DEVELOPMENTS SERIES

Developments in Petroleum Engineering—1

Edited by

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and

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ELSEVIER APPLIED SCIENCE PUBLISHERS

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THE DEVELOPMENTS SERIES

Developments in many fields of science and technology occur at such a pace that frequently there is a long delay before information about them becomes available and usually it is inconveniently scattered among several journals.

Developments Series books overcome these disadvantages by bringing together within one cover papers dealing with the latest trends and developments in a specific field of study and publishing them rapidly.

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PREFACE

Over the last decade or so the advances in petroleum engineering have been described in an ever-increasing deluge of papers prepared for local, national and international meetings. Publication is often erratic, with papers initially being only available to those who attend a particular conference and proving difficult to find at a later date. As a result, it is often difficult to know where to start to get a sensible, and up-to-date, review of a particular subject. This new series of volumes—*Developments in Petroleum Engineering*—is intended to fill this gap and will contain reviews of recent developments. The chapters are written by specialists at a level which summarises the progress, but does not necessarily cover every facet and detail, of a particular subject. Rather, they direct the reader to the most useful of the original sources.

Any assessment of the progress of the exploration and petroleum production divisions in the industry must take into account various factors. The first is that over 60 per cent of the world's energy utilisation comes from oil and gas—which are non-renewable finite resources. The second is that the recoverable reserves for many oil provinces should be capable of extension by proper application of efficient reservoir depletion methods. The third is that the average recovery factor of oil from producing reservoirs does not appear to have greatly increased over the last three decades. The fourth is that although the principles of oil recovery appear better understood, the detailed behaviour of reservoirs is still unpredictable in spite of improvements in data acquisition and interpretative concepts. Finally, that there has been an explosion in computer-based reservoir analyses which combine physical flow principles with detailed geophysical and geological reservoir descriptions which now provide management with the basis for considering alternative development strategies. All the contributions in *Developments in Petroleum Engineering* will consider the progress in the light of these points.

In this first volume we start with the reservoir and its characterisation.

The reservoir is a complex geological area with, initially, only a very few data description points. However, the petroleum engineer does not in general have to have fine geological detail but rather a deep understanding of the trends which cause variations of porosity and permeability, which affect reservoir productivity and development strategy. These trends will guide his decisions in planning reservoir development. This is emphasised in the chapter.

Data from the wellbore are the major sources of information for reservoir delineation, but nowadays the manipulation and analysis of these data have become, in many instances, so specialised that many individuals are dedicated to only one particular task. We have included three aspects: those of well logging, recent hardware developments for well testing and new analysis techniques for the data obtained from well tests. Well logging provides data on the near wellbore description of reservoir lithology, porosity and fluid saturations. Sophisticated instruments are continually appearing as an improved understanding of the near-borehole physics occurs. Well testing is the process whereby the pressure response at the wellbore is observed after a volume of reservoir fluid has been produced. The configuration and physical properties of the reservoir away from the wellbore influence this response. New hardware has continually been brought on to the market, but is not often described, except in trade literature. The analysis of the pressure response is a specialised 'art', and a chapter is devoted to describe its role in management decisions.

Improvements in the numerical methods for reservoir analysis and simulation have occurred along with the new generations of larger and faster computers. Two chapters are devoted to the development of numerical techniques used for reservoir simulation codes. Finite difference schemes are the mainstay of the multiphase multidimensional simulator, and finite element methods are used in some special cases.

Finally, although thermal enhanced oil recovery is the most widely used of the enhanced oil recovery (EOR) methods (some 80 per cent of EOR production is due to thermal techniques) and descriptions of the processes involved abound, the requirements of the physical property database are often overlooked. This chapter attempts to rectify the situation and brings together a collection of suitable sources of information.

The contributors to this volume are experts in their particular field and the editors are extremely grateful to them, especially for their care in the preparation of their chapters and for their patience before the final production.

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Chapter 1

PETROLEUM ENGINEERING: THE STATE OF THE ART

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1. INTRODUCTION

The object of this chapter is to discuss the present state of knowledge in petroleum engineering and the direction of research and development over the next twenty years.

When considering the likely path of future developments it is of course necessary to remember the complex political and economic changes that have occurred over the last decade. Before the first oil price explosion of 1973–74, the world had enjoyed several decades during which the price of hydrocarbon energy had slowly decreased, when measured in real terms. The majority of the oil was produced and transported, at will, by the large major multinational oil companies. This had led to rapid economic growth and an attitude of mind which was not energy-conservation minded. For example, plans were being considered in Saudi Arabia for increasing oil production capacity from about 10 million barrels per day to at least 20 million barrels per day and projections of continued growth of world oil demand were usually presented in terms of increases of between 3 and 6 per cent per annum. Political factors then intervened so much so that oil is now regarded as a national resource, with the host nation having total control over its production and, often, its processing.

Projections in 1985 are therefore very different. Not only because of this nationalism, but also because there is a high level of overcapacity on a world basis, the price of oil is under severe downward pressure and is only

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being sustained by severe production restrictions within the OPEC countries. Instead of the planned 20 million barrels per day Saudi Arabian production is currently no more than 5 million barrels per day. High cost North Sea production is now the market leader from a price point of view. Indeed it is salutory to remember that total production costs in the Middle East onshore are probably less than US$1 per barrel compared with the US$10 to US$20 per barrel that is more the norm for the most recent developments in the North Sea.

In dollar terms the price of oil peaked in 1979 at approximately US$40 per barrel and has since fallen back to the current levels of less than US$30 per barrel. With the advantage of hindsight it is easy to see that the lead times associated with measures for energy substitution and improvements in the efficient use of energy, combined with the economic slowdown to which high energy prices have contributed, inevitably led to the current situation.

The consequences of these economic and political changes can be clearly seen in the number of enhanced recovery projects that are in operation today in relation to the projections that were being made when the price of oil appeared to be on an ever increasing spiral.

Nevertheless, it cannot be emphasised too much that we are dealing with a finite resource. It is generally agreed that the following figures are a reasonable representation of the world resource base of conventional oil.

(a) An original resource base (including yet to be discovered oil accumulations) of some 5500 to 6500 billion (10^9) barrels of conventional oil. Conventional oil is that which will flow naturally if the applied pressure differential is sufficient and the specific gravity is above 20–25 degrees API.
(b) A worldwide average recovery factor of about 30 per cent, predicted on the basis of the application of the normal primary and secondary recovery techniques.
(c) A postulated ultimate recovery of some 1650 to 1950 billion barrels of conventional oil.
(d) An estimated ultimate recovery of some 1200 billion barrels based on discoveries to date.
(e) A cumulative production of some 570 billion barrels at the end of 1984.
(f) A postulated remaining reserve of 1100 to 1400 billion barrels of which only 630 billion barrels have already been discovered.
(g) A current annual consumption of some 20 billion barrels.

On the basis of the reserves suggested above we can rapidly come to two conclusions. First, a considerable effort is going to be needed in the exploration phase if the yet to be discovered reserves are to be found. Secondly, fertile areas for research and development effort are the extremely large quantities of oil that remain unrecovered when recovery by primary and secondary methods has been completed.

The petroleum engineer is of course primarily concerned with recovery efficiency and it is to a discussion of this that the rest of this chapter is devoted.

2. THE INTEGRATED APPROACH

'Synergy' is the word that has become most popular to describe what may seem to many to be a statement of the obvious—namely, that it is necessary for all the disciplines within exploration and production to cooperate and work together in order that recovery factors may be maximised. In no particular aspect of petroleum engineering is this more necessary than in the case of reservoir simulation. The advent of ever faster computers and the creation of much more sophisticated computer programs to describe the dynamics of reservoir fluid flow is of little avail unless there is a corresponding increase in the interpretative capabilities of both the geophysical and geological disciplines. In fact, the advent of reservoir simulation has not apparently been accompanied by any significant change in recovery factors. There are many engineers who, after the euphoria of the early years of simulation, have now come to the conclusion that the effect of the early attempts at modelling was to reduce recovery factors. This was caused by simplifying the reservoir description to a point that was unrealistic and as a result reducing the required well density for efficient recovery. While there are reservoirs which are sufficiently simple to justify large well spacings it is still probably true that the most potent method of increasing the recovery factor is to drill infill wells.

In recent years, however, the advances in geophysical interpretation with the advent of three-dimensional techniques and the much greater understanding of depositional processes on a reservoir scale have led to much better reservoir descriptions being available on a macro basis.

The current limit of seismic resolution is approximately 10 to 20 metres and it will require major advances in technique before this can be improved. Similarly, the study of any outcrop is a revelation to the geologically uninitiated and illustrates the complexity of the geological input from the point of view of reservoir description. Nevertheless our basic understanding of geophysical and geological processes has advanced to the point where the advances in reservoir simulation described in later chapters of this book can now be used to their full advantage.

The petroleum engineering contributions to advances in reservoir description have centred (other than simulation) on advances in petrophysical interpretation, including *in-situ* point pressure measurements, and in pressure analysis techniques. It is important that petrophysical information and analysis be combined with core-measured values of porosity, mineralogical content of the matrix and the general description of sedimentary structures as the problems are, in general, ill posed with multiple solutions and only the use of all available information channels will give satisfactory results. Very similar comments can be made about pressure analysis techniques where it is vital to have a geological model in mind when trying to interpret a specific pressure response. By way of example an upward slope on a Horner plot can be caused by many factors but two possible interpretations would be either declining permeabilities away from the well bore or else an actual formation boundary. The decisions taken might be very different depending on which model represented the preferred explanation for the pressure behaviour.

Nowhere more than offshore, for instance the North Sea, can it be said that the integrated approach is vital. It is instructive to consider why this is so and to see what lessons for future developments can be deduced. Several points of difference occur between the major offshore developments and their counterparts onshore. Perhaps the most obvious difference is the level of appraisal that is undertaken before major investments are made. In most North Sea fields currently on production the development decision was taken after no more than five exploration and appraisal wells had been drilled; that point was reached in the case of Mobil's Beryl field after only two wells had been drilled. In a land development, on the other hand, providing government regulations do not stop piecemeal development, there is an almost overwhelming argument for a stepwise approach.

Why is this? The simple answer is that the stepwise approach is the correct one under all circumstances if economic considerations are eliminated. Production performance under primary depletion is the most revealing indicator of reservoir continuity and in all but the simplest of reservoirs is absolutely necessary if a secondary recovery scheme is to be designed to the maximum level of efficiency. It is here that the multiple pressure recorder or, as it is commonly known, the repeat formation tester, comes into its own. However for offshore developments, where a platform production system is needed, the huge 'front-end loaded' investments are such that the interest rates alone are greater than many countries' gross national products. The platform and its production facilities must be planned and executed before there is much, if any, production history and the production rates must be such as to ensure a reasonable rate of return on investment. There is, therefore, a second difference between previous developments and that of recent ones such as the North Sea—that is the rate of depletion. The North Sea is unique in that giant oilfields are being produced at a peak rate of 10 to 15 per cent of ultimate recovery per annum. This compares with an average rate in the Middle East of less than 2 per cent per annum and in the case of some of the largest fields of less than 1 per cent per annum. Time is therefore not on the side of the petroleum engineer and it is perhaps just as well that the tools at his disposal have been improved over the last decade.

3. ENHANCED OIL RECOVERY

As stated in Section 1 the worldwide ultimate recovery factor, assuming primary and secondary recovery only, appears to be no more than 30 per cent. Therefore, there is an immediate incentive to look for recovery methods which would have an appreciable effect on this.

Simply increasing the recovery factor to 45 per cent, at first sight perhaps an apparently not too ambitious target, would have the effect of increasing the known world remaining reserves by a factor of nearly two. The same point can be made by considering that increasing the recovery of the Forties field in the British Sector of the North Sea from 50 to 60 per cent would be equivalent to finding another eight fields of the size (about 50 million barrels of reserves) currently being considered as marginal candidates for development.

Before discussing the state-of-the-art position as regards enhanced oil recovery it is perhaps as well to formalise the definition of some terms.

Primary recovery is that which occurs due to the natural energy of the reservoir system and is based on the expansive capabilities of the reservoir rock and the reservoir fluid.

Secondary recovery is that which occurs when energy in the form of water or gas is artificially introduced into the reservoir in order to maintain pressure and to move the oil to the production wells.

Tertiary or *enhanced* recovery (EOR) consists of applying further recovery techniques which are devised by the petroleum engineer and which do not mimic naturally occurring processes in the reservoir. In this sense conventional gas injection is not an enhanced recovery process as it merely mimics solution gas drive or gas cap drive. Similarly, water injection is not an enhanced recovery process as it merely mimics aquifer drive.

EOR processes can be divided into three main categories:

(a) Thermal processes consisting of steam flooding, cyclic steam injection, hot water injection and *in-situ* combustion.
(b) Chemical processes including surfactant combined with polymer injection, polymer flooding and caustic flooding.
(c) Miscible displacement processes including miscible hydrocarbon injection, carbon dioxide injection and nitrogen injection.

Steam flooding applications are by far the most numerous and, with certain notable exceptions to be mentioned later, the only wholly proven method of EOR from an economic point of view. The principle, if not the execution, is extremely simple and very similar to pattern water flooding except that it is the application of heat energy rather than pressure energy that is the main contributor to improving the recovery. The energy source is the latent heat contained in the steam and the main effects are thermal expansion of the oil, combined with large reductions in viscosity, causing the oil to flow much more easily. Secondary effects include reduction of residual oil saturations by distillation of the lighter components and changes in relative permeabilities. Most developments are based on very close well spacing and, as such, are usually restricted to areas where such spacings are economic or already drilled. In California, for example, 5 acre spacing or less is the norm. Further limiting factors are depth and reservoir thickness. The depth limitation is caused by the critical pressure of steam which at 218 bar (3200 psia) restricts reservoir depths to about 2000 m (6000 ft) as an absolute maximum while the thickness limitation is related to loss rates of heat to the over- and under-burden which makes thin reservoirs (say less than about 5 m) very inefficient. Hot water injection can be used but has, thus far, been beset with problems of premature breakthrough caused by lack of mobility control.

In situ combustion consists of heating the reservoir fluid by means of combustion gases which pass ahead of a burning front. The primary requirement is, again, close spacing as a flow path for the gas must be established prior to ignition in order that oxygen can be continually supplied to the combustion zone. There are several variations on the process. Wet and partially quenched combustions seem to offer the most effective variations as they involve *in situ* generation of considerable quantities of steam which itself aids the recovery process. The products of combustion include considerable quantities of acid gases resulting in difficult corrosion problems.

The chemical processes have shown significant potential in the laboratory but as yet have proved disappointing in field trials. It is evident that although the potential of surfactants to reduce the interfacial tension of an oil–water interface to near zero values can be easily demonstrated, the problems associated with applications under reservoir conditions have yet to be overcome. Furthermore, the problem of adsorption of surfactants on the reservoir rock is an important consideration as is the effect of saline conditions combined with temperature and pressure on the stability of both the surfactant and the chase polymer. In the case of polymer, degradation due to shear, bacteria and free radicals are also major problems.

One further difficulty which is often ignored is the question as to the exact disposition of residual oil. Surfactants can only work to remove residual oil if the distances are very small so that if the oil is in larger clumps the surfactant can only 'nibble' round the edges. Detailed descriptions of swept and unswept areas of the reservoir are absolutely essential. The effects of heterogeneities, especially those within supposedly uniform sands, are, in reality, still totally unknown. A major research effort, both theoretically and with pilot field trials, is absolutely essential.

Caustic flooding is simply a method of changing the wettability characteristics of the reservoir and of generating surfactants *in situ*. It has the advantage of being inexpensive compared to surfactant injection but it is not very obvious at this stage of development whether worthwhile improvements in recovery will be achieved.

Miscible displacement consists of eliminating all interfacial tension forces between the displacing and displaced fluids so that, in principle, there is no residual saturation of the displaced fluid within the contacted area. In principle, the displacing fluid could be any of LPG, condensed hydrocarbon gases, carbon dioxide, nitrogen, exhaust gases or even certain alcohols. To date there have only been field trials based on gas or gas liquids injection. LPG has been used most often and, in certain reservoirs of high relief with good gravity segregation, it has been very successful with recovery factors in excess of 80 per cent being predicted. In these cases a gravity stable sequence of oil, LPG and dry gas banks are formed in the reservoir and move downwards towards the producing intervals. This process is known as first contact miscibility.

All the other injection gases are initially immiscible unless the temperature and pressure are very high and the miscible bank is formed by