DEVELOPMENTS IN PETROLEUM SCIENCE 21
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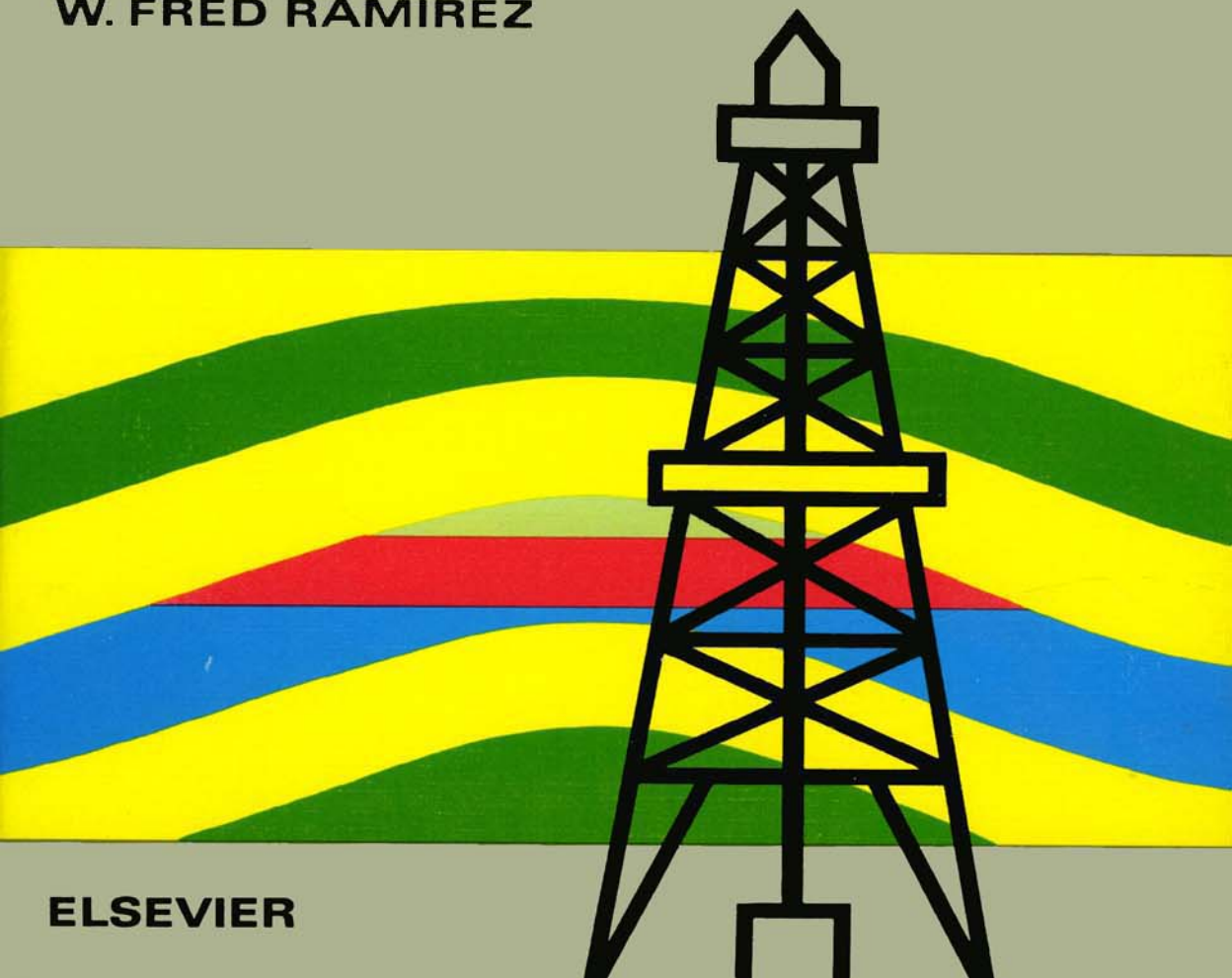
application of optimal control theory to enhanced oil recovery

W. FRED RAMIREZ



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ELSEVIER — Amsterdam — Oxford — New York — Tokyo 1987

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

Distribution for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
52, Vanderbilt Avenue
New York, NY 10017, U.S.A.

ISBN 0-444-42835-6 (Vol. 21)
ISBN 0-444-41625-0 (Series)

Printed in The Netherlands

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Chapter One

ENHANCED OIL RECOVERY

1.1 Introduction

In recent years, enhanced oil recovery techniques have received much attention in the oil industry. This activity has been motivated by the rapid escalation in the price of oil during the 1970's, uncertainties in supplies, a depletion of known reserves, and low efficiencies associated with current recovery techniques. Enhanced oil recovery methods can be divided into three major categories: thermal processes which include steam flooding, steam stimulation, and in-situ combustion; chemical processes which include surfactant-polymer injection, polymer flooding, and caustic flooding; and miscible displacement processes which include miscible hydrocarbon displacement, carbon dioxide injection, and inert gas injection. All methods involve the injection of large amounts of rather expensive fluids into oil bearing reservoir formations. Commercial application of any enhanced oil recovery process relies upon economic projections that show a decent return on the investment. Because of high chemical costs, it is important to optimize enhanced oil recovery processes to provide the greatest recovery at the lowest chemical injection cost. The purpose of this book is to develop an optimal control theory for the determination of operating strategies that maximize the economic attractiveness of enhanced oil recovery processes. The determination of optimal control histories or operating strategies is one of the key elements in the successful usage of new enhanced oil recovery techniques.

1.2 Need For Energy

Modern industrial societies consume large quantities of energy. The annual world oil consumption rate is around 20 billion barrels of oil per year. Figure 1.1 shows the annual production rates from 1945 to 1980 for various production regions of the world. The world cumulative production is given in Figure 1.2. This figure shows that we have currently produced over 470 billion barrels of oil. For the past 10 years the United States has consumed about 34% of the annual produced oil. Oil and natural gas comprise the source for over 70% of the world's energy needs.

It is obvious that we consume vast amounts of energy in order to maintain today's high standard of living and that most of that energy comes as a result of the technology of oil production. One of societies' continuing concerns is the availability of abundant and relatively cheap sources of energy.

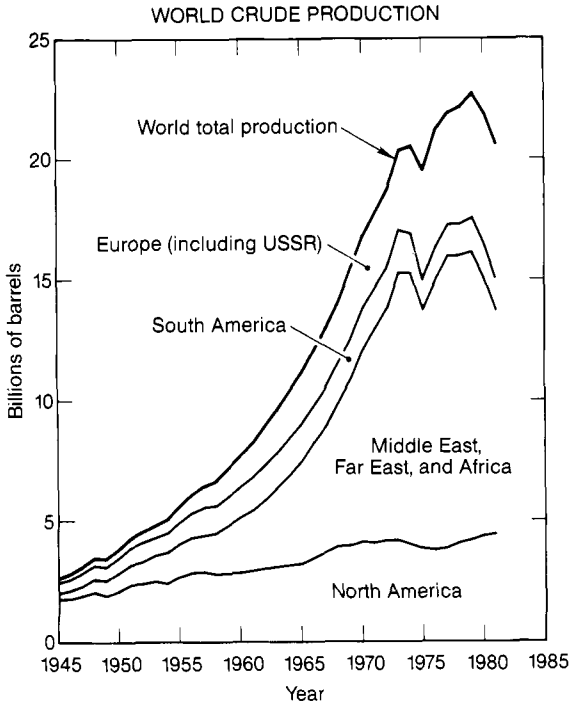

Figure 1.1. World Crude Oil Production Rate.
Source: DeGolyer and MacNaughton, *Twentieth Century Petroleum Statistics*, 1982

1.3 Current Oil Production Methods

The production technologies currently used by the oil industry are primary recovery and secondary waterflooding.

Primary production as the term suggests, is the first method of producing oil from a reservoir. When discovered, a crude oil reservoir has a mixture of water, oil and gas contained in the small pore spaces or void volume that exist between the reservoir rock grain matrix. Initially, these fluids are under considerable pressure, caused by the hydrostatic pressure of ground water. At these high pressures a large portion of the gas is dissolved in the oil phase. The initial connate water and the solution gas combine to provide the driving force for moving the oil into a well where it is pushed by the underlying pressure or is lifted by pumps to the surface.

Reservoir pressure decline adversely affects oil production in two ways. First, it diminishes the force which drives oil into the well bore. Second, and more important, a decline in reservoir pressure soon causes some of the gas held in solution to be released as discrete gas bubbles in the pore spaces of the porous media. Such a discrete gas phase impedes the flow of oil toward the well while increasing the flow of gas.

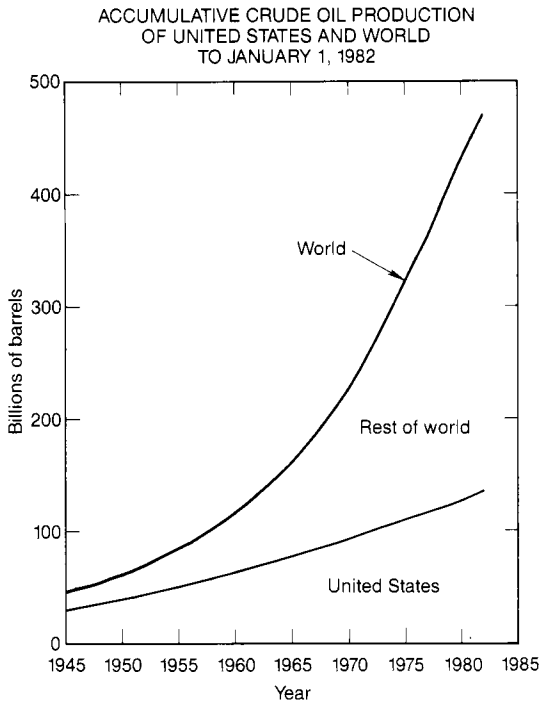

Figure 1.2. Cumulative World Crude Oil Production.
Source: DeGolyer and MacNaughton, *Twentieth Century Petroleum Statistics*, 1982

A traditional step for increasing oil recovery is to inject gas or water in to an oil reservoir for the purpose of delaying the pressure decline during oil production. This technique is called pressure maintenance and the oil produced is still part of primary recovery.

Even after a decline in reservoir pressure has caused the oil recovery rate to become uneconomical, oil production can again be increased through continuous injection of a fluid, normally water, into the reservoir. This is called secondary waterflooding.

1.4 Efficiency of Present Production Techniques

Using today's technology of primary production including pressure maintenance and secondary waterflooding, over half of the original oil in place remains unrecoverable. Producing naturally, a field may yield 20 to 30% of the original oil in place. While naturally flowing wells are sought after by all producers, only about 70% of the more than 500,000 wells in the U.S. were naturally flowing at the end of 1977 (Schumacher, 1980). Primary oil production amounted to about half of the U.S. production in 1976. The National Petroleum Council estimates that less than 10% will come from primary production from known fields by the year 2000.

By 1973 waterflooding had become one of the major contributors to the United States' oil recovery with about one-half of domestic oil being produced from reservoirs partially or completely under waterflooding. Waterflooding is common in fields through out the world with projects in place in Canada, Venezuela, Iraq, and Saudi Arabia. Geffen (1973) places the average cost of waterflood recovery at 30 cents to 50 cents per barrel as past practice. Some recent reports, however, on new projects indicate somewhat higher costs.

For a typical gas depleted field with oil above 30 degrees API, the incremental waterflood recovery is in the range of 15% to 20% with total primary and secondary recovery efficiencies of about 30% to 45%. The following data (Table 1.1) are given in EPA 68-01-2445 for several U.S. fields,

Table 1.1
Primary and Secondary Recovery Efficiencies

Field	Primary Recovery	Incremental Waterflood Recovery
Eldorado	21%	22%
Jay	17	21
Penbina Cardium	15	15
Sawn Hills	17	25
Weyburn	14	17
West Burk Burnett	15	17