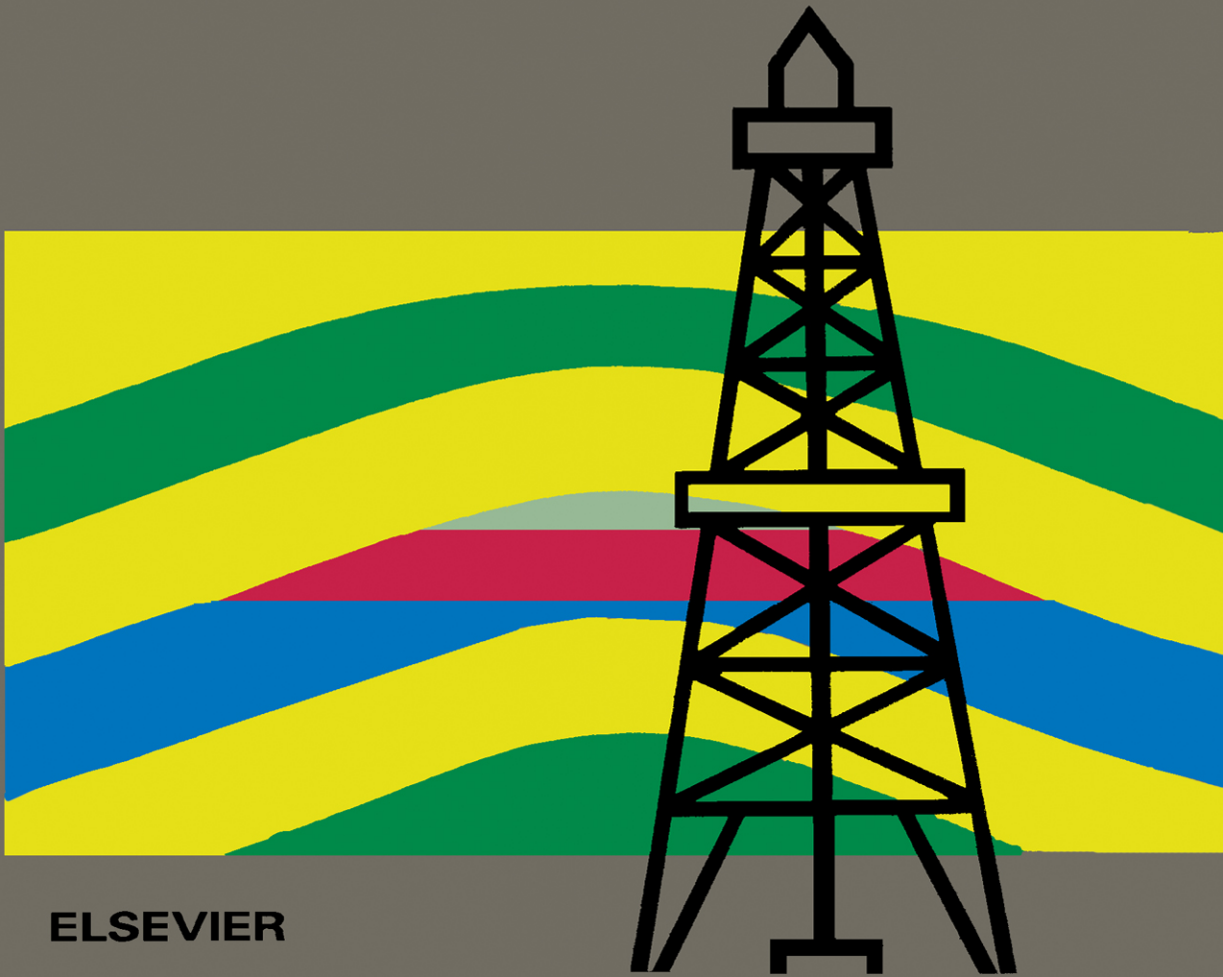


DEVELOPMENTS IN PETROLEUM SCIENCE 36

the practice of reservoir engineering

L.P. DAKE



ELSEVIER

Developments in Petroleum Science, 36

the practice of reservoir engineering

DEVELOPMENTS IN PETROLEUM SCIENCE

Volumes 1, 3, 4, 7 and 13 are out of print

2. W.H. FERTL – Abnormal Formation Pressures
5. T.F. YEN and G.V. CHILINGARIAN (Editors) – Oil Shale
6. D.W. PEACEMAN – Fundamentals of Numerical Reservoir Simulation
8. L.P. DAKE – Fundamentals of Reservoir Engineering
9. K. MAGARA – Compaction and Fluid Migration
10. M.T. SILVIA and E.A. ROBINSON – Deconvolution of Geophysical Time Series in the Exploration for Oil and Natural Gas
11. G.V. CHILINGARIAN and P. VORABUTR – Drilling and Drilling Fluids
12. T.D. VAN GOLF-RACHT – Fundamentals of Fractured Reservoir Engineering
14. G. MÓZES (Editor) – Paraffin Products
- 15A. O. SERRA – Fundamentals of Well-log Interpretation, I. The acquisition of logging data
- 15B. O. SERRA – Fundamentals of Well-log Interpretation, I. The interpretation of logging data
16. R.E. CHAPMAN – Petroleum Geology
- 17A. E.C. DONALDSON, G.V. CHILINGARIAN and T.F. YEN (Editors) – Enhanced Oil Recovery, I. Fundamentals and analyses
- 17B. E.C. DONALDSON, G.V. CHILINGARIAN and T.F. YEN (Editors) – Enhanced Oil Recovery, II. Processes and operations
- 18A. A.P. SZILAS – Production and Transport of Oil and Gas, A. Flow mechanics and production (second completely revised edition)
- 18B. A.P. SZILAS – Production and Transport of Oil and Gas, B. Gathering and Transport (second completely revised edition)
- 19A. G.V. CHILINGARIAN, J.O. ROBERTSON Jr. and S. KUMAR – Surface Operations in Petroleum Production, I
- 19B. G.V. CHILINGARIAN, J.O. ROBERTSON Jr. and S. KUMAR – Surface Operations in Petroleum Production, II
20. A.J. DIKKERS – Geology in Petroleum Production
21. F. RAMIREZ – Application of Optimal Control Theory to Enhanced Oil Recovery
22. E.C. DONALDSON, G.V. CHILINGARIAN and T.F. YEN – Microbial Enhanced Oil Recovery
23. J. HAGOORT – Fundamentals of Gas Reservoir Engineering
24. W. LITTMANN – Polymer Flooding
25. N.K. BAIBAKOV and A.R. GARUSHEV – Thermal Methods of Petroleum Production
26. D. MADER – Hydraulic Proppant Fracturing and Gravel Packing
27. G. DA PRAT – Well Test Analysis for Naturally Fractured Reservoirs
28. E.B. NELSON (Editor) – Well Cementing
29. R.W. ZIMMERMAN – Compressibility of Sandstones
30. G.V. CHILINGARIAN, S.J. MAZZULLO and H.H. RIEKE – Carbonate Reservoir Characterization: A Geologic-Engineering Analysis, Part I
31. E.C. DONALDSON (Editor) – Microbial Enhancement of Oil Recovery - Recent Advances
32. E. BOBOK – Fluid Mechanics for Petroleum Engineers
33. E. FJÆR, R.M. HOLT, P. HORSRUD, A.M. RAAEN and R. RISNES – Petroleum Related Rock Mechanics
34. M.J. ECONOMIDES – A Practical Companion to Reservoir Stimulation
35. J.M. VERWEIJ – Hydrocarbon Migration Systems Analysis
36. L. DAKE – The Practice of Reservoir Engineering
37. W.H. SOMERTON – Thermal Properties and Temperature related Behavior of Rock/fluid Systems
38. W.H. FERTL, R.E. CHAPMAN and R.F. HOTZ (Editors) – Studies in Abnormal Pressures
39. E. PREMUSIC and A. WOODHEAD (Editors) – Microbial Enhancement of Oil Recovery – Recent Advances – Proceedings of the 1992 International Conference on Microbial Enhanced Oil Recovery

Developments in Petroleum Science, 36

the practice of reservoir engineering

L.P. DAKE

Edinburgh, Scotland



1994

ELSEVIER

Amsterdam — Lausanne — New York — Oxford — Shannon — Tokyo

ELSEVIER SCIENCE B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

First edition 1994
Second impression 1997

ISBN: 0-444-88538-2 (Hardbound)
ISBN: 0-444-82094-9 (Paperback)

© 1994 Elsevier Science B.V. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Science B.V., Copyright & Permissions Department, P.O. Box 521, 1000 AM Amsterdam, The Netherlands.

Special regulations for readers in the USA - This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the USA. All other copyright questions, including photocopying outside of the USA, should be referred to the publisher.

No responsibility is assumed by the publisher 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.

This book is printed on acid-free paper.

Printed in The Netherlands

to Grace

This page intentionally left blank

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 collec-

tion 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

ABOUT THE AUTHOR

Laurie Dake graduated in 1964 having read Natural Philosophy at the University of Glasgow, after which he joined Shell International with whom he was associated for 14 years practising petroleum/reservoir engineering in the Netherlands, Australia, Brunei, Turkey and Venezuela. He was chief reservoir engineer of the British National Oil Corporation in Glasgow until its privatisation in 1982. Since then he has been an independent consultant based in Edinburgh, Scotland. He has worked on the appraisal/development of over 100 oil and gas fields worldwide from which he draws on practical experience in the writing of this book. Author of *Fundamentals of Reservoir Engineering* (Elsevier, 1978) he has also had 20 years experience of lecturing in reservoir engineering both at universities and in 25 different countries. He is an honorary professor of petroleum engineering at Heriot Watt University, Edinburgh and in 1987 was awarded the OBE for services to reservoir engineering. Laurie Dake remains at the sharp end of the industry through his consultancy business and is currently technical adviser to the Bank of Scotland in Edinburgh.

This page intentionally left blank

CONTENTS

Preface	vii
About the Author	xi
Nomenclature	xix
<i>Chapter 1. INTRODUCTION TO RESERVOIR ENGINEERING</i>	1
1.1. Activities in reservoir engineering	1
(a) Observations	1
(b) Assumptions	2
(c) Calculations	3
(d) Development decisions	4
1.2. Basic themes of the text	4
(a) Simplicity	4
(b) What works and what does not — and why?	5
(c) Analytical methods	6
(d) Offshore versus onshore developments	7
1.3. The role of reservoir engineers	11
1.4. Technical responsibilities of reservoir engineers	17
(a) Appraisal	18
(b) End of appraisal	19
(c) Development	19
1.5. The physical principles of reservoir engineering	26
References	28
<i>Chapter 2. THE APPRAISAL OF OIL AND GAS FIELDS</i>	29
2.1. Introduction	29
2.2. Pressure–volume–temperature fluid properties for oil	29
(a) Basic PVT parameters	29
(b) Sampling reservoir fluids	33
(c) Laboratory experiments	37
(d) Comparison of laboratory and field PVT data	40
(e) PVT for volatile oil systems	43
2.3. Calculation of the stock tank oil initially in place	44
2.4. Field unitization/equity determination	45
(a) Oil initially in place (OIIP)	46
(b) Stock tank oil initially in place (STOIIP)	47
(c) Recoverable reserves	48
(d) Movable oil	49
2.5. Calculation of gas initially in place (GIIP)	50
2.6. Pressure–depth plotting	51
Exercise 2.1: Gas field appraisal	53
2.7. Application of the repeat formation tester	58
2.8. Pulse testing using the repeat formation tester	63
2.9. Appraisal well testing	66
2.10. Extended well testing	70
References	72

<i>Chapter 3. MATERIAL BALANCE APPLIED TO OILFIELDS</i>	73
3.1. Introduction	73
3.2. Derivation of the cumulative material balance for oil reservoirs	74
(a) Left-hand side (underground withdrawal — rb)	75
(b) Right-hand side (expansion plus water influx)	75
3.3. Necessary conditions for application of material balance	78
3.4. Solving the material balance (knowns and unknowns)	81
3.5. Comparison between material balance and numerical simulation modelling	82
3.6. The opening move in applying material balance	85
3.7. Volumetric depletion fields	86
(a) Depletion above the bubble point	86
Exercise 3.1: Material balance applied to an undersaturated volatile oilfield	87
Exercise 3.2: Identification of the drive mechanism and calculation of the STOIP for a depletion type reservoir	92
(b) Depletion below the bubble point (solution gas drive)	98
Exercise 3.3: Application of the Muskat material balance in history matching and prediction of solution gas drive	106
3.8. Water influx calculations	110
(a) Carter-Tracy water influx calculations	110
(b) Aquifer “fitting” using the method of Havlena-Odeh	111
Exercise 3.4: History matching using the Carter-Tracy aquifer model and the “fitting” technique of Havlena and Odeh	112
(c) History matching with numerical simulation models	116
3.9. Gascap drive	117
Exercise 3.5: Application of material balance to the early production performance of a gascap drive field	119
3.10. Compaction drive	124
Exercise 3.6: Compaction drive	128
3.11. Conclusion	133
References	134
 <i>Chapter 4. OILWELL TESTING</i>	 137
4.1. Introduction	137
4.2. Essential observations in well testing	138
(a) Rate, pressure, time	138
(b) Core/log data	139
(c) RFT, pressure–depth profiles	141
(d) Geological model	142
(e) Drive mechanism	142
(f) PVT fluid properties	143
(g) Well completion	143
(h) Equipment	143
(i) Tests in neighbouring wells	144
4.3. Well testing literature	145
4.4. The purpose of well testing	147
(a) Appraisal well testing	147
(b) Development well testing	152
4.5. Basic, radial flow equation	154
(a) Radial diffusivity equation	154
(b) Investigation of the validity of linearizing the basic radial flow equation by the method of deletion of terms	156
4.6. Constant terminal rate solution of the radial diffusivity equation	159
(a) Bounded reservoir conditions	161
(b) Steady-state condition	165

4.7. The transient constant terminal rate solution of the radial diffusivity equation	168
4.8. Difficulties in application of the constant terminal rate solution of the radial diffusivity equation	176
4.9. Superposition of CTR solutions	177
4.10. Single-rate drawdown test	180
(a) Inspection of the flowing pressure	181
(b) Time derivative of drawdown pressures	182
4.11. Pressure buildup testing (general description)	183
4.12. Miller, Dyes, Hutchinson (MDH) pressure buildup analysis	185
4.13. Horner pressure buildup analysis	190
4.14. Some practical aspects of appraisal well testing	195
(a) Determination of the initial pressure	196
(b) Afterflow	196
Exercise 4.1: Pressure buildup test: infinite acting reservoir	199
4.15. Practical difficulties associated with Horner analysis	205
(a) Flowing time/superposition	206
(b) The meaning of p^*	210
4.16. The influence of fault geometries on pressure buildups in appraisal well testing	213
(a) General description	213
(b) Single fault	213
Exercise 4.2: Pressure buildup test: single fault analysis	217
(c) Some general considerations in defining fault positions	223
(d) Definition of more complex fault geometries	228
4.17. Application of the exponential integral	230
(a) Example: interference between oilfields	231
4.18. Pressure support during appraisal well testing	235
(a) Pressure buildup performance	236
(b) Dimensionless pressure-radius of investigation	238
(c) Miller, Dyes, Hutchinson interpretation	240
(d) Horner interpretation	242
(e) Variable skin factor (well clean-up)	245
Exercise 4.3: Pressure buildup test: steady-state flow condition	246
4.19. Well testing in developed fields	253
(a) Pressure buildup analysis method of Horner-MBH for bounded reservoir systems	254
(b) Pressure buildup analysis method of MDH-Dietz for bounded reservoir systems	257
(c) Buildup analysis for systems with constant pressure or mixed boundary conditions	260
(d) Example well test	264
(e) Practical difficulties in testing development wells	271
(f) Relationship between wellbore and numerical simulation grid block pressures	273
(g) Afterflow	275
(h) Extended well testing	275
(i) Radius of investigation	277
4.20. Multi-rate flow testing	279
(a) Two-rate flow testing	280
(b) Example well test	284
(c) Selective inflow performance (SIP) testing	288
4.21. Log-log type curves	290
(a) Conventional type-curve interpretation	290
(b) Time derivative type curves	294
(c) Practical aspects	296
4.22. Conclusions	299
(a) The elusive straight line	299
(b) Saving money in well testing	300
(c) Identification of the correct early straight line	304
References	307

<i>Chapter 5. WATERDRIVE</i>	311
5.1. Introduction	311
5.2. Planning a waterflood	312
(a) Purpose	312
(b) Permeability	315
(c) Oil viscosity	316
(d) Oil volatility	317
(e) Overpressures	320
(f) Reservoir depth	323
5.3. Engineering design of waterdrive projects	324
(a) Production plateau rate	324
(b) Number of production/injection wells	326
(c) Surface production/injection facilities	327
Exercise 5.1: Toppersides facilities design for an offshore waterdrive field	330
5.4. The basic theory of waterdrive in one dimension	336
(a) Rock relative permeabilities	337
(b) Mobility ratio	339
(c) Fractional flow	341
(d) The Buckley-Leverett displacement theory	345
(e) Welge displacement efficiency calculations	348
(f) Input of rock relative permeabilities to numerical simulation and analytical reservoir models	355
(g) Laboratory experiments	362
5.5. The description of waterdrive in heterogeneous reservoir sections	366
(a) Reservoir heterogeneity	366
(b) Recipe for evaluating vertical sweep efficiency in heterogeneous reservoirs	369
5.6. Waterdrive under segregated flow conditions (vertical equilibrium)	373
(a) Basic description	373
(b) Data requirements and interpretation for input to the generation of pseudo-relative permeabilities	375
(c) Catering for the presence of edge water in VE flooding	384
(d) VE displacement in a homogeneous acting reservoir	386
Exercise 5.2: Water–oil displacement under the vertical equilibrium condition	388
Exercise 5.3: The influence of distinctive permeability distributions on the vertical sweep efficiency for the VE-flooding condition	398
5.7. Waterdrive in sections across which there is a total lack of pressure equilibrium	405
(a) Reservoir environment	405
(b) Data requirements and interpretation for input in the generation of pseudo-relative permeabilities	409
(c) Stiles method	411
(d) Dykstra-Parsons method	413
(e) Well workovers	416
Exercise 5.4: History matching and prediction of a waterdrive field performance using the method of Stiles	416
Exercise 5.5: Dykstra-Parsons displacement calculations	423
5.8. The numerical simulation of waterdrive	427
(a) Purpose	427
(b) Generation of pseudo-relative permeabilities using cross-sectional simulation modelling	429
(c) Areal numerical simulation modelling	435
5.9. The examination of waterdrive performance	436
(a) Fractured reservoir simulation	438
(b) Examining field performance	441
5.10. Difficult waterdrive fields	445
(a) Field A	445

(b) Field B	450
(c) The overall management of waterdrive fields	456
References	458
Chapter 6. GAS RESERVOIR ENGINEERING	461
6.1. Introduction	461
6.2. PVT requirements for gas-condensate systems	461
(a) Equation of state	463
(b) Surface/reservoir volume relationships	464
(c) Constant volume depletion (CVD) experiments	465
(d) Gas compressibility and viscosity	467
(e) Semi-empirical equations of state (EOS)	467
6.3. Gas field volumetric material balance	469
(a) Appropriateness in application	469
(b) Havlena-Odeh interpretation	471
(c) p/Z -interpretation technique	473
(d) Example field	477
(e) Gas field development	488
6.4. The dynamics of the immiscible gas–oil displacement	494
(a) Mobility ratio	495
(b) Heterogeneity/gravity	496
(c) Displacement condition	501
Exercise 6.1: Immiscible gas drive in a heterogeneous reservoir under the VE condition	505
6.5. Dry gas recycling in retrograde gas-condensate reservoirs	511
(a) Mobility ratio	512
(b) Heterogeneity/gravity	514
(c) Vertical sweep efficiency	517
Exercise 6.2: Generation of pseudo-relative permeabilities for dry gas recycling	518
References	523
Subject Index	525

This page intentionally left blank

NOMENCLATURE

A	area (sq.ft)
B_g	gas formation volume factor: gas (rcf/scf) : oil (rb/scf)
B_o	oil formation volume factor (rb/stb)
B_w	water formation volume factor (rb/stb)
c	isothermal compressibility (1/psi)
c_f	pore compressibility (1/psi)
c_o	oil compressibility (1/psi)
c_w	water compressibility (1/psi)
C_A	Dietz shape factor (dimensionless)
C'_A	Larsen shape factor (dimensionless)
D	vertical depth (ft.ss)
e	exponential
ei	exponential integral function
E	gas expansion factor (scf/rcf)
$E_{f,w}$	term in the material balance equation accounting for connate water expansion and pore compaction (rb/stb)
E_g	term in the material balance equation accounting for the expansion of the gas cap (rb/stb)
E_o	term in the material balance equation accounting for the expansion of the oil and its originally dissolved gas (rb/stb)
f_g	fractional flow of gas (dimensionless)
f_w	fractional flow of water (dimensionless)
F	underground withdrawal of fluids (rb)
G	gas initially in place (scf)
G	gravity number in the fractional flow equation (dimensionless)
G_p	cumulative gas production (scf)
h	formation thickness (ft)
k	permeability (mD)
k_r	relative permeability (dimensionless)
k'_r	end point relative permeability (dimensionless)
\bar{k}_r	pseudo relative permeability (dimensionless)
l	length (ft)
L	length (ft)
m	ratio of the initial hydrocarbon pore volume of the gascap to that of the oil column (material balance) (dimensionless)
m	slope of the early linear section of semi-log plots for well test interpretation psi/log cycle

$m(p)$	pseudo pressure (psi ² /cp)
M	end point mobility ratio (dimensionless)
n	number of lb moles
N	stock tank oil initially in place (stb)
N_p	cumulative oil recovery (stb)
N_{pd}	dimensionless cumulative oil recovery (PV)
N_{pD}	dimensionless cumulative oil recovery (HCPV)
p	pressure (psia)
p_b	bubble point pressure (psia)
p_D	dimensionless pressure
p_e	pressure at the external boundary (psia)
p_i	initial pressure (psia)
p_{sc}	pressure at standard conditions (psia)
p_{wf}	wellbore flowing pressure (psia)
p_{ws}	wellbore static pressure (psia)
p_{wsl}	static pressure on the early linear trend of a semi-log buildup or two rate drawdown plot (psia)
\bar{p}	average pressure (psia)
p^*	specific value of p_{wsl} at infinite closed-in time (Horner plot) (psia). (See also Z^* .)
q	liquid production rate (stb/d)
q_{wi}	water injection rate (b/d)
Q	gas production rate (MMscf/d)
r	radial distance (ft)
r_e	external boundary radius (ft)
r_{eD}	aquifer/reservoir radius ratio (dimensionless)
r_o	reservoir radius (ft)
r_w	wellbore radius (ft)
R	producing (instantaneous) gas oil ratio (scf/stb)
R	universal gas constant
R_p	cumulative gas oil ratio (scf/stb)
R_s	solution or dissolved gas oil ratio (scf/stb)
S	skin factor (dimensionless)
S_g	gas saturation (PV)
S_{gr}	residual gas saturation (PV)
S_o	oil saturation (PV)
S_{or}	residual oil saturation (PV)
S_w	water saturation (PV)
S_{wbt}	breakthrough water saturation (PV)
S_{wc}	connate water saturation (PV)
S_{wf}	shock front water saturation (PV)
\bar{S}_g	thickness averaged gas saturation (PV)
\bar{S}_{gd}	thickness averaged dry gas saturation (PV)
\bar{S}_w	average water saturation (PV)

t	time hours to years, as appropriate
t_D	dimensionless time
t_{DA}	dimensionless time ($t_D r_w^2 / A$)
Δt	closed-in time (pressure buildup) (hours)
Δt_s	closed-in time during a buildup at which p_{wsi} extrapolates to p_i or \bar{p} on an MDH plot
T	absolute temperature (degrees Rankin)
U	aquifer constant (bbl/psi)
v	velocity (ft/d)
V	volume (cu.ft)
W	width (ft)
W_D	dimensionless cumulative water influx
W_e	cumulative water influx (bbl)
W_i	cumulative water injected (bbl)
W_{id}	dimensionless cumulative water injected (PV)
W_{iD}	dimensionless cumulative water injected (HCPV)
W_p	cumulative water produced (bbl)
Z	Z-factor (dimensionless)
Z^*	alternative symbol to replace p^* in Horner buildup analysis (psia)

GREEK

α	volumetric sweep (dimensionless)
γ	specific gravity (liquids: relative to water = 1, gas: relative to air = 1, at standard conditions)
γ	exponent of Euler's constant (1.781)
Δ	difference
θ	dip angle (degrees)
μ	viscosity (cp)
ρ	density (lb/cu.ft)
σ	coefficient in well testing equations = $7.08 \times 10^{-3} kh/q\mu B_o$

SUBSCRIPTS

b	bubble point
bt	breakthrough
d	differential (PVT analysis)
d	dimensionless (PV)
d	displacing phase
D	dimensionless (pressure, radius, time)
D	dimensionless (HCPV)
DA	dimensionless (time)
e	production end of a system
f	flash separation

f	flood front
g	gas
i	cumulative injection
i	initial
o	oil
p	cumulative production
r	relative
r	residual
s	solution gas
sc	standard conditions
t	total
w	water
wf	wellbore, flowing
ws	wellbore, static

ABBREVIATIONS

CTP	constant terminal pressure
CTR	constant terminal rate
CVD	constant volume depletion
DST	drill stem test
EOR	enhanced oil recovery
EOS	equation of state
EWT	extended well test
FIT	formation interval tester
FVF	formation volume factor
GDT	gas down to
GOC	gas oil contact
GOR	gas oil ratio
HCPV	hydrocarbon pore volume
IARF	infinite acting radial flow
JOA	joint operating agreement
KB	kelly bushing
MDT	modular formation dynamic tester
MGV	movable gas volume
MOV	movable oil volume
OWC	oil water contact
PV	pore volume
PVT	pressure, volume, temperature
RF	recovery factor
RFT	repeat formation tester
SCAL	special core analysis
SIP	sequential inflow performance
WUT	water up to

Chapter 1

INTRODUCTION TO RESERVOIR ENGINEERING

1.1. ACTIVITIES IN RESERVOIR ENGINEERING

Reservoir engineering shares the distinction with geology in being one of the great “underground sciences” of the oil industry, attempting to describe what occurs in the wide open spaces of the reservoir between the sparse points of observation — the wells. In applying the subject, it is possible to define four major activities, which are:

- Observations
- *Assumptions*
- Calculations
- Development decisions

and these can be described as follows.

(a) *Observations*

These include the geological model, the drilling of wells and the data acquired in each: cores, logs, tests, fluid samples. Following the start of field production, the oil, gas and water rates must be continuously and accurately monitored together with any injection of water and gas. Frequent pressure and production logging surveys should also be conducted throughout the lifetime of the project. The importance of data collection is a subject that is frequently referred to throughout the book and is perhaps best illustrated in Chapter 3 when describing material balance which is so fundamental to reservoir engineering. It is pointed out that the material balance equation can easily contain eight “unknowns” and failure to collect the essential rate, pressure and pressure–volume–temperature (PVT) data to give oneself a “sporting chance” of attaining a meaningful solution of the equation can make the application of quantitative engineering impossible. The author has seen many fields in which the data collection was so inadequate that it would have been dangerous to attempt to apply any quantitative reservoir engineering technique and the alternative: guesswork, although occasionally unavoidable, is something to be shunned as much as possible. Thorough data acquisition is expensive (very expensive) and it is the duty of practising reservoir engineers to convince those who hold the purse strings of the necessity of the exercise. To do this, it is important that the engineer knows exactly to what use the data will be put and in this respect it is hoped this book will prove helpful in advising on the matter.

Once the data have been collected and verified, the engineer must interpret them very carefully and collate them from well-to-well throughout the reservoir and adjoining aquifer. This is a most delicate phase of the whole business of understanding reservoirs, in which it can prove dangerous to rely too much on automated techniques. It is fine to use computer programs to interpret well tests, for instance, but to apply sophisticated numerical methods to generalise about formation properties by such means as generating statistical correlations and use of regression analysis should be reduced to a minimum. Reservoir performance is so often dominated by some particular physical feature (the bit in the corner), which may be a weakness or strength, that can be completely overlooked through the smudging effect inherent in the application of number crunching methods. In this respect, three examples of the dangers of “statistical smearing”, which adversely affect the calculation of sweep efficiency in waterdrive or gas-drive projects, as described in Chapters 5 and 6, respectively are.

- The evaluation of formation heterogeneity using probability distributions of permeability. This totally neglects gravity and therefore disregards Newton’s second law of motion.

- Application of convoluted petrophysical transforms to generate permeability distributions across formations. Considering the expensive errors this leads to, it is much cheaper to core “everything”.

- Plotting core permeabilities on a logarithmic scale when viewing their distribution across a reservoir section. Darcy’s flow law specifically states that the velocity of advance of a fluid is proportional to the permeability of a layer: not the logarithm of its permeability.

These are not small, fastidious points. Together they have cost international operators billions of dollars in lost and deferred production in secondary recovery projects worldwide. Most of the difficulties mentioned would be overcome by adherence to the basic laws of physics in the interpretation and collation of reservoir data.

The most valuable reservoir engineers are those who *see* the clearest and the most and who know what they are looking for.

The last comment implies the need for experience, which may be a bit discouraging to newcomers to the subject but there has and always will be a very large element of *deja vu* associated with reservoir engineering.

(b) Assumptions

Now the main difficulty arises: having thoroughly examined and collated all the available data, the engineer is usually obliged to make a set of assumptions concerning the physical state of the “system” for which an appropriate mathematical description must be sought. For instance:

- The oil or gas reservoir is or is not affected by natural water influx from an adjoining aquifer.

- There will or will not be complete pressure equilibrium across the reservoir section under depletion or waterdrive conditions.

– The late-time upward curvature of points in a pressure buildup survey results from: the presence of faults, dual porosity behaviour or the breakout of free gas around the wellbore.

This is the crucial step in practical engineering, so much so that the word *assumptions* is highlighted (page 1) to signify that once they have been made that is effectively the end of the reservoir engineering. The third activity, calculations, is entirely dependent on the nature of the assumptions made as is the fourth, development decisions, which rely on the results of the calculations. It is therefore necessary to be extremely cautious when making physical assumptions and the most convincing reservoir studies are those containing the least number. In this respect, the application of material balance is strongly recommended (oil, Chapter 3; gas, Chapter 6), in history matching field performance, as being one of the safest techniques in the business for the simple reason that it requires fewer (far fewer) assumptions than the alternative technique, numerical simulation modelling, which should therefore be used as a logical follow-up (Chapter 3, section 3.5). Assumptions can usually be confirmed only by observation, not calculation, but this can be problematical. In the first two examples listed above, for instance, the observations necessary to confirm the influence of an aquifer or the degree of pressure equilibrium across a reservoir can only be made some time after the start of continuous field production, which causes difficulties in offshore developments, as described in section 1.2d. Finally, considering the importance attached to assumptions, it is mandatory that they be listed and rationalized right at the start of any study report — if for no other reason than to permit the reader the choice of whether to explore the text further or not.

(c) Calculations

While the above comments may seem to denigrate the importance of calculations, that is only meant to be relative to the physical assumptions upon which any mathematical model selected for use is entirely dependent. Once a physical condition has been defined (assumed) then calculations are an absolute must and it should be remembered at all times that we reservoir engineers receive our salaries to perform calculations rather than merely express opinions.

Since the 1960's mathematics has been awarded a much more exalted status in the business than ever before for the simple reason that now, with our sophisticated computers, we can do it, whereas previously we could not, or only with great difficulty. With each passing year and each improved mathematical model, there is a great danger that numerical modelling is becoming a subject in its own right in which there is a tendency for it to evolve in a direction that removes it ever further from the requirements of reservoir engineering. Hence the fairly new title in the Industry of "Simulation Engineers". There should be no such thing, only reservoir engineers who happen to have simulation packages at their disposal for use, amongst other tools, as and when required.

Engineers, and particularly those entering the subject, should be aware of this pitfall and not become too mesmerised by mathematical models — no matter how

user-friendly. It is not entirely unusual, for instance, to find a group of engineers slaving away in the back room for months with their computers only to emerge with the pronouncement that — “the model is great but there seems to be something wrong with the reservoir.” The majority of a reservoir engineer’s time should be spent looking at things very carefully and only then deciding on the correct approach to the problem rather than bombarding it with different mathematical models in the hope that one of them might fit. The approach to avoid is that noted recently by the author in which up to 600 computer runs were budgeted for in a study to history match the performance of a field. This sort of planning makes you wonder whether it was a reservoir engineering study or a lottery.

The requirement of the engineer is to assess in advance, through sound physical judgement, which of the runs is liable to be correct — and why. If mathematics is used carefully and correctly then we should have a great advantage over our predecessors in this subject but if it is abused by relying on mathematics to define physics, then reservoir engineering is itself in danger.

(d) Development decisions

Every action contemplated, planned and executed by reservoir engineers must lead to some form of development decision — otherwise it should not be undertaken in the first place.

1.2. BASIC THEMES OF THE TEXT

(a) Simplicity

Even if we could see in complete detail all the complications of the reservoir geology and its fluid contents, trying to describe it mathematically would be a daunting task. But since we hardly see anything of the systems we are attempting to describe and even when we formulate equations they contain far too many unknowns to provide a unique solution, then the situation begins to look grim. Under these circumstances, this book advocates that all problems be approached in a simple fashion, in fact, there seems to be an inverse law applicable to reservoir engineering that the more complex the system, the more appropriate is the attempt at simplicity and the more convincing. It is virtually impossible, for instance, to construct a reliable simulation model for waterdrive in a complex delta top reservoir, with criss-crossing channels that do not seem to correlate from well to well, for the simple reason that you cannot model what you cannot see — although it does not prevent people from trying.

The alternative approach (as illustrated in Chapter 5, section 5.9) is to apply the simple concept of material balance to match waterdrive history and make a reasonable attempt at prediction. This will provide an understanding of the physics of the system which enables sound operating judgements to be made, even though it may not yield exactly correct results which, by the very nature of the subject,

are usually unattainable. It is, therefore, frequently stressed in the text to adopt the simplest physical method possible in tackling all forms of reservoir engineering problems, although this must not be overdone. Albert Einstein appears to have summed up the situation in a concise manner:

“Let us do everything as simply as possible, but then, not more simply than that.”

(b) What works and what does not — and why?

Some time ago the author was confronted by a university geologist who declared that of all the subjects he had ever encountered, reservoir engineering was the one that stood in greatest need of an “Academic Audit”. In other words, it’s about time that somebody stood up and made a clear pronouncement about what works and what does not amongst the myriad of theoretical papers and books on the subject. Unfortunately, this is easier said than done because there is nobody in the business who knows, since we can never get down there in the reservoir and examine the *in situ* consequences of our elegant theories.

This author is certainly not in a position to attempt an academic audit but, nevertheless, it is possible to consider a damage-limitation exercise, merely by doing a “trace-back” through the history of the subject. Although the physics and mathematics applied date from earlier centuries and are, therefore, well founded, their application to reservoir engineering is comparatively new. It is only since the early 1930’s, with the introduction of such basic concepts as material balance (Chapter 3) and the Buckley-Leverett theory of immiscible displacement (waterdrive, Chapter 5; gas drive, Chapter 6) that field engineers were first provided with sound quantitative methods for describing reservoir performance. Therefore, it would be unwise to believe that this young subject is well established, in its present form, such that we can build upon it with confidence — far from it. One of the earlier difficulties was that our predecessors, armed only with log-tables and slide-rules, were trying to tackle the same mathematical problems that today we feed into our mega computers. Understandably, they were forced into making simplifying assumptions and tended to sweep inconvenient pieces under the carpet, where many of them remain to this day. In researching and writing this book, the author has delved into the history of the subject to determine the effect of removing these unnecessary assumptions and dragging out and inspecting some of the hidden detritus.

The effect is perhaps most noticeable in the subject of well testing (Chapter 4) in which the removal of the persistent and all pervasive assumption of transience (that every reservoir exhibits infinite acting behaviour on test) seems to work wonders in clarifying and simplifying the subject and even suggests the abandonment of some of our traditional testing practices, such as the indulgence in lengthy pressure buildups. Similarly, in Chapter 5, on waterdrive, the meaning and use of relative permeability functions (which have been a part of the folklore of the subject for the past 50 years: ever since they first knocked Buckley-Leverett off balance) is seriously questioned. It appears that, except in the most extreme case (the failure event),