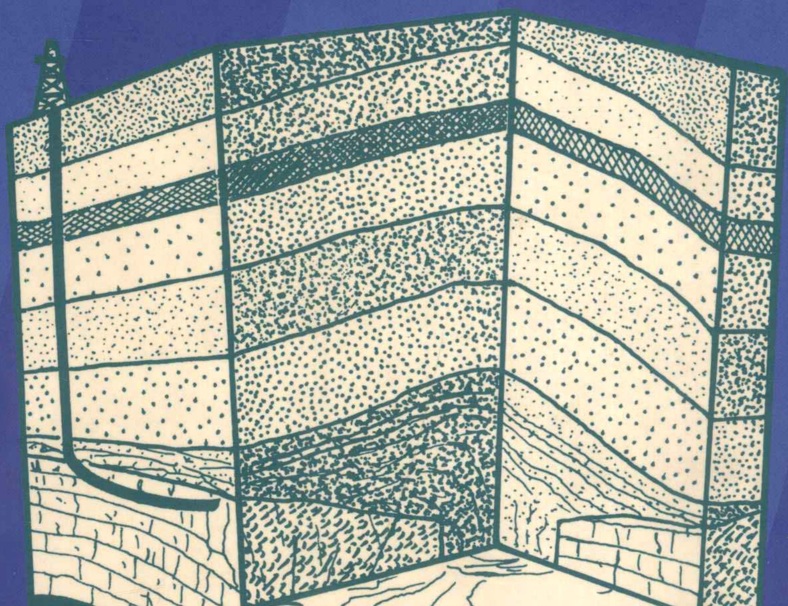
HORIZONTAL WELL TECHNOLOGY



SADA D. JOSHI, PH.D.

HORIZONTAL WELL TECHNOLOGY

S. D. JOSHI, Ph.D.
Joshi Technologies International, Inc.
Tulsa, OK, U.S.A.

PennWell Books

PENNWELL PUBLISHING COMPANY
TULSA, OKLAHOMA

PennWell Corporation
1421 South Sheridan Road
Tulsa, Oklahoma 74112-6600 USA

800.752.9764
+1.918.831.9421
sales@pennwell.com
www.pennwellbooks.com
www.pennwell.com

Marketing Manager: Julie Simmons
National Account Executive: Barbara McGee
Director: Mary McGee
Production Manager: Sheila Brock

Library of Congress Cataloging-in-Publication Data
Joshi, Sada D.
Horizontal well technology / Sada D. Joshi
p.cm.
Includes bibliographical references and index
ISBN 0-87814-350-5
ISBN13 978-0-87814-350-4
1. Horizontal oil well drilling. I. Title.
TN871.25.J67 1991
622'.3382—dc20 90–27822
CIP

Printed in the United States of America

2 3 4 5 6 11 10 09 08 07

This book is humbly dedicated to my mother, Sumati D. Joshi, my father, Dattatray M. Joshi and my wife, Claudette J. Joshi.

I am grateful to my parents for providing me with education, inspiration, and confidence. I am also indebted to my wife who provided the encouragement, fortitude, and extraordinary understanding which enabled me to steal many hours from our family while writing this book.

PREFACE

The major purpose of writing this book is to summarize the state-of-the-art of horizontal well technology. Recent advances in drilling and completion have resulted in a rapid increase in the number of horizontal wells drilled each year around the world. A horizontal well, to some extent, is different from a vertical well because it requires an interdisciplinary interaction between various professionals, such as geologists, reservoir engineers, drilling engineers, production engineers, and completion engineers. Because of the large volume of literature that is available in different disciplines, I have decided to divide this book into two parts. The first part (Volume 1), is presented here. This first volume mainly deals with reservoir and production engineering.

In this book, I have included published literature available as of June 1990. Additionally, I have included example problems to illustrate the use of various theoretical solutions. Wherever possible, I have not only discussed practical difficulties that one may encounter while using theoretical solutions, but I have also listed some of the methods that one can use to obtain the desired information. I have included descriptions on field histories wherever they were available. The available field histories that I have chosen not only represent successes of horizontal well technology but also include some economic failures.

To some extent, writing this book was difficult because of the interdisciplinary nature of horizontal well technology. The book is mainly directed to the practicing professionals who make engineering calculations and decisions on horizontal well applications. This book can also be used as a graduate level textbook. For managers, the book helps to review the present state of the art. I have also outlined some of the gaps in technology that exist today. These gaps in technology will be useful for research engineers and research professionals to determine the areas of future research.

Many solutions which are presented are based upon my personal experiences dealing with various vertical well and horizontal well field projects around the world. I am thankful to the many companies with whom I had the opportunity to work on the field projects. I am also thankful to all the people who have suffered through my teaching of horizontal well classes.

Our class discussions and their suggestions were very valuable in making this book useful to a practicing engineer.

Chapter 1 of this book is an overview of horizontal well technology and is a general introduction to the technology from a reservoir, drilling, and completion standpoint.

Chapter 2 mainly looks at the reservoir engineering concepts and their application for horizontal wells. The chapter also includes a discussion on well spacing of horizontal wells.

Chapter 3 includes steady state solutions and their applications. It also includes discussions on formation damage problems in horizontal wells. In addition to horizontal wells, it also contains a discussion of slant wells. There are cases where slant wells may be more beneficial than horizontal wells.

Chapter 4 deals with the influence of well eccentricity on productivity of a horizontal well. Well eccentricity represents a vertical distance between the horizontal well location and the center of the pay zone. Though influence of the well eccentricity on productivity of a well is minimal, it will have a strong influence on the ultimate reserves for a horizontal well drilled in reservoirs with top gas or bottom water.

Chapter 5 compares horizontal and fractured vertical wells. This chapter discusses practical aspects of hydraulic fracturing of a vertical well, its advantages, and the limitations. The chapter also includes reasons for stimulating horizontal wells and calculation of productivities for fractured horizontal wells.

Chapter 6 focuses on transient well testing. In general, transient well testing is a highly mathematical subject. At the same time, it is one of the most important and useful subjects to understand the well behavior in a given reservoir. To make the chapter complete, I have included all the necessary mathematics and many concepts which are essential to interpret the behavior of a horizontal well.

Chapter 7 deals with pseudo-steady state solutions. In this chapter, I have listed various solutions for vertical wells, fractured vertical wells, and horizontal wells. I have also included available solutions for the partially perforated or partially open horizontal wells. The chapter also describes the performance of horizontal wells completed in solution gas drive reservoirs.

Chapter 8 examines water and gas coning in vertical and horizontal wells. It outlines many of the available solutions for calculating water and gas coning behavior in horizontal and vertical wells. It also contains discussion of available field histories. The histories not only show successes but also the failure of horizontal wells in minimizing water and gas coning. The chapter also outlines benefits and risks associated with production testing of vertical wells to estimate the potential of horizontal wells.

Chapter 9 looks at the application of horizontal wells in gas reservoirs. In my opinion, horizontal wells are highly suitable for low permeability as well as high permeability gas reservoirs.

Chapter 10 deals with the pressure drop through a horizontal well and how important it is in the estimation of horizontal well performance.

To make the book complete, I have included *Appendix A* which refers to fluid properties. *Appendix B* includes data on gas compressibility. *Appendix C* contains various conversion factors. (I have included Appendix C because the book is written in U.S. field units, and Appendix C will be helpful to convert the examples to different field units.) *Appendix D* includes a discussion about various pseudo-skin factors and their definitions. *Appendix E* consists of tables of recovery factors that one can expect from various types of reservoirs and under different types of drive mechanisms. *Appendix F* is a glossary of the terms that are used in this book. I believe this glossary will be useful for people who are not familiar with reservoir and production engineering terminology.

To the readers, I would very much be interested in any comments, suggestions, or questions you may have about the contents of the book. Please feel free to contact me directly:

Sadanand D. Joshi, Ph.D.
Joshi Technologies International, Inc.
5801 E. 41st St., Suite 603
Tulsa, OK 74135
(918) 665-6419

I consider myself to be a student of this technology. After writing this book, reading many published papers and working on various field projects, I realized more than ever that there are many more things which I need to learn before I will ever know all the answers.

Tulsa, Oklahoma
Sept. 6, 1990

ACKNOWLEDGEMENTS

Several people were instrumental in helping me to complete this book. First of all, I would like to acknowledge my family which has been very encouraging and understanding while I spent time away from them to write this book. I am also thankful to three engineers at our company, JTI; George Saville, Pralhad N. Mutalik, and Dr. Wenzhong Ding, who also spent many hours proofreading and solving some of the examples which have been included in the book. Without their help, it would not have been possible to complete this book. I am especially thankful to Dr. Wenzhong Ding, whose attention to details helped to eliminate many typographical errors in the book.

I have also been privileged to work with many professionals in the oil industry who have taught me many things and helped me grow and develop as an engineer. I have been fortunate to be associated with Dr. R. Raghavan who taught me how to think rationally. I am also thankful to: W. B. (Ben) Lumpkin, who taught me many skills in practicing reservoir engineering; Thomas B. Reed of the Department of Energy, who persuaded me in 1980 to start studying horizontal wells; M. J. Fetkovich and R. B. Needham of Phillips Petroleum Company and P. H. Doe of Shell Research Company, who taught me how to use reservoir engineering.

I am indebted to Frank J. Schuh, an outstanding drilling engineer, who introduced me to the drilling part of horizontal well technology. By teaching classes with Frank and working with him on field projects, I have learned about horizontal drilling operations and design. I will be eternally indebted to him for teaching me the practical part of the business. I would also like to thank R. V. Westermark of Phillips Petroleum Drilling Department, for working with me and educating me in this technology from day one. I would like to thank Dr. W. M. Maurer of Maurer Engineering, for all the encouragement and assistance that he provided. I am also thankful to many companies who were generous in providing the field histories and data which were used in the book. In particular, I would like to thank T. O. Stagg of British Petroleum, Alaska, and Barry Anderson of Western Mining Ltd., Australia, for being generous in providing all the necessary information to make this book complete. I am also thankful to Dr. D. K. Babu of Mobile Research who was kind enough to read Chapter 7 and provide many valuable suggestions.

There are numerous other individuals who have been very helpful in teaching me the various aspects of horizontal well technology. If I omitted any names, it is simply an oversight on my part.

CONTENTS

CHAPTER 4
Influence of Well Eccentricity

CHAPTER 5
Comparison of Horizontal and Fractured Vertical Wells

CHAPTER 6
Transient Well Testing

CHAPTER 7
Pseudo-Steady State Flow

CHAPTER 8
Water and Gas Coning in Vertical and Horizontal Wells

CHAPTER 9
Horizontal Wells in Gas Reservoirs

CHAPTER 1

Overview of Horizontal Well Technology

INTRODUCTION

In the last few years, many horizontal wells have been drilled around the world.[1–27] The major purpose of a horizontal well is to enhance reservoir contact and thereby enhance well productivity. As an injection well, a long horizontal well provides a large contact area, and therefore enhances well injectivity, which is highly desirable for enhanced oil recovery (EOR) applications.

In general, a horizontal well is drilled parallel to the reservoir bedding plane. Strictly speaking, a vertical well is a well which intersects the reservoir bedding plane at 90°. In other words, a vertical well is drilled perpendicular to the bedding plane (see Fig. 1–1). If the reservoir bedding plane is vertical, then a conventional vertical well will be drilled parallel to the bedding plane and in the theoretical sense it would be a *horizontal well*. As shown in Figure 1–2, even in the reservoirs with vertical bedding plane, it is still possible to

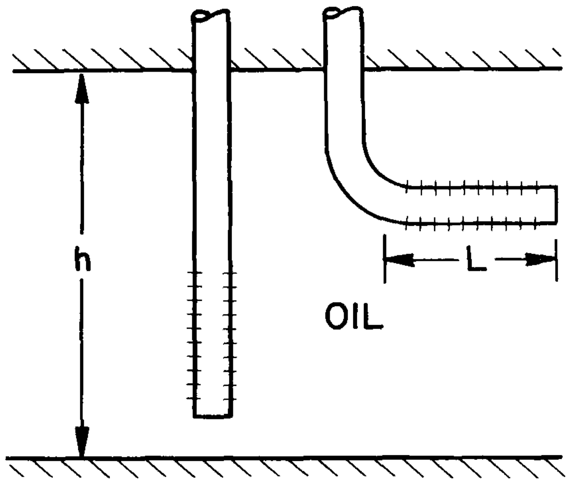


Figure 1–1 A Schematic of a Vertical Well Drilled Perpendicularly to the Bedding Plane, and a Horizontal Well Drilled Parallel to the Bedding Plane.

drill down vertically and then drill sideways. The objective here is to intersect multiple pay zones. (In some instances, from the drilling standpoint, it may be easier to stay in one zone to have effective control on well trajectory.) In the mid-continental region and in the Gulf Coast region of the United States, some reservoir bedding planes are almost vertical. Similarly, in California some reservoirs are steeply deepening. Thus, while analyzing hori-

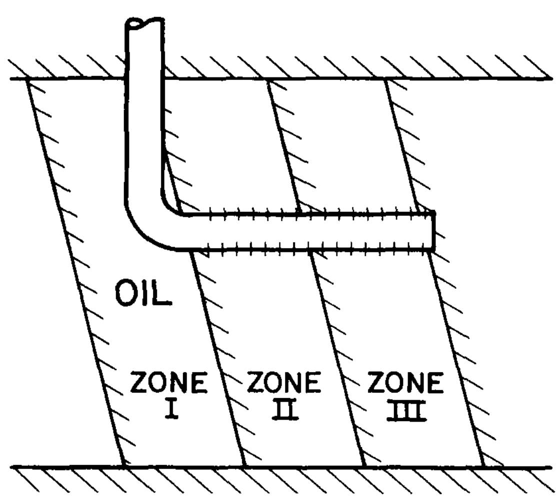


Figure 1–2 A Horizontal Well in a Reservoir With Vertical Bedding Planes.

zontal well performance, geometric configuration of the reservoir bedding planes should be considered.

A typical horizontal well project is different from a vertical well project because productivity of a well depends upon the well length. Moreover, the well length depends upon the drilling technique that is used to drill the well (See Table 1–1).[6] Therefore, it is essential that reservoir and drilling engineers work together to choose the appropriate drilling technique which will give the desired horizontal well length.

The other important consideration is well completion scheme: one can either have an open hole, insert a slotted liner, insert a liner with external casing packers, or case the hole and perforate the casing, depending upon local completion needs and experience. The type of completion affects horizontal well performance, and certain types of completions are possible only with certain types of drilling techniques. Thus, well length, the well's physical location in the reservoir, the tolerance in drilling location, and the type of completion that can be achieved strongly depend upon the drilling method. Therefore, it is very important for reservoir engineers to understand different drilling techniques, their advantages and disadvantages. Similarly, drilling engineers, completion engineers, production engineers, and geologists

TABLE 1–1 HORIZONTAL WELL LENGTHS[6]

TYPE	HOLE DIAMETER (in.)	RADIUS (ft)	RECORDED† (ft)	EXPECTED (ft)
Ultrashort*		1–2		100–200
Short**	4¾	30	425	250–350
(Rotory)	6	35	889	350–450
Short**	4¾	40	—	—
(Mud motors)	3¾	40	—	—
Medium	4½	300	1300	500–1000
	6	300	2200	1000–2000
	8½	400–800	3350	1000–3000
	9⅞	300	—	—
Long	8½	1000	4000	1000–3000
	12¼	1000–2500	1000	—

* several radials can be drilled from a single vertical well
** several drainholes at different elevations can be drilled from a single vertical well
† In early 1990, over 4500 ft long, medium radius horizontal wells were drilled.

should also understand and appreciate different factors that influence a horizontal well's performance. Hence, cooperation and teamwork of different professionals is essential to ensure the successful horizontal well project. A horizontal well project requires a multidisciplinary approach for an economic success.

LIMITATIONS OF HORIZONTAL WELLS

As noted earlier, the major advantage of a horizontal well is a large reservoir contact area. Currently, one can drill as long as 3000- to 4000-ft-long wells, providing significantly larger contact area than a vertical well. The major disadvantage is that only one pay zone can be drained per horizontal well. Recently, however, horizontal wells have been used to drain multiple layers. This can be accomplished by two methods: 1) one can drill a "staircase" type well where long horizontal portions are drilled in more than one layer, and 2) one can cement the well and stimulate it by using propped fractures. The vertical fractures perpendicular to the wells could intersect more than one pay zone and thereby drain multiple zones. It is important to note that in some cases due to strength of each pay zone and intermediate barriers, it may not be possible to interconnect the zones at different elevations by fracturing horizontal wells.

The other disadvantage of horizontal wells is their cost. Typically, it costs about 1.4 to 3 times more than a vertical well, depending upon drilling method and the completion technique employed. The incremental cost of drilling horizontal wells over vertical wells has reduced significantly over the last 10 years. Some of the early horizontal well projects listed in Tables 1–2 and 1–3 show that in the late seventies and the early eighties, horizontal well costs were six to eight times more than vertical well costs. By the mid-eighties and late eighties, typical drilling costs were two to three times more than vertical well costs.

An additional factor in cost determination is drilling experience in the given area. Typically, a first horizontal well costs much more than the second well. As more and more wells are drilled in the given area, an incremental drilling cost over a vertical well is reduced. Thus, there is a learning curve.

Field experience and published results of horizontal well costs in Cold Lake, Canada;[7] Prudhoe Bay, Alaska;[8] offshore Indonesia;[9] offshore The Netherlands;[10] Austin chalk formation in the United States;[11] and Bakken formation in North Dakota, U.S.A,[12] show a significant reduction in drilling costs over time and with experience. In these projects, a typical first horizontal well cost was two to four times more than a vertical well, but after drilling a few wells, a typical horizontal well cost is only about 1.4 times the vertical well cost. In some cases, with extensive drilling experiences, the horizontal well costs are reported to be almost the same or even lower than vertical well costs.[7] This tells us that for an economic success, the preferred option is to undertake a multiwell rather than a single well horizontal drilling program.

Costs for horizontal drilling and completions for 16 wells in Prudhoe Bay,[8] Alaska, are shown in Figures 1–3a and 1–3b. The figures show that drilling costs have decreased initially over time and have remained constant over the last two years. However, completion costs have remained constant over a four-year period. As shown in Figures 1–4a and 1–4b, similar cost

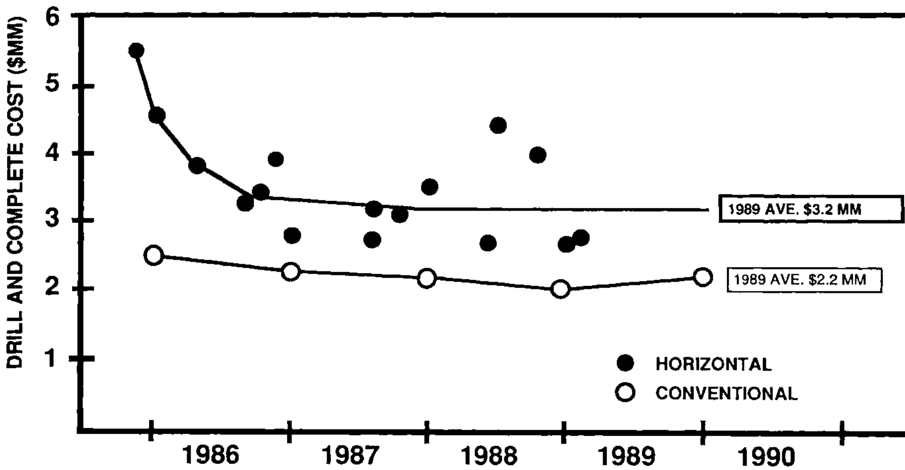


Figure 1–3a A Comparison of Horizontal and Vertical Well Costs for Prudhoe Bay, Alaska (CIM/SPE 90–124, Broman et al.).

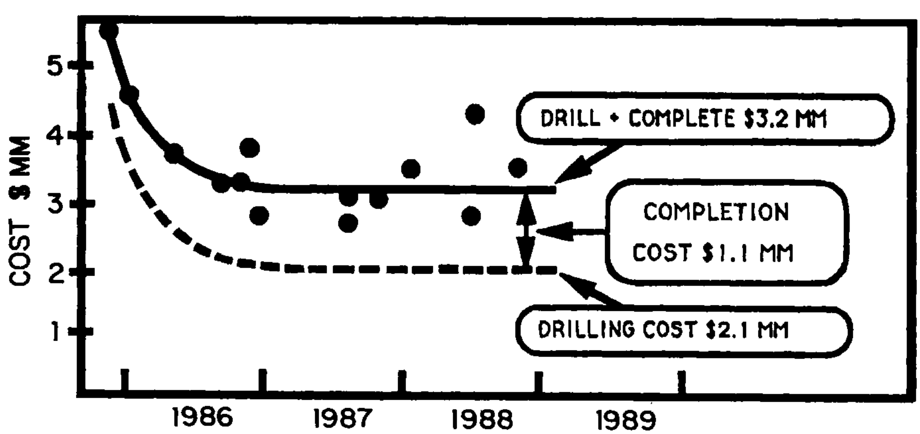


Figure 1–3b A Comparison of Drilling and Completion Costs of Horizontal Wells in Prudhoe Bay, Alaska (CIM/SPE 90-124, Broman et al.).