ENHANCED OIL RECOVERY

Field Planning and Development Strategies

VLADIMIR ALVARADO

EDUARDO MANRIQUE

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Gulf Professional Publishing is an imprint of Elsevier

G P P

Gulf Professional Publishing is an imprint of Elsevier
30 Corporate Drive, Suite 400
Burlington, MA 01803, USA

The Boulevard, Langford Lane
Kidlington, Oxford, OX5 1GB, UK

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data
Alvarado, V. (Vladimir)
Enhanced oil recovery : field planning and development strategies — V. Alvarado and E. Manrique
p. cm.
Includes bibliographical references and index.
ISBN 978-1-85617-855-6
1. Enhanced oil recovery. I. Manrique, E. (Eduardo) II. Title
TN871.37.A485 2010
622′.33827–dc22 2010012466

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

For information on all Gulf Professional Publishing publications
visit our Web site at *www.elsevierdirect.com*

Printed in the United States
10 11 12 13 14 10 9 8 7 6 5 4 3 2 1

To our loving and patient wives,
Teresa and Elimar

Contents

Preface

Developing a book of any magnitude requires time away from family and friends, so as we finish this one, we must confess that despite the obvious intellectual and personal satisfactions we enjoyed while writing this book, it was not always a pleasant experience. The book's contents are for the most part the result of scribbling on napkins over numerous macchiati and espressos away from the office at different posts over the years. As researchers and consultants, perhaps our most creative moments arose during lengthy informal, and somewhat dreamy, discussions about enhanced oil recovery. That is why many projects came to fruition after consuming many heavily caffeinated cups of coffee.

We have taken a practical approach to describing our thoughts on decision making when applied to enhanced oil recovery (EOR). We know that EOR requires patience, perseverance, and (yes, we admit it) stubbornness, but the final goal is field implementation. Our modest contribution to decision making is aimed at facilitating and encouraging more EOR activities.

ACKNOWLEDGMENTS

We are indebted to numerous colleagues for their contributions in the form of ideas, encouragement, support, and friendship. Aaron Ranson and his team were a creative force behind the efforts to develop screening technologies that simultaneously accommodate both objectivity and practicality—not at all a simple demand. Several staff members of the Oil Recovery Methods Department at a former company provided the necessary feedback as we struggled to find solutions to EOR decision problems. The dedication of young and senior engineers and geologists to many of the EOR projects we participated in generated some of the input for our analyses. We would like to acknowledge some of those colleagues and friends.

Tamara Liscano patiently looked at numerous databases, making sure everything made as much sense as possible. A number of colleagues offered critiques (some that were not always gentle) of our efforts, to which Guillermo Calderon and José Manuel Alvarez can probably relate. E.-M. Reïch, K. Potsch, Y. Yunfeng, and L. Surguchev generously shared their thoughts for a number of years. Jane and John Wright provided a

nurturing atmosphere at Questa Engineering, where many fields were evaluated, and improvements to our methods soon followed.

Two Questa junior colleagues and collaborators, Mehdi Izadi and Curtis Kitchen, patiently generated modeling data and tested some of our most recent ideas. Our joint article served as the starting point for this book, and we will always be thankful for their efforts. Many thanks go to Mahdi Kazempour, a graduate student at the University of Wyoming, for providing simulation data and plots.

We are truly indebted to our editor Ken McCombs and to Elsevier for the opportunity to publish this book. It was certainly a matter of serendipity, but no doubt Ken found value in some of our ideas.

Last, but not least, our families have been supportive and patient to the extreme. Teresa knows what this means to Vladimir, and she has always worked to make a home wherever the family has moved. Elimar, Anjuli, and Eduardo Andres are certainly proud of Eduardo, just as he is of them.

We probably have forgotten to mention many colleagues and friends who were sources of inspiration and ideas. We know they will forgive us for this, understanding that they are always in our thoughts.

Introduction

This book explains strategies for evaluating reservoir development plans (RDPs) based on enhanced oil recovery (EOR). In this sense, it focuses on the decision-making that leads to launching EOR projects. In the context of this book, any strategy that ultimately increases oil and gas recovery is under consideration for EOR decisions. The definitions of EOR will be explored in detail, but the authors introduce important concepts through examples and by briefly reviewing the evolution and history of these methods. Although only a modest fraction of global oil production (3 to 5 percent) can be attributed to EOR, a number of oil provinces in the world rely on it as the main recovery mechanism. This trend will very likely see an increase running apace with a decrease in the number of discoveries and the sizes of hydrocarbon pools, or as new discoveries are made in harsher environments such as deepwater offshore locations.

We examine both already completed and ongoing reported projects to exemplify the value of proper decision making in EOR. The authors have been working in the oil and gas industry in several upstream segments, including research and development and planning and execution of pilot projects, as well as in support activities as consultants for major oil companies and small operators for more than 20 years. A resource, and central theme, here is the workflow that came to light after many years of professional practice, which resulted from the need to develop tools and procedures to deal with improved EOR decision making.

The oil market in recent years has triggered a significant increase in property evaluation and acquisition and development of enhanced oil recovery projects. This upsurge in EOR activities has been motivated not only by an invigorated oil market, which remains relatively strong despite an economic slowdown, but also by, to a great extent, better-known provinces reaching maturity and the possibility of increasing reserves in well-known locations.

In perspective, out of the 3 trillion barrels of oil known to exist in conventional reservoirs, only one-third have been produced and consumed in the market since the early times of the oil business. An additional one-third of the oil in place is expected to be produced by techniques beyond traditional oil and gas activities, including advanced, but commercially viable, EOR. Entire conferences and conference sessions have been dedicated to this issue in recent times, and it is likely to become even more relevant at future meetings; the 2009 SPE Research and Development Conference is a good example.

Future sustainable hydrocarbon production will involve combining yields from both unconventional resources and fields in harsher environments such as deep offshore and politically and/or ecologically sensitive areas. Digital technologies have been predicted to become a large part of the any solution related to the next-trillion problem (Miller, 2008; Moon, 2008). These technologies include automation, data mining, and smart-field technologies.

One important consideration while producing this book was the scarcity of properly trained personnel who can deal with some of the decision challenges associated with EOR. The lack of required teams of engineers and geoscientists can be associated with the oil price collapse during the 1980s and with the later phase-out of R&D centers in major oil companies. There are only a few groups at well-recognized universities and oil companies that continue to develop, evaluate, and/or understand the key features of EOR technologies today.

This state of affairs in our industry has strongly impacted EOR decision making over the last two decades, leading to delays and, probably, missed opportunities when it comes to increasing oil recovery. The main factor impacting financial investments in EOR operations is oil price volatility. EOR initiatives are often delayed under these conditions because of either perceived or real financial risk.

Time is also an issue for EOR decision making. If you are unfamiliar with EOR recovery mechanisms and the known consequences of delaying implementation decisions, it is important for you to develop a sense about the window of opportunity. For example, a common naive conclusion, usually resulting from incorrectly framed financial decisions, is to postpone EOR projects until the economic limit of primary or secondary projects has been attained. This type of decision making assumes that favorable conditions for EOR activities found in a given reservoir at a given time will prevail for the rest of reservoir's productive life. Another way of looking at this is by considering analyses that lead to decisions. For instance, it is a good idea to use a variety of screening methods as part of your decision-making framework. If screening is executed once and never reviewed as reservoirs evolve, you might be left with scenarios with expiration dates.

To exemplify the window of opportunity, or the time issue, consider a screening exercise for a miscible process. (*Miscibility* refers to the ability of two or more fluids to mix at the molecular level.) For example, your can of soda is bubbly because carbon dioxide (CO_2) is dissolved at high pressure in the liquid. But as soon as the can is popped open, the CO_2 comes out, and eventually the soda goes flat. This process is very similar to the loss of energy that occurs in reservoirs as the pressure is depleted and the oil becomes "flat," with frequent undesirable consequences.

Now, let us go back to the issue of decisions in the face of time. In essence, the ability of a solvent (e.g., carbon dioxide) to efficiently sweep the oil-containing pores it contacts very much depends on pressure in the case of gases. As we will see, a condition, variable, or parameter that impacts reservoir recovery this way is referred to as *critical*. The fact that miscibility is so important for recovery means, in practice, that pressure is a critical variable. If the reservoir pressure remains higher than the so-called minimum miscibility pressure (i.e., the value of the pressure required for dissolving the solvent in the oil phase), can the injection fluid (solvent) be a good recovery agent? If the reservoir's initial pressure is adequate for a miscible process, then a screening exercise will likely show it to be a good candidate for this recovery strategy.

Such screening procedures should not be used to produce a go or no-go answer but should provide a feasibility determination on the basis of only a few relevant rock and fluid variables, typically the critical ones. Now, for instance, if a viable miscible EOR process at time t is delayed because it is simply less expensive to produce under primary or secondary recovery strategies (i.e., for purely economic reasons), the window of opportunity for miscible EOR might be missed, even if it was originally technically viable. This is a consequence of the reservoir's energy (i.e., pressure) being depleted irreversibly for lack of pressure-maintenance mechanisms.

As a result, reservoirs do not remain static during any exploitation phase, and so the time allotted for a decision in EOR is constrained. This is not as uncommon as you might think. To help you to understand the underlying problems, the revision of reservoir development plans are discussed in Chapter 1.

Another case is property acquisition, which involves limited time for making a decision. Overanalyzing a purchase without introducing new, relevant data, however, can destroy the value of an acquisition because the chances for success can diminish if the number of decisions is perilously insufficient (Begg, Bratvold, and Campbell, 2003).

Most likely, one of the reasons that overanalysis has become so deeply rooted in the oil and gas industry is that analysis through detailed modeling can reduce uncertainty. The belief that numerically accurate reservoir dynamic models can overcome the hurdles of ambiguity, or even uncertain data sources, is groundless. Modeling should be the least complex as possible to support rational decision making. Bos (2005) shows that lower precision and a higher level of modeling of uncertainty and integration might be necessary to optimize the E&P decision-making process. This may be attainable at the expense of a trade-off between the degree of "model precision" and the degree of uncertainty modeling and integration in favor of the latter.

The oil and gas industry presents its own peculiarities with respect to decision making (Mackie and Welsh, 2006). A pressing issue in decision-making problems is framing (Skinner, 1999), which helps to lower ambiguity with respect to goals or even to eliminate conflicting objectives by developing a decision hierarchy, strategy tables, and an influence diagram (see Chapter 6). In practice, framing signifies knowing exactly what the focus of the decision is and, just as important, what it is not. The importance of understanding the EOR decision focus cannot be overstated, so it is crucial that the object of EOR decision-making exercises be clearly defined to avoid a fishing expedition.

One of the difficulties with decision making is risk avoidance, which is as much a trait of humans as it is a characteristic of organizations. As the complexity of field operations increases, risk avoidance in decision makers triggers "the overanalysis loop." When this occurs, decision makers resort to increasing levels of analysis and modeling or simulation in the hope that uncertainty will be reduced and the possibility of undesirable outcomes can be lowered to negligible levels. The mistake with this view is that uncertainty is not the same as ambiguity, so ill-defined objectives are often confused with lack of certainty. If critical data are not available, analysis will not provide the desired certainty. Even when the decision-making process is rational and reasonable, the outcome can still be negative.

Pedersen, Hanssen, and Aasheim (2006) discuss qualitative screening and soft issues, which are important considerations in EOR analysis and decision making. Petroleum and, more specifically, reservoir engineering professionals focus on the quantitative analysis of production mechanisms and on the evaluation of reserves and performance (reservoir simulation), among many other analytical tasks. Decision making relies on the quantifiable aspects of a problem, such as the net present value of the project, so rational decisions can be made. The difficulty arises when unquantifiable issues become part of the decision problem.

Social and environmental considerations often present themselves as qualitative aspects of a problem, which can be difficult to put into quantifiable terms. For EOR, sources of raw materials (e.g., water), disposal of by-products or waste, and proximity to sinks and sources frequently barely become quantifying matters and must be incorporated into the analysis as soft issues. Retraining of analysts is then necessary to weigh in some of these considerations so that resources are not unnecessarily committed to hard analysis before barriers associated with soft issues are overcome or at least understood.

Ensuring that the model focuses on relevant decision criteria is a prerequisite for overall model relevance. The point is that NPV or other economic (hard) indicators should be used for hard, quantifiable issues, while a variety of methods can be implemented to address soft issues. In this way, the balance between the two provides a good basis for decision alternatives. A balanced analysis of soft and hard issues is an important aspect of decision making discussed in this book.

The oil and gas industry devotes much effort to complex analyses of uncertainty quantification, hoping to eliminate, or at least reduce, it. Bickel and Bratvold (2007) present the results of a survey of decision makers, support teams, and academics to define the value of uncertainty quantification in decision making. The Society of Petroleum Engineers (SPE) as a professional community has held a significant number of forums on uncertainty evaluation but few on decision making. This might explain why such an intense focus has been place on uncertainty analysis as a goal in itself.

One conclusion from Bickel and Bratvold's survey is that the complexity of decision analysis has not greatly contributed to improving the decision-making process in our industry, at least as perceived by those who responded to the survey. The decision-analysis cycle can also be considered iterative in the sense that if more assessments are required (or if profitable data are being gathered), then the information should be compiled and the cycle repeated.

Another frequently encountered problem in decision making is the use of "expert opinion." That the answer came from an expert on the subject, does not necessarily make it correct. Often, excessive use of intuition, which can be mistaken for expertise, can create significant bias. Although intuition may very well have its place in decision making (Dinnie, Fletcher, and Finch, 2002), it can hurt the decision-making process itself. For example, the chemical flooding problem in the 1970s caused many to declare that the processes being used were not sufficient for the commercial market.

Despite the technical merits attributed to the designs produced by the research laboratories involved, they were deemed economic failures. Today, new chemistry and process designs have produced a significant number of technical and economical successes for chemical flooding operations. Thus, the ability to determine what is necessary to make chemical flooding both economically feasible and technically viable has improved considerably.

An additional important consideration in EOR decision making is cognitive bias (Welsh, Bratvold, and Begg, 2005). This can take many forms, one of which reflects the cognitive limitations of the human mind (Begg, Bratvold, and Campbell, 2003). The level of risk avoidance may not be consistent with goals, objectives, and prudent decision making.

This is patently clear when value is destroyed because the decision maker's aversion to risk is higher than the organization's.

A number of methodological strategies have been developed over the years to deal with decision making for EOR projects. In Goodyear and Gregory's studies (1994), screening based on critical variables for the enhanced oil recovery processes is used to determine feasibility early on in an evaluation.[1] This step, however, should not be performed before the problem is framed, including some important soft issues (e.g., local availability of resources or even experience in EOR deployment). EOR decision making must be considered a continuous exercise in screening and scoping (preliminary economics) to provide the best combination of soft and hard issues as inputs for decision makers. In this sense, it is often found that data gathering is one of the most recommended courses of action.

To mitigate cognitive bias, several different database approaches are needed. Data-mining strategies can be used as part of advanced screening with this intent in mind. Thus, instead of relying on a few experts' biases, numerous biases are incorporated into the framed decision problem as emerging from the data structure. EOR screening techniques have been widely documented in the literature. Most of them rely on conventional and advanced approaches (Al-Bahar et al., 2004; Guerillot, 1988; Henson, Todd, and Corbett, 2002; Ibatullin et al., 2002; Joseph et al., 1996). However, very few studies focus on the decision-making process initiated from well-documented screening exercises.

This book provides elements of decision making that are tailored to EOR practices to give readers and practitioners the tools necessary to become more effective at deploying EOR projects. Elements of successful enhanced oil recovery methods and fundamental concepts are discussed to serve as background materials for readers who are unfamiliar with modern EOR technologies. The steps making up a flexible screening methodology are included, as well as details on various analytical and numerical simulation approaches that can be used for different field studies as part of the continuous development of the proposed EOR screening methodology. Performance estimations by means of simplified models illustrate a wide range of decision opportunities, as highlighted by Bos (2005). The case studies are based on examples from the authors' research and consulting practice.

Chapter 1 reviews reservoir development plans as the starting point for EOR decisions. Chapter 2 provides some important definitions associated with EOR and oil recovery concepts. Chapter 3 discusses the elements of reservoir simulation, most of which focus on analytical

[1] The decision-making workflow that is discussed in this book was partially inspired by Goodyear and Gregory's work.

simulation. Chapter 4 examines screening methods for EOR, which are a central aspect of the methodology for decision making. Chapter 5 presents important decision criteria based on soft issues. Chapter 6 provides elements of framing and discusses the tools used for this purpose and the fundamentals of financial evaluation.

Chapter 7, which is this book's pivotal chapter, describes the workflow used for EOR decision making. If you have not read the earlier chapters and are unfamiliar with these topics, we suggest you scan them. Chapter 8 reviews the current status of enhanced oil recovery in general. It is a practical summary that should help you integrate the ideas in the book and understand future EOR goals. Numerous references—some of which are not cited in this book—are provided in the last section. We hope that readers will find that the list adds extra value to the important subject of enhanced oil recovery.