



General Introduction and Recovery Factors

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Chapter A of
**Three Approaches for
Estimating Recovery Factors in
Carbon Dioxide Enhanced Oil Recovery**

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Chapter A. General Introduction and Recovery Factors

By Mahendra K. Verma¹

Introduction

The U.S. Geological Survey (USGS) compared methods for estimating an incremental recovery factor for the carbon dioxide enhanced oil recovery (CO₂-EOR) process involving the injection of CO₂ into oil reservoirs. In order to show the significance of the recovery factor (*RF*), equation A1 relating the recoverable hydrocarbon volume with the *RF* and various reservoir parameters is given below. Although the reservoir parameters used in equation A1 are generally known, the *RF* for CO₂-EOR is unknown for individual oil reservoirs and needs to be established for estimating the recoverable hydrocarbon volume. This chapter first provides some basic information on the *RF*, including its dependence on various reservoir and operational parameters, and then discusses the three development phases of oil recovery—primary, secondary, and tertiary (EOR). It ends with a brief discussion of the three approaches for estimating recovery factors, which are detailed in subsequent chapters.

For calculating technically recoverable hydrocarbon volumes from a volumetric approach, it is necessary to have the values of all the reservoir parameters that make up the volumetric equation, as given below:

$$\text{recoverable HC} = RF \left[7758.4 \cdot \frac{A \times h \times \phi \times (1 - S_{wi})}{FVF_{oil}} \right] \quad (\text{A1})$$

where

- HC* is the hydrocarbon volume, in stock tank barrels (STB);
- RF* is the recovery factor;
- 7758.4 is the conversion factor from acre-foot (acre-ft) to barrel (bbl);
- A* is the area, in acres;
- h* is the formation average net thickness, in feet;
- ϕ is the porosity, expressed as a fraction;
- S_{wi}* is the initial or connate water saturation, expressed as a fraction; and
- FVF_{oil}* is the formation volume factor for oil, in reservoir barrel per stock tank barrel of oil (bbl/STB).

The values of all the parameters except for the *RF* are available from the comprehensive resource database (CRD) developed by INTEK Inc., a petroleum engineering consulting company under contract to the USGS (Carolus and others, in press). The data within the CRD are proprietary because they include field and reservoir properties from the “Significant Oil and Gas Fields of the United States Database” (NRG) from Nehring Associates Inc. (2012) and proprietary production and drilling data from IHS Inc. (2012). These proprietary data cannot be released directly to the public in this or other related reports.

The recovery factor for a reservoir is a function of lithology; porosity; rock permeability (including relative permeability of the fluids present in the reservoir); capillary size; rock wettability; oil properties such as oil gravity, viscosity, and percentage of medium to higher molecular weight components; and the reservoir driving mechanism in two types of oil reservoirs that are potentially suitable for CO₂-EOR: (1) undersaturated oil reservoirs with or without aquifer support and (2) saturated oil reservoirs with a gas cap with or without aquifer support. The recovery factor may also be affected to some extent by other factors, such as using advanced technologies for drilling horizontal wells and multilateral wells and using more effectively the interpretation of production logs as well as seismic surveys. Of course, good reservoir management plays an important role in improving the recovery factor as managers continuously monitor the reservoir performance and proactively take measures to remedy various adverse operational situations.

Of the three approaches that are included in this report, the decline curve analysis and review of papers and reports on reservoirs with CO₂-EOR do provide the *RF* information for a certain number of reservoirs but do not help establish a technically sound basis for estimating recoverable hydrocarbon volumes for a large number of reservoirs. The third approach, reservoir simulation, is a proven and reliable procedure to estimate the *RF* and hence help assess the technically recoverable hydrocarbon potential of all oil reservoirs that meet the screening criteria.

¹U.S. Geological Survey.

Three Phases of Oil Recovery in Oil Fields

The history of an oil field may have three main developmental phases—primary, secondary, and tertiary recovery, also known as enhanced oil recovery (EOR)—all of which are intended to progressively improve the total recovery. Wells are drilled during the reservoir development phase, which is generally associated with the **primary production phase** when the reservoir is produced under its own energy that is manifested through the expansion of oil and rock with the decline in reservoir pressure. In **conventional reservoirs** (where oil is trapped due to the low permeability of an overlying formation), continued development calls for drilling more wells either as step-out wells or as in-fill wells to reduce the spacing among the existing wells. All these development wells accelerate the reservoir depletion rate, but the increase in the overall recovery factor depends on the permeability distribution and fluid properties of the individual reservoir. In **unconventional reservoirs** (where oil is trapped due to the ultralow permeability of the reservoir rock), additional wells are continually drilled to maximize the recoverable hydrocarbon volumes and thereby directly affect the recovery factor.

During the primary phase, oil production eventually declines to such a low level that the project becomes only marginally profitable, at which point, a **secondary recovery phase** is introduced. During this phase, either water is injected at the bottom of the reservoir structure or gas is injected at the top of the reservoir structure to raise the reservoir pressure, augmenting the reservoir energy for improved recovery. However, such injections are effective only if the reservoir has good horizontal and vertical permeability allowing gravity to keep the fluid segregated and resulting in higher displacement efficiency. In other places, where the geology is complex, the reservoir is produced with a waterflood on a line-drive or a normal or inverted five-spot, seven-spot, or nine-spot well pattern for better sweep efficiency and hence an improved recovery. During this phase, additional producers and injectors are drilled, and old wells are recompleted, worked over, or converted to either production or injection wells across the entire reservoir. In large reservoirs, the development is often carried out in phases.

At the end of the secondary phase, as the production begins to decline because of increasing water-cut or producing gas:oil ratio (GOR), the profitability once again becomes marginal. The decline in profitability may prompt the initiation of a **tertiary phase**, also called **enhanced oil recovery (EOR)**. There are several EOR methods (chemical, thermal, and CO₂ injection) for improving the oil recovery, but for the purpose of this study, the focus is on the CO₂-EOR process. During the CO₂-EOR phase, more wells may be drilled and existing wells recompleted or worked over depending on the well pattern for optimum recovery. Under CO₂-EOR miscible conditions, theoretically oil recoveries could be as high as 90 percent of the

oil in place in the CO₂-swept region (Taber and others, 1997), but they are generally lower because of reservoir complexity in terms of lithology, structure, fractures, capillary pressure, rock wettability, oil viscosity and gravity, and permeability contrast between various zones in the reservoir. Application of economic filters to the CO₂-EOR project further lowers the recovery factors.

Three Approaches for Determining the Recovery Factor

Due to the reliability and the ease of its use, reservoir simulation by CO₂ Prophet was considered the preferred approach by the USGS for determining recovery factors for the CO₂-EOR application in oil reservoirs within the United States. Two additional methods were considered valuable and were used to verify *RF* values obtained from the simulation—the widely used empirical decline curve analysis (DCA) for estimating recoverable hydrocarbon volumes, and a review of published papers and reports on the performance of active or previously active CO₂-EOR fields and reservoirs.

CO₂ Prophet.—The CO₂ Prophet model was developed for the U.S. Department of Energy by Texaco Inc. under contract DE-FC22-93BC14960 and was described by Dobitz and Prieditis (1994). Its application for reservoir simulation in this study is discussed in chapter B of this report.

Decline curve analysis.—Decline curve analysis is an empirical method and is used to estimate recoverable hydrocarbon volumes by analyzing the plots of the historical production rate against time or cumulative production from a reservoir. The *RF* is determined by dividing the recoverable hydrocarbon volume with CO₂-EOR method by the original-oil-in-place (OOIP) volume. This simple method for estimating the *RF* is discussed in chapter C of this report.

Literature review.—A review of the publicly available literature has identified 53 CO₂-EOR projects in the United States and 17 abroad. The available information on *RF* values from these 70 projects has been analyzed and is discussed in chapter D of this report.

Because the production data for the DCA are from either EOR pilot projects or portions of reservoirs, they pose a challenge for the estimation of oil-in-place values due to uncertainty in defining the area and (or) the layers within a reservoir affected by the EOR. Therefore, even with good values of ultimate production from DCA, there is a certain amount of uncertainty in the *RF*, which is a function of both the ultimate production and the oil-in-place values. The *RF* values from a review of published papers and reports come from reservoirs with profitable CO₂-EOR projects. Because of economic factors, they may be lower than *RF* values obtained by CO₂ Prophet for technically recoverable oil resources that are calculated as being producible by using current technology and industry practices without any economic constraint.

However, the RF values from DCA and from the review of published papers and reports will still help provide values of the RF range, which will be useful in preparing a probabilistic estimate of technically recoverable oil volumes.

With the advancement of computer technology in terms of its affordability and the versatility of available models, reservoir simulation has become an invaluable tool to evaluate reservoir performance and recovery factors. Because CO₂ Prophet models a simplified physical process occurring in the reservoir and does not capture the chemical processes that would be described by a sophisticated compositional model, it should not be expected to reflect all the subtleties of real-world petroleum operations. All three approaches will help to establish the range of recovery factors for various reservoir types and therefore are discussed in chapters B, C, and D.

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