—	Imai and Reeves (2004); Kuuskraa and Koperna (2006).