DEVELOPMENTS IN PETROLEUM SCIENCE 36

THE PRACTICE OF RESERVOIR ENGINEERING

(Revised Edition)

L.P. Dake

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to Grace

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FOREWORD TO THE REVISED EDITION

This revised edition presents a series of small text improvements throughout the book and a certain revision of the text of chapter 4 which was required to enable a better understanding of some physical explanations.

A more important change was carried out in subchapter 5.9 in relation to "the examination of water drive performance", where an excellent demonstration for a new procedure was developed for two real field cases. All elements of design, such as injection pressure, oil rate, and recovery prediction are explained in detail and illustrated with two field examples: one in the North Sea and another one in East Texas.

The philosophy introduced by Laurie Dake in chapter 5.9 concerns the key to understanding the reservoir fractional flow technique by the appreciation that the Buckley-Leverett theory is dimensionless and thus represents the simplest statement of the material balance for water drive.

In this book, containing the basic material and modifications prepared by the author Laurie Dake, any Petroleum Engineer will find the essential basis not only for understanding a gas or oil field, but also for predicting the future behaviour of a reservoir. It represents one of the most precious heritages of one of the most brilliant minds who dedicated his life to the advancement of Petroleum Science and Engineering.

Prof. Dr. T.D. van Golf Racht
Petroleum Department
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PREFACE

The *Practice of Reservoir Engineering* has been written for those in the oil industry requiring a working knowledge of how the complex subject of hydrocarbon reservoir engineering can be applied in the field in a practical manner. The book is a simple statement of how to do the job and is particularly suitable for the hard pressed reservoir/production engineers in its advice, illustrated with 27 examples and exercises based mainly on actual field developments. It should also be useful for those associated with this central subject of hydrocarbon recovery, from geoscientists and petrophysicists to those involved in the management of oil and gas fields.

Reservoir engineering is a complex subject for two reasons. In the first place, we never see enough of the reservoirs we are trying to describe. Therefore, it is difficult to define the physics of the system and, therefore, select the correct mathematics to describe the physics with any degree of certainty. The second problem is that even having selected a sensible mathematical model there are never enough equations to solve for the number of unknowns involved. The latter problem extends across the broad spectrum of the subject, from material balance application to well test interpretation and leads to an inevitable lack of uniqueness in describing reservoirs. Given these basic limitations, the only approach to the subject must be one of simplicity and such is the theme of the book. In fact, the basic tenet of science: Occam's Razor, applies to reservoir engineering to a greater extent than for most physical sciences — that if there are two ways to account for a physical phenomenon, it is the simpler that is the more useful.

Chapter 1, *Introduction to Reservoir Engineering*, is a description of the subject and of the main themes of the book. It was inspired on reading the excellent history of the industry *The Prize (The Quest for Oil, Money and Power)* written by Daniel Yergin and published by Simon and Schuster in 1991. Rather surprisingly, in the extensive index to this 880 page treatise the word "Reservoir" does not appear and, therefore, neither does "Reservoir Engineering", practitioners of which will appreciate is the most important subject in the whole industry. Chapter 1, therefore, attempts to redress the balance with a statement of the meaning of reservoir engineering. It includes a description of the main activities and the role of engineers, particularly in offshore developments, which is a topic that has received little attention in the literature. The history and future of reservoir engineering are considered and the chapter ends with a description of the basic physical principles involved in its application.

Chapter 2, *The Appraisal of Oil and Gas Fields*, focuses on the appraisal stage of field development, which is particularly relevant to offshore projects. Subjects covered include: PVT-fluid properties, with particular emphasis on sample collection and the correction of laboratory data to match field conditions, the estimation of hydrocarbons in place and the contentious issue of equity determination. The chapter concludes with a description of pressure–depth relations and, in particular, RFT-interpretation, the purpose and practice of appraisal well testing (DSTs) and the design of extended well tests (EWTs). The chapter is written in such a manner as to serve as a useful introduction to field appraisal for all disciplines involved in this activity.

Chapter 3, *Material Balance Applied to Oilfields*, is on the application of material balance to fields influenced by a variety of different drive mechanisms. In the author's opinion, the subject has become as dead as the Dodo in recent years, the general belief being that it has been superseded by the more sophisticated technique of numerical simulation modelling. Nothing could be further from the truth, however, since material balance is the fundamental physical statement of reservoir engineering, not only explaining the mechanics of reservoir behaviour but also being the basic principle of the mechanics of fluid displacement (Buckley-Leverett). The chapter points out that material balance and simulation should not be regarded as competitive modes of describing field performance but must instead be fully supportive. The former is the ideal tool for history matching field performance, the results of which are used to construct a simulation model for the purpose of prediction. Such has been the neglect of material balance, however, that younger engineers have neither experience nor confidence in its application. To overcome this, the chapter contains six fully worked examples of material balance application to real field developments.

Chapter 4, *Oilwell Testing*, is devoted to the examination of the purpose, practice and interpretation of well tests in both appraisal and development wells. Since the early 1980's, the subject has been dominated by the philosophy of attempting to solve the *inverse problem*: using mathematics to define the physical state of a system. With the exception of developments at the forefront of physical science, this is an unconventional approach in practical physical/engineering disciplines and amounts to little more than curve fitting, which suffers from a severe lack of uniqueness. The chapter attempts to persuade the engineer that the only rational approach to test interpretation is to first define the physical state of the system under test by comprehensive observation of all relevant reservoir/mechanical data and then reach for the appropriate mathematical model (if it exists) to analyse the test. This is a much more difficult approach but, bearing in mind the importance of the field development decisions based on well test interpretation, is one that is mandatory.

In examining the history of well testing, the author has had cause to revise some of the earlier, simplifying assumptions that have dominated the subject. The most pervasive is that of *transience* (infinite acting behaviour) which, on account of its mathematical simplicity, has long prevailed in the subject and is still enshrined in many modern texts and computer software for test interpretation. Removal of this assumption on fifteen occasions, from the conventional presentation of the subject, confronts the engineer with a completely different perspective on test interpretation; in some respects more restrictive, in others more liberating but always more realistic.

In spite of the burgeoning use of log–log pressure plotting since the early 1980's, by far the most popular means of pressure buildup interpretation remains the

Horner semi-log plot (1951). Yet the most widespread error in the whole subject lies in its interpretation: where should the straight line be drawn and what does it mean? To overcome this, the author has resurrected and extended application of the simpler form of buildup analysis technique of Miller, Dyes and Hutchinson (MDH-1950) and demonstrated that it is capable of matching anything that Horner analysis can do — and a little bit more, in a simpler and less error prone manner. Use of the technique suggests that perhaps we waste too much time and money indulging in lengthy pressure buildups, when a few hours of closure is all that is ever required. Examining Horner and MDH time derivative plots in conjunction is presented as a *guaranteed* method for defining the correct straight line on semi-log buildup plots.

Chapter 5, *Waterdrive*, describes the most widespread form of secondary recovery technique: engineered waterdrive. Some of the description relates to the development of North Sea fields, the majority of which operate under this condition. This is not chauvinistic because the argument is made that the North Sea has been the biggest laboratory ever for the study of waterdrive.

The chapter starts with a description of the practicalities of waterdrive with particular emphasis on matching the capacities of surface facilities for injection/production of liquids to the reservoir performance. Next, the basic theory of waterdrive (Buckley-Leverett) and its components are examined in detail. These consist of relative permeabilities and the concept of the fractional flow of water. It is argued that the former have little relevance in themselves and it is the fractional flow relationship that predominates in the subject. In fact, it is the main purpose in writing the chapter to try and re-assert the importance of fractional flow, which, like material balance, has practically disappeared from reservoir engineering in recent years simply because the concept has never (or only recently) been incorporated in the construction of numerical simulation models — and, therefore, it has ceased to exist. Data requirements and their interpretation and incorporation in the calculation of vertical sweep efficiency in heterogeneous reservoir sections are described, all using pseudo fractional flow functions in Welge calculations. The chapter finishes with an account of methods for history matching and predicting the performance of *difficult* waterdrive fields, which sometimes defy the use of numerical simulation due to their sheer complexity.

Chapter 6, *Gas Reservoir Engineering*, covers three aspects of gas reservoir engineering: material balance, immiscible gas drive and dry gas recycling in retrograde gas condensate reservoirs. Gas material balance is probably the simplest subject in reservoir engineering, yet the universal use of p/Z-plots in isolation leads to some alarming errors in overestimating the GIIP, the worst example noted by the author being an excess of 107%. Surely we can do better than that — and indeed we can. A more rational and sensitive approach to material balance application, to be used in conjunction with p/Z-plots, is suggested and its use illustrated.

The mobility ratio for immiscible gas–oil displacement is very unfavourable, making the process intrinsically unstable, unless the gravity term in the gas fractional flow is dominant. The section concentrates on the vetting of reservoirs for their suitability for gas drive and provides an example of gas drive efficiency calculations.

In considering dry gas recycling, much of the analysis in the literature is focused on compositional effects and what is overlooked is that the process is basically unstable. The section describes the influence of heterogeneity and gravity on the efficiency of recycling, which is illustrated with an example.

Acknowledgements. I should like to thank all those who have helped me during the course of writing this book. Foremost are all those engineers with whom I have worked or who have attended my lecture courses in reservoir engineering. I am particularly indebted to Scottish Enterprise (formerly the Scottish Development Agency) for their support and Enterprise Oil of London for their continual assistance. My thanks are also due to the staff of the Department of Energy, London (now the Department of Trade and Industry) and also to members of the staff of The Danish Energy Agency in Copenhagen. Particular thanks also to my colleague Professor Th. van Golf Racht of Paris for his advice.

Laurie Dake

IN MEMORIAM: LAURENCE P. DAKE

In the family of reservoir and petroleum engineers it was always so natural and rewarding to talk about "Laurie" (the name he preferred to his official one, Laurence Patrick Dake) about his point of view, and about his acceptance of, or opposition to, certain ideas or procedures. Today, sitting in front of a blank sheet of paper, I understand for the first time how difficult, how sad, and how impossible it is for any of his friends to talk about Laurie in *memoriam*. The only way to proceed is by remembering Laurie's life and his contribution to our petroleum engineering profession, and in evoking his exceptional creative spirit.

I remember the unforgettable conversations during the long winter nights of 1985 in my Norsk Hydro Oslo Office, when Laurie elaborated on the key objective of reservoir engineering: The capacity to turn the time-mirror around, so that a coherent image of the future prediction of an oil field can in return give us valuable insight into today's understanding of the same field, in order to ensure that every statement about the future behaviour of the reservoir is not accompanied by a long series of "ifs", "buts" and an avalanche of "maybes".

It was during this period that Laurie began using this approach to lay the foundations for the book "Practice of Reservoir Engineering".

Laurence Dake was born *11 March 1941* on the Isle of Man. He received his education at King Williams College and graduated in Natural Philosophy at the University of Glasgow in *1964*.

Recruited by Shell in *1964*, he joined Shell International as a Petroleum Engineer. Following a thorough training program at the Shell Training Center in The Hague, he participated as Petroleum Engineer in a variety of field operations in Australia, Brunei, Turkey and Australia until 1971, when he was once again called back to the Shell Training Center in The Hague. For seven years, from *1971 until 1978*, he taught the subject of Reservoir Engineering to Shell graduates.

In *1978* Laurie Dake left Shell after 14 years of service, at which time he made two significant steps which would determine his further professional career:

(1) He joined the newly established State Oil Company BNOC (British National Oil Cooperation) as Chief, Reservoir Engineering. In this function he participated in the discovery, development and deciphering of the secrets of the large North Sea reservoirs. His contribution during the early days of the UK offshore industry was so significant that in *1987* he received the OBE recognition for his Reservoir Engineering services to the UK industry. In these days this recognition not only honoured him for his exceptional work, but also indirectly honoured the reservoir engineering profession for its potential to influence the results of the oil and gas industry.

(2) In *1978* Laurie Dake published his first book with Elsevier on reservoir engineering under the title "*The Fundamentals of Reservoir Engineering*". In this work he introduced a modern vision on Reservoir Engineering based on the

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synthesis between rigorous physics and applied science, necessary in any field operative work. The exceptional success of this book with the entire petroleum world resulted from:

- its utility for Petroleum Engineers in applying simplified procedures to complex problems of hydrocarbon reservoirs;
- its utility as fundamental text for students at almost every University where the scientific basis of the reservoir discipline is combined with a large amount of field applications and examples.

In *1982* Laurie Dake left BNOC at the time of its privatisation and started as an independent consultant, based in Edinburgh. His comprehensive activities were divided among:

- a "direct consulting activity" with medium and large companies where Laurie made a substantial contribution to the appraisal and development of over 150 world wide oil and gas fields, *between 1982 and 1994*. He became one of the most appreciated international petroleum consultants, and was consulted by very large companies (BP, Agip, Norsk Hydro, Statoil, etc.) and banks (Bank of Scotland – Edinburgh, BankWest Perth, Australia, etc.);
- an important collaboration with the Petroleum Department of the Heriot—Watt University, where he started initially (*after 1978*) as an external examiner and where he later became a "Honorary Professor";
- the elaboration of his second book " The Practice of Reservoir Engineering", published by Elsevier in *1994*. In addition to many field operative concepts, the text included specific procedures and analyses developed by Laurie and proven successful in various fields studied by him.

In the middle of these exceptional activities, his real help to the entire petroleum engineering family through his books and courses, his consulting activities and his advice to the Financial World and Petroleum Companies, Laurie Dake's death on *July 19, 1999* left us disoriented. All of us who appreciated him, who admired his work and loved him for his exceptional qualities and distinction suddenly felt impoverished.

However, if we now look back to the horizon opened by Laurie, knowing that there exists an accepted horizon — visible but sterile, and another . . . an imaginative and creative one, we may change our point of view. Knowing that the creative horizon in a sense defines the boundaries between spirit and matter, between resources and platitude, we start to understand the role played by Laurie Dake — who disregarded the customary procedure and fought to grasp the real meaning of reservoir behaviour.

He has been able with his intelligence to enlarge the opened horizon by combining the will of creativity with the knowledge of reality versus the size of possibility . . . , all of which we find in the solutions proposed by him.

It is this enlarged horizon which Laurie left to all of us as a splendid heritage . . .

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