8324897

Yu, John Pingshun

MULTI-CRITERIA OPTIMIZATION MODEL FOR THERMAL RECOVERY PROCESSES

The University of Oklahoma PH.D. 1983

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy. Problems encountered with this document have been identified here with a check mark _√_.

1. Glossy photographs or pages _____
2. Colored illustrations, paper or print _____
3. Photographs with dark background _____
4. Illustrations are poor copy _____
5. Pages with black marks, not original copy _____
6. Print shows through as there is text on both sides of page _____
7. Indistinct, broken or small print on several pages _✓_
8. Print exceeds margin requirements _____
9. Tightly bound copy with print lost in spine _____
10. Computer printout pages with indistinct print _____
11. Page(s) __________ lacking when material received, and not available from school or author.
12. Page(s) __________ seem to be missing in numbering only as text follows.
13. Two pages numbered __________. Text follows.
14. Curling and wrinkled pages _____
15. Other ____

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

MULTI-CRITERIA OPTIMIZATION MODEL
FOR
THERMAL RECOVERY PROCESSES

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

JOHN PINGSHUN YU

NORMAN, OKLAHOMA

1983

MULTI-CRITERIA OPTIMIZATION MODEL

FOR

THERMAL RECOVERY PROCESSES

Approved By

DISSERTATION COMMITTEE

To my dear parents,

for their love and encouragement, and
strong will of helping others.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author is grateful to Dr. D.E. Menzie, Professor of Petroleum Engineering, and to Dr. A.A. Aly, Professor of Industrial Engineering, for their careful review, helpful guidance, continuous encouragement, and for generously giving their knowledge and time throughout this work as chairman and co-chairman of the author's Graduate Committee.

The author wishes to express his sincere appreciation to Dr. R.M. Knapp, Professor and Director of the School of Petroleum and Geological Engineering (PG&E); Dr. D. Tiab , Associate Professor of the PG&E; and Dr. J. Vadiveloo, Assistant Professor of Business and Finance for their review of this work, for their guidance and encouragement. He also expresses his appreciation to Dr. J. Morris, Assistant Professor of the PG&E, who served as a research faculty member.

The author gratefully acknowledges the financial supports from the Energy Resources Institute (ERI) and Oklahoma Mining and Mineral Resources Institute. The author also wishes to express his personal thankfulness to Dr. C. Mankin, the director of ERI; Mrs. J. Wilke, Associate Director of ERI programs; Mrs. V. Brown, the Secretary for the Directors and all the colleagues for their kind help.

The author is grateful to Dr. David A.T. Donohue, the president of the International Human Resource Development Corp. (IHRDC), for his favourable critics on the dissertation draft. Also the author expresses his appreciation to Ms. M. Benner for typing and all the colleagues at IHRDC for their kind help.

The author is deeply indebted to his eldly mother and father for their inspiration, encouragement, and the many sacrifices during my study in this country. The author also wishes to express his love to his friend, Tina Lin, for her patience, understanding and devotion. He also expresses his thankfulness to Dr. Frank Tsay, Mrs. Harris and all friends for their friendship in Norman.

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

The thermal process screening guide, a pilot test, or a reservoir simulation model are applied to evaluate the thermal processes. However, the evaluation is unrealistic if problems arise. Hence, a new evaluation method is necessary.

The Marx and Langenheim solution and the oil recovery/ volume burned method are used as the basic formulations to develop the performance model for steam drive and in-situ combustion processes. One hundred reservoir cases have been evaluated by the performance model for the thermal processes. (Petroleum Data System is used for reservoir data validation .) The trends of thermal processes can be generalized into regression equations which will be used as the objective functions. Priorities can be set for the objective functions to determine their achievements. A multi-criteria programming technique is applied. Both the optimal designs as well as optimized profit are obtained.

In the Loco field case study, the steam drive enhances the heavy oil recovery by decreasing the oil viscosity and increasing the injectivity; therefore, a quicker return of investment is predicted. However, the in-situ combustion has a higher thermal efficiency and the steam injection adds a high cost which makes the steam drive undesirable for the Pauls Valley Field.

I. INTRODUCTION

1.1 Background

The Shell Oil Company has done much research work on the thermal recovery method since 1951 (Offeringa et al.,[49] 1981). From their publications, it is evident that they are attempting to handle the complicated calculations of thermal recovery methods in a simple, workable fashion (Newman,[48] 1975; Myhill,[47] 1978; Vogel,[68] 1982; etc.). Some other leading research papers have also dealt with this issue (Farouq Ali,[23] 1970; and, Gates and Ramey,[29] 1980). However, it has been mentioned (Offerenga et al.,[49] 1981) that the major reservoir engineering problem in designing new thermal projects is still the lack of a simple but reliable evaluation method.

This dissertation has been done with the intention of trying to handle the complicated engineering design problem with a reliable but simple method. This design scheme can be accomplished for three reasons:

i) The performance, regression and optimization models have been built using most of the pertinent theories in this area. Comparison and analysis of the results are being made in almost all of the appropriate modeling procedures. The performance model has also been built on a "pilot design." Application of the actual field data has shown in model building procedures.

ii) Economic analysis is usually done independently when the other engineer optimal parameters have obtained from the evaluation process. However, this optimization model is both applicable to engineering optimal design as well as to optimum decision-making.

iii) The great advances in minicomputers and micro-computers ensure easy access to computer data and modeling. A relatively smaller computer model is necessary for the microcomputer application. The model has been built for this purpose.

This dissertation is written in six chapters. The first three chapters review the pertinent literature and the details of model-building procedures. In several appropriate sections of each chapter, the author has also included an additional literature review in order to explain the reasons why the theories and techniques are being used in this work. The last three chapters cover the information regarding the thermal recovery methods relating to heavy oils, optimization model formulation and field case studies using the optimization model. Oklahoma field data is used. The data is cited from published literature and Petroleum Data System data.[50]

1.2 Statement of the Problem

An enhanced oil recovery (EOR) screening guide is usually applied for the selection of a EOR process for a particular reservoir. However, the screening guide initial selection will not promise the success of the EOR process application. Then, a simulation approach is used to evaluate the process performance. These process parameters are usually employed for economic evaluation of the reservoir. These evaluation procedures pose two types of problems:

1) The EOR process simulation requires actual well data and production history to confirm the results. If those data are unavailable, a pilot test has to be conducted in the field in order to evaluate the process. Thus, this evaluation process is always a time-consuming stage. Sometimes, the time factor is a critical consideration in the business world.

2) The EOR process performance model evaluates the process parameters at the maximium states; i.e., the maximum injection rate, injection pressure, and production rate, etc. Based on the maximum parameters, the economic

evaluation will be too optimistic. If the results of the pilot test turn out to be a failure, the evaluation will be too pessimistic. Neither cases are realistic in evaluation!

Therefore, a new evaluation approach is necessary. An optimization model normally handles an evaluation problem in a more practical aspect because the mathematical optimization programming technique evaluates the parameter in the feasible region. The economic evaluation based on the optimized parameter makes the estimates more realistic. The traditional optimization model is always unidimensional; i.e., only one parameter is optimized and the other parameters are the decision variables. For example, the profit is the optimized value and the process parameters are the decision variables. Actually, this unidimensional model also poses a design problem for the engineer.

An engineer always optimizes the design parameters and evaluates the economic benefit of the process (Akindale[3]. 1982). If all the designed paramters and economic profit could be optimized simultaneously, an overall evaluation would be very practical. This overall evaluation is particularly necessary for comparison of two processes in the same conditions and reservoir. This new evaluation approach would be the multi-criteria optimization method which is the main study of this dissertation. The author hopes a bridge is being built between the engineering and the decision-making aspects.

Heavy oil implies crude oil having an API gravity of 25 degrees or less (Farouq Ali,[25] 1974; and, Dietzman,[18] 1965) and crude oil having viscosities in excess of 30-40 cp. Heavy oil reserves are one of the greatest potential fossil fuel resources both in the U.S. and worldwide. Reservoirs with heavy oil reserves have been reported in northern and southern Oklahoma. In southern Oklahoma, at least one steam and seven in-situ combustion projects have been initiated (Dietzman,[18] 1965; and, Martin,[43] 1968). Two of these field cases are used for the optimization applications.

The in-situ combustion process is one of the predominate thermal recovery processes because the in-situ combustion process has the highest thermal efficiency, lower surface fuel requirment, and no well depth restriction. The in-situ combustion and steam drive processes are being applied to heavy oil recovery. Steam drive is the more widely used process in the field. A sensitivity analysis is being made on both of these processes; therefore, a comparison of the processes can be made.

1.3 Literature Survey

Since the dissertation work involves the Petroleum Data System (PDS), the thermal recovery performance model and the optimization model, the literature survey covers these three areas individually.

1.3.1 Petroleum Data System applications

On March 18, 1975, in recognition of the enhanced oil recovery (EOR) potential, the Assistant Secretary of the Interior asked the National Petroleum Council to conduct a complete study of EOR methods in the United States. The Council agreed, and PDS was one of the data bases chosen for the study. A relatively complete analysis was made on the feasibility of using EOR methods on different types of reservoirs. Based on 245 known reservoirs located in California, Texas, and Louisiana, the author listed a screening guide for EOR methods (Hayes,[38] 1976).

In 1980, Venkatesh[67] completed two steps for PDS research. In the first step, a survey of PDS users was conducted, and an analysis of the survey indicates that the PDS is an excellent source of oil field-related information. However, some data are missing in the data file. In the second step, he used an enhanced oil recovery screening guide for the three basic EOR methods (thermal, miscible, and chemical) for feasibility tests. However, his computer screening methods lacked accuracy in modeling real reservoir evaluating criteria.

In the same year ,1980, Saisasong and Yu[57] started out using a statistical approach (the Monte Carlo Simulation technique) to obtain the most likely value of residual saturation in oil reservoirs after water-flooding. Through statistical analysis, it was found that the distribution of residual oil saturation is an asymmetric bell-shaped curve lognormal distribution type. Knowing the type and a probability distribution of residual oil saturation can lead to a better understanding of a reservoir and can also lead to a better decision concerning EOR prospects. David Jones[37] (1980) presented his work on the application of basin analysis to exploration strategy determination. He used the Permian Basin data base to do a risk analysis in an uncertain environment. James Gumnick et al.[32] (1981) used the cluster analysis in the field test database studies. Robert Crovelli[17] (1981) also used the Monte Carlo Simulation technique in a gas resource appraisal study. Goodbread et al.[31] (1981) published a DOE report about PDS data validation by using computer procedures. In the report, the correlation equations are used to setup the validation range for the database data. Basically, their approaches are statistical analysis for the Petroleum Data System applications. An engineering application for the data base is almost a necessity. It is the author's hope that this dissertation will give some guidance for future engineering applications.

1.3.2 Enhanced oil recovery methods evaluations

Currently, EOR evaluation is the main concern of most research workers. Mathematical EOR performance models are the most popular topics. Numerous mathematical EOR models (Newman,[48] 1975) were built between 1975 and 1977 based on linear or radial numerical solutions (Van Lookeren,[65] 1977). The mathematical models predict the production performance. Most of the models are for the simulation of the steam drive and the steam cycling processes (Crichlow,[15] 1974; and, Jones,[38] 1981). Progress in simulating the performance of the in-situ combustion process is not as advanced as the steam drive process, mainly because of its complexity and our lack of understanding of all the mechanisms involved. Not many papers have been published pertaining to the evaluation of the in-situ combustion process with the exception of Solimon et al.[60] who developed a numerical model for the in-situ combustion process in 1981. In the same year, Chapman Cronquist et al.[16] published another DOE report about using a computer model for comparative economic analysis of enhanced oil recovery projects. Because of the complexity of the in-situ combustion process, the studies of the plateau were preliminary and unsatisfactory. In 1978, Satman et al.[58] did an in-depth study of the process, and he developed correlation equations for oil recovery. In 1977, Chu[12] used statistical regression models of the process parameters, such as fuel content, air-oil ratio, fuel burned, and air requirement. There is also a similar correlation approach study for the steam drive process, but the approach is based on mathematical solutions rather than a statistical approach (Gomma,[30] 1980).

Studies on the comparison of the steam drive and the in-situ combustion processes were intensive because both processes are the thermal methods for heavy oil recovery, and we would like to know which process is better for a particular reservoir. In 1966, Wilson et al.[71] discussed the cost comparison of using steam or air for reservoir heating, and they indicated that compression is the major cost for the in-situ combustion process. In 1973, Baker[6] discussed the effects of pressure and injection rate in the steam drive process, and he indicated that the injection rate is the major cost of the steam drive process. In 1978, Doscher et al.[20] did a study based on the economic reasoning that the discounted cost for producing oil by in-situ combustion was found to be higher than that of the comparable steam drive. Following this paper, Stanford University Petroleum Research Institute conducted a thorough study of an engineering economic model for thermal recovery methods(Williams et al.,[69] 1980). They used two independent performance models for different processes to obtain the recovery and production rates, and evaluated the actual economic value of both processes. They concluded that whether one process is more profitable than the other should be based on the individual reservoir case. In 1982, Burger[7] studied two different processes in the energy balance aspect and concluded that the in-situ combustion is more favorable than the steam drive. However, none of these studies have ever attempted to use the optimization programming techniques for the evaluations.

1.3.3 Optimization models:

In the petroleum industry, the optimization technique (mathematical programming) was applied as early as 1957. Arnofsky and Lee[4] developed a linear programming model that scheduled oil production. Following the optimization applications, many authors (Rowan and Warren,[56] 1967; and, Asward and Aly,[5] 1980) applied linear, nonlinear, integer and dynamic programming techniques in all areas of petroleum engineering, e.g., production, drilling, and gas storage. In 1969, Bentsen and Donohue[8] applied a dynamic programming model to the cyclic steam injection process. The authors optimized the steam soak process with respect to net profit. Romero[55] did his M.S. thesis work on optimization of the steam drive process by geometric programming in 1974. These two studies are the process optimization models for the enhanced oil recovery processes. However, there was not a single study regarding the performance optimization model for the steam drive and in-situ combustion processes.

In this dissertation, a relatively new optimization programming technique is used for the performance optimization model for the steam drive and in-situ combustion processes. This programming technique solved the multiple objective functions for injection rate, injection pressure, production rate, oil recovery, and net profit. A comparison of these parameters was used for the decision making. As a result, engineering designed parameters for a better process can be used in a particular reservoir.

1.4 General Approach

The general approach of the multi-criteria optimization modeling is done in two stages:

Stage 1: The mathematical formulations provide the basic theory for building the steam drive and in-situ combustion performance model. Actual reservoir data are input into the performance model to evaluate the process parameters and the results are used for regression analysis.

Stage 2: The trends of both processes can be generalized into regression equations which will be used as objective functions; such as injection pressure, injection rate, production rate, and oil recovery. The profit equation can also be formulated as another objective function. Different objective functions will be ranked into priority of pursuing achievements.

Any given reservoir case can be used for the field case study. The reservoir data is input into the performance model for evaluation and the process parameters will be used as the real constraints. A special optimization programming technique is applied to obtain the optimum solution. The optimum designed parameters are injection pressure, injection rate, production rate, oil recovery and profit. These optimized parameters would be the optimal engineering design and the optimum decision for a particular reservoir.

II. THE PERFORMANCE MODEL

2.1 Introduction

In any optimization model, objective functions are the essential functional equations required. In this dissertation, the author adopted the method of using regression models to generate objective functions for the optimization model, which is a modified method from Crichlow[15] (1977). The data being used for the regression models are preferred in the ranges of the most efficient process. Although the reported thermal recovery reservoir data may be used for the same purpose, the data are either incomplete or having inherited errors (Buhima,[10] 1981). Therefore, we want to generate the best thermal recovery processes data for the process evaluation, e.g., process efficiency, injection rate, injection pressure, and production rate, etc. The performance model for the steam drive and the in-situ combustion processes is essential for this purpose.

Coats[14] (1969) emphasized the best methods for modeling and using mathematical reservoir simulations. The simulation model has to be tailored according to the complexity of the question being asked. The accuracy of any model depends on the amount and reliability of data available for the simulation procedures. These two factors determine the sophistication of the mathematical system to be used.

The author adopts his principles for the simulation model. The reservoir parameters are used as a pilot test for the thermal recovery process evaluation. The input data are screened according to the thermal processes criteria and the missing data are validated, therefore, the data are unique for each process. (The screening criteria for the thermal processes are attached in Appendix A.) The simulation model is one-dimensional for both thermal processes, but the author uses the most updated concepts to perfect the deficiencies of the basic model structure. The simulated pilot results may be projected for the reservoir evaluation.

The performance model is subdivided into three major parts: the screening guide, the steam drive process and the in-situ combustion process. The screening guide actually acts as the main program of the performance model because the reservoir has to be screened before it is considered as a candidate for thermal recovery methods.

The steam drive process and the in-situ combustion process are attached to the main program. Each thermal recovery process also has several calculation procedures for a complete computation. The performance model is outlined in the following flow chart (Figure 2.1).

The author selected 45 field cases for the steam drive process and 35 field cases for the in-situ combustion process from the latest publications (Oil and Gas Journal Annual Production Reports, 1982;[2] and SPE Improved Oil Recovery Reports, 1975-1981 [35]). In these field cases, reservoir parameters are input as the data for the simulation model. The output process parameters, for both processes, will be used as the input data for the regression modeling.

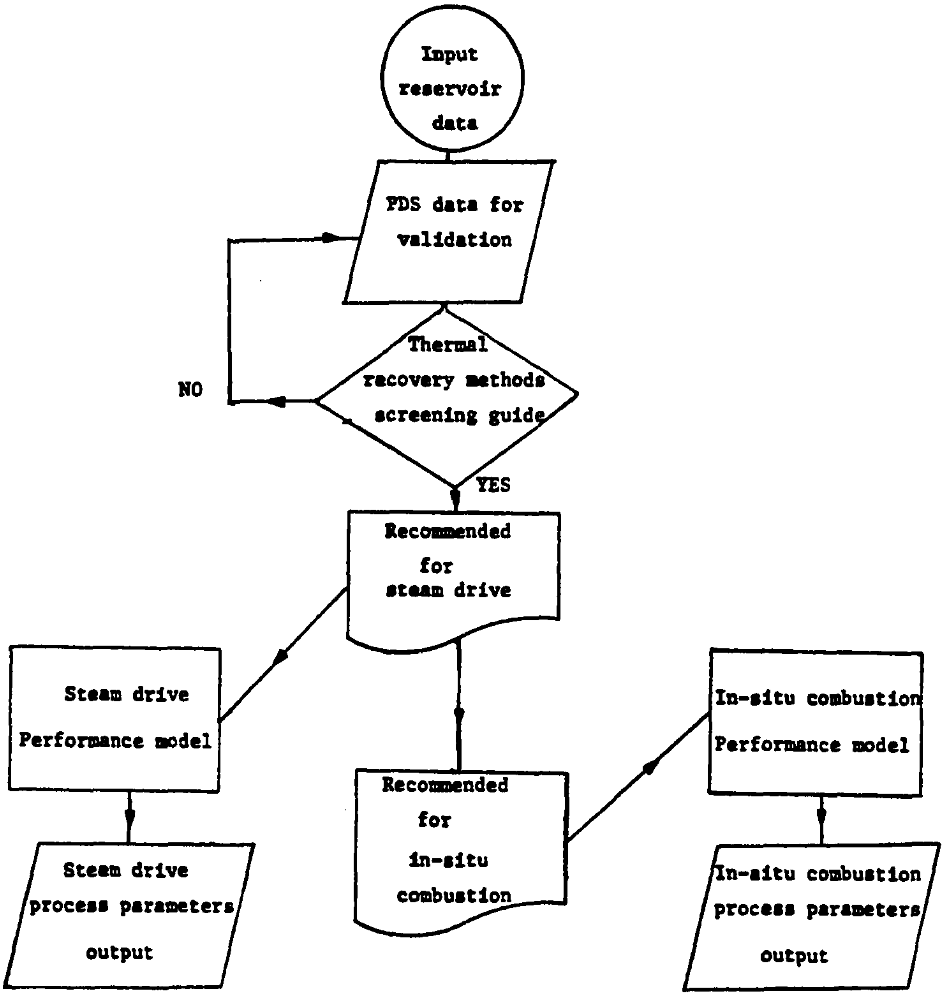


Fig. 2.1 Flowchart of Performance Model.

2.2 Steam Drive Process Simulation Model

The limitations of given reservoir data is imposed, i.e., no pressure decline, no production history. The average values of parameters are being used for the simulation model (homogeneous reservoir). The author chooses to build a one-dimensional analytical solution steam drive model. The author attempts to improve the accuracy and feasibility of the model by implementing several modeling techniques.

A one-dimensional analytical model is usually very good for thin layer formation modeling because steam zone shape and steam overriding problems are very common for thicker formations. This model incorporates Van Lookeren's steam zone approximation method to handle the above problem. In the steam drive process, the hot water condensation zone usually causes excess heat loss to the formation. The Mandl-Volek refinement solution is used for the hot water bank correction. The procedures are discussed in detail in the following sections.

Finally, an inverted 5-spot and 5-acre flood pattern is chosen for the pilot test in the whole reservoir. This is a common evaluation method used for a reservoir by oil companies.

The steam drive performance model is formulated in five parts:

i) Van Lookeren's[65] (1977) sweep efficiency approach for maximum injection rate and pressure evaluations.

ii) Marx and Langenheim solution[44] (1959) to heat transfer equation.

iii) Mandl-Volek refinement[41] (1969) on the hot water bank.

iv) Production rate and cumulative production calculation.

v) Projection of the pilot test results to the whole reservoir.

In the performance model, the detailed derivation of the equations are incorporated. This performance model is programmed in FORTRAN computer language.

2.2.1 Maximum injection rate and injection pressure evaluation

Farouq Ali[23] (1970) indicated that sweep efficiency has a direct correlation with injection rate,i.e., vertical sweep efficiency was found to increase with an increase in injection rate. The ultimate sweep efficiency was very close to the steam breakthrough sweep efficiency. In most cases, the two are identical as in the case of highly viscous oils, such as heavy oil. Another advantage to using sweep efficiency as an indicator of the injection process is that it has a direct relationship with recovery, which has been proven experimentally (Van Lookeren,[65] 1977; and Farouq Ali,[23] 1970). This idea was adopted in Van Lookeren's paper (1977). He developed equations for steam-zone development around an injection well in a radial steam drive system, which comes from a series of steady state equations for radial flow in a horizontal layer. The details and experimental results are outlined in the paper. The mathematical relationship is described as follows:

$$AR = \left[\frac{5{,}900\ \mu_s\ m_s\ X_i}{(\rho_o - \rho_s) h_n^2\ k_s\ \rho_s} \right]^{1/2} \tag{2.1}$$

where:

AR = vertical conformance factor, radial flow case
m_s = steam injection rate, B/D/pattern
X_i = steam quality, fraction
T_s = $115.1\ P_s^{8.225}$, °F
ρ_s = $5.06\ e^{0.000359P_s}$ -5 , lb/cu-ft.
ρ_o = $\frac{141.5}{API + 131.5}$ 62.4 , lb/cu-ft.
μ_s = $0.0000517T_s + 0.00049$, cp
h_n = net pay thickness, ft
k_s = permeability of steam, md

The radial sweep efficiency is in the range of 0.383 to 0.626; therefore, this value will varies according to the degree of steam overlay, e.g. vertical sweep efficiency (VTSW) = 0.623 X AR

We assume the injection presure increases in an exponential fashion:

$$P_s = P_1 exp^{m(m_s - i_{s1})} \qquad (2.2)$$

where:

$$m = \frac{\ln (P_2/P_1)}{(i_{s2} - i_{s1})} \qquad (2.2a)$$

i_{s2} = maximum allowable steam injection rate, B/D
i_{s1} = initial steam injection rate, B/D
m_s = steam injection rate, B/D
p_1 = initial injection pressure, psia
p_2 = incremental injection pressure, psia.
p_s = steam injection pressure, psia

There are several advantages in using Van Lookeren's steam zone approximation method. The analytical solution model can be used for any formation thickness. The maximized injection rate and injection pressure can reach the most efficient design requirements (Jones,[38] 1981). The injection rate and injection pressure are used directly as the design criteria for optimization and achievement goals.

Evaluation of oil viscosity at reservoir conditions

The given reservoir data on oil viscosity had not indicated the conditions under which the data was taken.

Actually, most viscosity data were taken under laboratory conditions. Therefore, it is necessary to evaluate the oil viscosity at reservoir conditions. The Beggs and Robinson correlations are used for the viscosity evaluations which will be explained in the in-situ combustion model.

2.2.2 Marx and Langenheim solution

This model was first introduced by Marx and Langenheim[44] in 1959 and was further clarified by Farouq Ali[24] in 1966. Although the authors did not discuss the basic assumptions upon which the model was formulated, they have implicitly assumed that the reservoir base and cap rock are geometrically, hydrologically and thermally homogeneous and isotropic, and that radial heat conduction can be ignored. In addition, they have assumed that only steam displaces the oil, without a hot water bank ahead of it, and that the fluids are incompressible.

As shown in the Appendix A, the Marx Langenhein solution yields the steam flooding heated area as:

$$A(t) = \frac{m_s H_t \, h(\rho c)_{R+F} \, D}{4K_h^2 \, \Delta T} \, \xi_s/\theta \tag{2.3}$$

where:

$$\xi_s/\theta = e^{\tau/\theta} \operatorname{erfc}\left(\sqrt{\tau/\theta}\right) + \frac{2\sqrt{\tau/\theta}}{\sqrt{\pi}} - 1 \tag{2.3a}$$

and

$$\tau/\theta = \frac{4K_{hob}\,(\rho c)_{ob}\,t}{h^2\,(\rho c)^2_{R+F}} \tag{2.3b}$$

which is the dimensionless time

H_t = the specific enthalpy of steam P_i, T_i at reservoir conditions
m_s = rate of steam injection, lb/hr
h = pay thickness, ft
D = thermal diffusivity of cap rock ($K_h/\rho c$), ft^2/D
k_h = thermal conductivity, Btu/ft-hr-^oF
ΔT = temperature difference, ^oF
$(\rho c)_{R+F}$ = heat capacity of fluids saturated rock, Btu/ft^3-^oF
$(\rho c)_{ob}$ = heat capacity of overburden rock, Btu/ft^3-^oF
and the complementary error function is defined as:
$erfc(X) = 1 - erf(X)$

Derivation of other thermal expressions from the Marx-Langenheim solution is shown in detail in this section. Those expressions are very important for the calculation of the actual performance in the steam drive process, such as thermal efficiency and steam oil ratio.

The thermal efficiency is defined as:

$$E_h = \frac{\text{The energy remaining in the oil sand}}{\text{the total energy injected}}$$

$$= \frac{h_t A\,(\rho c)_{R+F}\,(T_s - T_r)}{m_s\, t\, H_t}. \tag{2.4}$$

where:

t = time, days
h_t = gross thickness of formation, ft
T_s = temperature of steam, °F
T_r = formation temperature, °F

From Equations 2.3 and 2.3b, we obtain A and t terms and substitute them into Equation 2.4 and cancelling the terms, we obtain the following thermal efficiency expression:

$$E_h = (\xi_s/\theta)/(\tau/\theta) = \xi_s/\tau . \qquad (2.4a)$$

The oil-steam ratio is defined as:

$$Ros = \frac{N_p}{m_s t} \qquad (2.5)$$

and the oil recovery N_p, is defined as:

$$N_p = A_s h_n \phi (S_{oi} - S_{or}), \qquad (2.6)$$

where:

A_s = the area swept by steam, ft
h_n = the net sand thickness, ft
ϕ = porosity, fraction
S_{oi} = the initial oil saturation, fraction
S_{or} = the average steam zone saturation, fraction

Substitute Equation 2.5 by m_s from Equations 2.3, 2.6 and rearrange terms:

$$R_{os} = \frac{A_s h_n \phi (S_{oi} - S_{or}) h_t H_t (\rho c)_{R+F} \xi_s/\theta}{4K_{hob}(T_s - T_r)(\rho c)_{ob}\, t\, A} \qquad (2.7)$$

but

$$\tau/\theta = \frac{4K_{hob}\,(\rho c)_{ob}\,t}{h_t^2\,(\rho c)^2_{R+F}} \qquad (2.3b)$$

In Equation 2.3b, a distinction is made between the net sand thickness, h_n, and the gross sand thickness (including shale stringers), h_t. It is assumed that these are relatively thin shale stringers which are heated to steam temperature uniformly as the steam front passes.

Hence, substituting τ/θ in Equation 2.7:

$$R_{os} = \frac{A_s\,h_n\,\phi\,(S_{oi}-S_{or})\,H_t\,\xi_s/\theta}{A(T_s-T_r)\,(\rho c)_{R+F}\,h_t\;\tau/\theta} \qquad (2.7a)$$

Upon substituting the relation for thermal efficiency:

$$E_h = \frac{\xi_s/\theta}{\tau/\theta} \qquad (2.4a)$$

and supplying a conversion factor for consistent units:

$$R_{os} = \frac{62.4\,\phi\,h_n\,E_h\,A_s\,[H_t\,(S_{oi}-S_{or})]}{h_t\,(T_s-T_r)\,(\rho c)_{R+F}\,A} \qquad (2.7b)$$

An empirical relation between steam area (A_s) and heated Area (A) assumes that these areas are proportional to the following ratio:

$$\frac{A_s}{A} = \frac{\text{(Total energy injected)-(energy injected as hot water)}}{\text{total energy injected}}$$

$$= \frac{H_t - (H_{ws} - H_{wr})}{H_t} = \frac{\bar{X}_i H_{wv}}{H_t} \qquad (2.8)$$

where:

H_{wv} = latent heat of vaporization at P_s, T_s, Btu/lb.

H_{ws} = the enthalpy of wet steam at P_s, T_s, Btu/lb

H_{wr} = the enthalpy of saturated water at P_s, T_s, Btu/lb

$\bar{X}_i$ = steam quality at the sandface, fraction

Making this substitution:

$$R_{os} = \frac{62.4\, \phi h_n E_h [\bar{X}_i H_{wv} (S_{oi} - S_{or})]}{h_t (T_s - T_r)(\rho c)_{R+F}} \qquad (2.7c)$$

R_{os} is the cumulative oil-steam ratio in steam swept area.

In applications of the Marx and Langenheim solutions, thermal properties of steam and rock have to be calculated. Their relationships with pressure can be obtained from the publication (Farouq Ali,[25] 1978). The following equations are used to estimate the above properties. These equations are valid at pressures ranging from 1,000 to 3,000 psia:

Steam temperature: $T_s = 115.1\, P_s^{0.225}$, ^oF

Evaporation enthalpy: $H_{wv} = 1318\ P_s^{-0.08774}$, Btu/lb

Rock thermal conductivity: $K_h = 34$ BTU/d-ft-^oF

Again heat capacity of fluids saturated rock:

$$(\rho c)_{R+F} = S_o \rho_o c_o + S_w \rho_w c_w + (1-\phi)\rho_r c_r$$

where:

ϕ = porosity, fraction

ρ_r = rock gain density 165 lb/ft^3 and the subscripts o,w, refer to oil, and water

c_o, c_w, c_r = heat capacity with respects to oil, water,and rock

P_s = steam generation pressure, psia

and assuming,

$(\rho c)_{R+F} = 38$ BTU/ft^3-^oF

To standardize the oil-steam ratio to an equivalent 1,000 BTU/lb steam at the boiler outlet, the following correction is required.

$$R'_{os} = \frac{1{,}000}{(C_w \times (T_s - 75) + X_i \times H_{wv})\ (R_{os})} \qquad (2.7d)$$

2.2.3 Mandl-Volek Refinement:

In the actual world, steam-injection tests in the field have shown that heat transport into the oil/water region, ahead of the steam zone, may have a significant effect on the production process. An extension of the model of Marx and Langenheim was developed by Mandl and Volek to account for the fall-off temperature in the region of the hot-water bank. This extension does not account for horizontal conduction, but it does account for heat transported by the flow of hot water beyond the leading edge of the steam zone. Their solution for the area of the steam zone, A, is valid only for the time (t) is greater than critical time (t_c), or if the area of the hot water bank is larger than the area of the steam flooding front.

In programming the Mandl-Volek refinement, the thermal properties of fluids and rocks are used as before in the Marx-Langenheim solution, except that the thermal capacity of the water condensation zone has to be recalculated as:

$$A(t) = A_w(t)$$

$$H_t = 14.6\ m_s\ (H_{wrt} + X_i\ H_{wv} - C_w(T_r - 32)) \qquad (2.10)$$

which substitutes into equation (2.3) to obtain the water condensate zone area.

If $A_w(t)$ is calculated to be greater than $A_s(t)$ from the Marx and Langenheim solution, then the Mandl-Volek refinement has to be used for water condensation zone correction. The thermal efficiency for this particular case can be calculated as:

$$Eh = \frac{\xi_s/\theta - MVT}{\tau/\theta} \tag{2.11}$$

where:

$$MVT = \sqrt{\frac{\epsilon}{\pi}}\left(\beta + \frac{\epsilon e^{\tau/\theta}}{3} \operatorname{erfc}\sqrt{\frac{\tau}{\theta}} - \frac{\epsilon}{3\sqrt{\frac{\pi\tau}{\theta}}}\right)$$

$$\beta = \left(1 + \frac{H_{wv}X_l}{c_w \Delta T}\right)^{-1}$$

$$\epsilon = \frac{\tau}{\theta}\,(1 - t_c/t)$$

t_c = a critical time

The calculated thermal efficiency (Eh) substituted into equation (2.4) and the oil-steam ratio can be obtained as before in equation (2.7c).

2.2.4 Production rate and cumulative production calculation

When a one-dimensional, analytic technique is considered for predicting oil recovery by hot water or steam flooding, the Shutler method[59] (1969) has been used in several publications. This method is no other than the Buckley-Leverett frontal flow calculations. In a very viscous oil, the steam channels through the reservoir usually overlying the oil column, and sweeps or drags the underlying oil to the producer (Van Lookeren,[65] 1977; and, Doscher et al.,[21] 1982). Frontal drive displacement calculations would not be appropriate for heavy oil recovery. However, the actual dynamics at the steam-oil interface controls the mobilization of the oil. It is the viscosity of the oil at the steam temperature that affects the production rate of a steam drive, except when the oil viscosity has been decreased to a sufficiently low level. Then frontal displacement may occur. In addition, relative permeability is the critical data required for the Buckley-Leverett calculations. The given PDS reservoir data or other published data are commonly lacking in the relative permeability data. Therefore, the Shutler method is abandoned in this performance model. In the previous sections, the steam-oil interface relationships and the viscosity of the oil have been incorporated into the formulations, such as oil-steam ratio. Therefore, the oil-steam ratio can be used for production rate and cumulative production calculations. The equations are listed as follows:

Cumulative production:

$$Np = \sum_{c=1}^{c=t_f} R_{os} * M_s * t_c \tag{2.12}$$

Production rate: $q_o = N_p/t$ (2.13)

where:

N_p = cumulative production, bbls
R_{os} = oil-steam ratio, bbl/bbl
M_s = steam injection rate, B/D
t_c = production time period, days
q_o = production rate, B/D

There are several criteria to stop the steam drive process. Many operators have found that the economic limit of the oil-steam ratio varies between 0.11 to 0.17 (steam-oil ratio = 6 to 9 bbl/bbl) (Williams et al.,[69] 1980). The other criterion is the ultimate recovery of the reservoir. In this model, the program is assigned to terminate if either the oil-steam ratio falls below 0.11 or the ultimate recovery is reached. In this case, this steam drive performance model is competitive with other existing models.

2.2.5 Projection of the pilot test results to the whole reservoir

An inverted 5-spot, 5-acre pattern pilot test was simulated in the steam drive performance model. While the results of the pilot test are encouraging, this 5-acre flood pattern would be extended for the entire reservoir. The designed parameters have remained the same because the reservoir is considered to be in a homogeneous condition, e.g., injection rate, injection pressure and oil-steam ratio.

In order to project the pilot results for the whole reservoir, the following parameters are evaluated for references:

(i) Evaluate the possible maximum number of flooding patterns: inverted 5-spot, 5-acre pattern has one injection well per pattern; therefore, we can obtain the total number of injection wells as:

$$Iinj = \frac{\text{Entire reservoir area, acres}}{\text{5-acres/pattern}} \qquad (2.14)$$

(ii) Project the cumulative production, oil-steam ratio, and cumulative steam requirement. The cumulative production is evaluated as:

$$CN_p = 7758\ (AE)(VTSW)(AXh)(\Phi)(S_o - S_{or})/B_{oi} \quad (2.15)$$

The steam requirement is evaluated as:

$$V_s = m_s \times Iinj \quad (2.16)$$

The cumulative oil-steam ratio is evaluated as:

$$R_{os} = CN_p/V_s \quad (2.17)$$

where:

- AE = area sweep efficiency, fraction
- VTSW = vertical sweep efficiency, fraction
- A = entire reservoir area, acres
- h = formation thickness
- CN_p = projected total production of a whole reservoir, bbls.
- m_s = steam injection rate, B/D
- V_s = total steam injection rate, B/D

The author searched through the latest publications pertaining to steam drive process field reports, and 45 steam drive process field cases were selected from the literatures[2, 35]. Only 42 field cases passed the screening criteria in the steam drive performance model. The pilot test of each field case was projected to the whole reservoir evaluation. A list of the reservoir evaluations is attached in Appendix A.

2.3 Validation of the Steam Drive Performance Model

The one-dimensional, radial flow analytical model proved to be a complete and valid model for generating a data base for the regression modeling. The following arguments support this statement.

1. Van Lookeren's vertical conformance factor in the radial flow case is used for calculation of steam injection rate and injection pressure. The steam zone conformance factor solves the deficiency that the one-dimensional, analytical model is good for only thin layer formation. Also, the maximum steam injection rate and injection pressure can be used as the decision parameters. The optimization model evaluates how far the designed parameters can be achieved.

2. This model uses the Marx and Langenheim solution method to develop the calculation algorithm for the steam zone. In addition, the Mandl and Volek hot water bank refinement is used when the water condensation zone is significant for correction. In this case, a better accuracy of thermal efficiency and oil-steam ratio can be obtained.

3. From those 45 selected field reports, only 42 field cases passed the screening criteria for the steam drive process. The pilot simulation results were projec-

ted to the whole reservoir evaluation. Since the given field reports did not list out the detailed process data for comparison, the reservoir projection is evaluated individually. The evaluation indicates that most of the process parameters are in reasonable range for all the field cases (Appendix A).

4. The steam drive process parameters are calculated daily, but the results are printed in monthly records. The process monthly parameters form the data base which is input into the regression analysis procedure for the objective functions formulation.

5. In comparison with other similar steam drive simulation models, this one-dimensional, analytical simulation model does as good a job as the other multi-dimensional simulation models. This model needs less computer time, and a lot less data, particularly, the well-to-well data.

The steam drive performance model is outlined in the following flowchart (Fig. 2.3) and the program listing is attached in Appendix A.

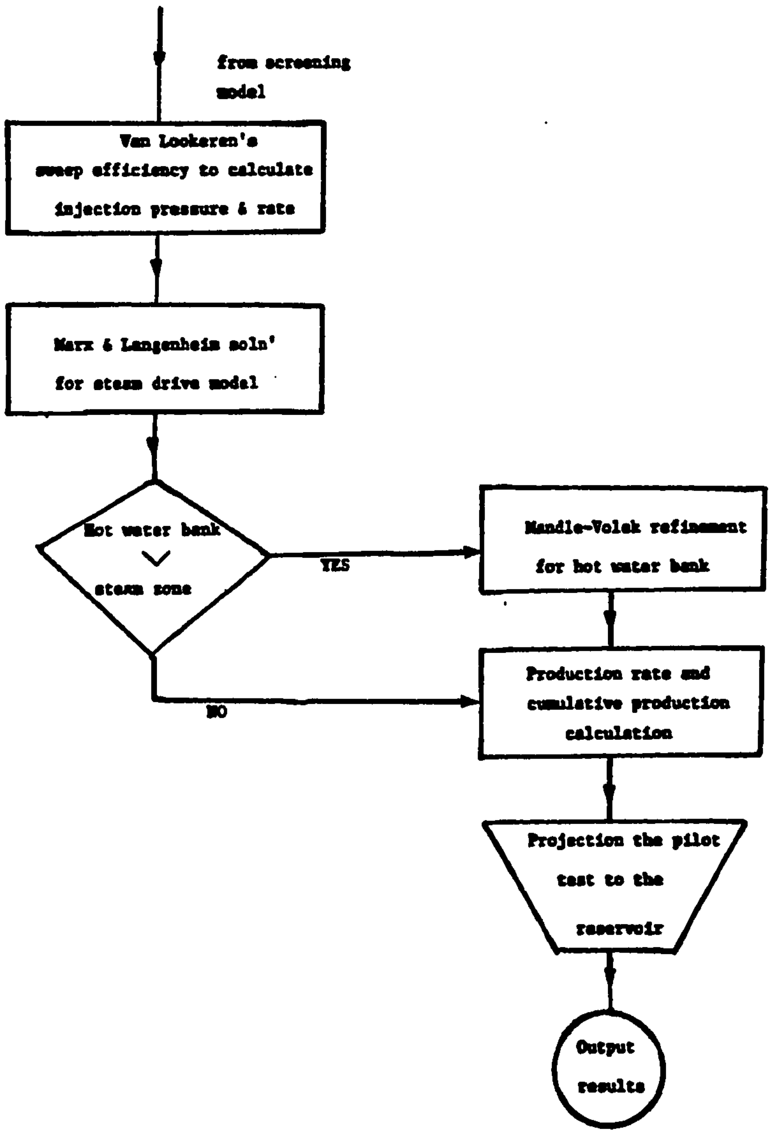


Fig. 2.3 Steam drive performance model

2.4 In-situ Combustion Performance Model

Engineering calculations for in-situ combustion are often made with the assumption that oil is recovered only by frontal displacement from the sand volume burned (Wilson,[70] 1965). Both laboratory combustion tube runs and field applications indicate that oil is recovered more rapidly in the early life of burns that have low initial gas saturations than is indicated by simple frontal displacement. Additional oil is recovered early from the unburned volume, ahead of and adjacent to, the burned volume. Recognition of the actual behavior of the combustion oil recovery process led to the development of a method called "oil-recovery/volume-burned" (Gates and Ramey,[29] 1980) as opposed to the older "frontal displacement" method. Ideally, both the frontal displacement calculation and oil-recovery/volume-burned method have the same total oil recovery and total air required at 100% volume burned, but the oil-recovery/volume-burned method indicates that considerably less air may be required at intermediate stages of in-situ combustion. Therefore, the new method has a better prediction of oil recovery than the frontal displacement method.

The modified oil-recovery/volume-burned method can be used to make accurate engineering and economic evaluations for the design and monitoring of in-situ combustion projects. An algorithm based on this method is programmed to provide a quick estimate of the oil recovery, air-oil ratio, oil producing rate, cumulative air requirement, air injection rate, and injection pressure.

2.4.1 Oil recovery/volume burned method

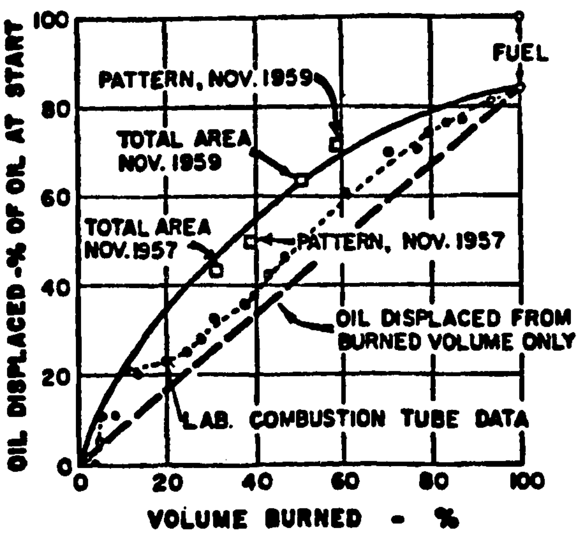


Fig. 2.4 Oil Displaced % Vs Volume Burned

(Adapted from Gates & Ramey)

The above figure is a graph of oil displaced vs. volume burned for both laboratory and field combustion experiments (Gates and Ramey,[28] 1958). The horizontal axis represents the percent of the combustion tube's total length travelled by the combustion front in the laboratory or percent of the total pattern volume burned in the field. The percent of total oil displaced is graphed on the vertical axis and differs from the original oil in place by the amount of oil consumed as fuel.

The straight, heavy-dashed line represents the amount of oil displaced from the burned volume only. However, the data taken in both the laboratory and the field show higher oil recovery (represented by the short-dashed line through the data points) and, therefore, a lower air/oil ratio than indicated by the straight, heavy-dashed line. This difference appears to be due to the oil recovery mechanisms of in-situ combustion which affect oil movement ahead of the burning front. These mechanisms include hot water, gas and steam drive, vaporization, miscible displacement, expansion, and gravity drainage. The example cited in the above figure assumed zero gas saturation.

Similar curves can be obtained for different gas saturations. Obviously, a high gas saturation would require a longer fill-up time and less recovery. Figure 2.5 shows this behavior for several combustion tube runs using San Ardo crude oil. The vertical axis is normalized with respect to consumed fuel to yield total oil displacement to total volume burned. As is shown at the higher gas saturations, the oil recovery curve is straighter. These results also match those previously obtained by Gates and Ramey which are graphed in Figure 2.6. Hence, the field

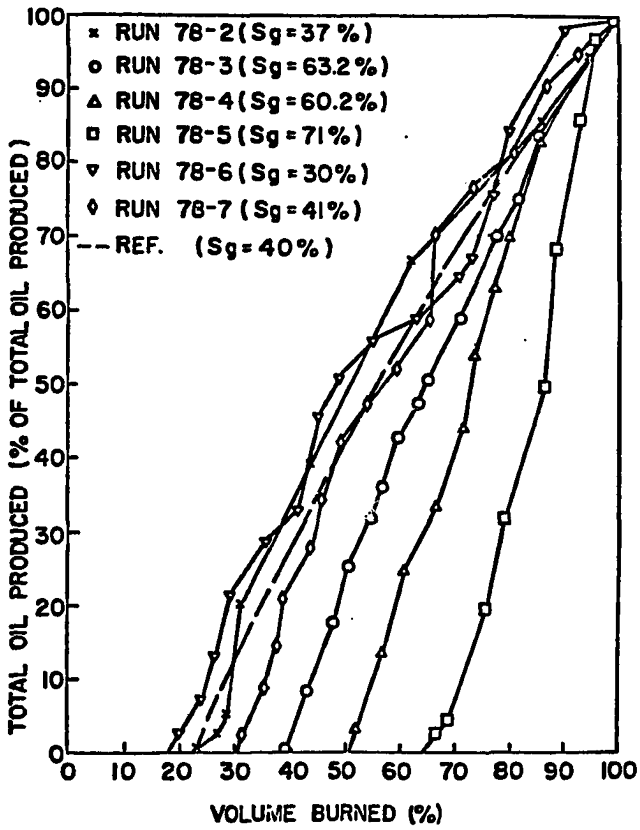


Figure 2.5 Oil recovery vs. Volume Burned for Laboratory Combustion Tube Runs (Adapted from Gates and Ramey)

and laboratory data correlations were combined and used for predicting the oil recovery for in-situ combustion process. These curves are applicable to most heavy oil fields similar to the South Belridge field.

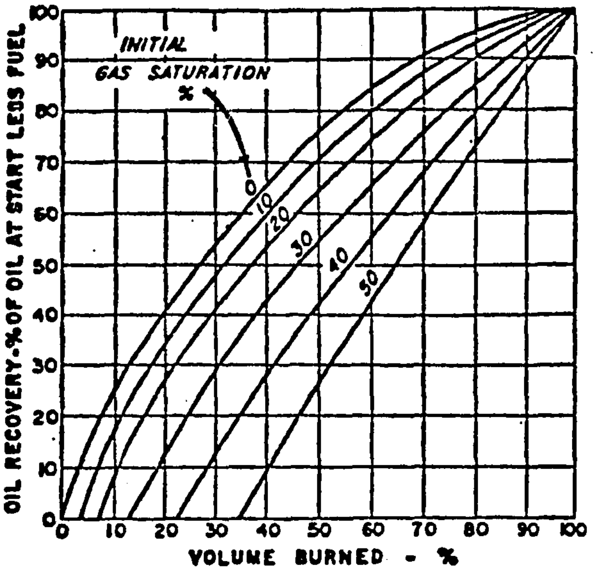


Fig. 2.6 Oil recovery vs volume burned
(Adapted from Gates and Ramey)

2.4.2 Modeling Algorithm

This modeling algorithm is completed in five steps. The first four steps estimate the basic fluid properties required for the oil recovery / volume burned method. The application of the method is illustrated in the fifth step. Since this method is represented in a correlation graph, a curve-fitting procedure is applied to obtain the correlation equation for the model formulation. The curve-fitting procedure is shown in Appendix B.

1. Estimation of oil viscosity at reservoir conditions:

Most of the reported oil viscosity data is either at the stock tank temperature or without temperature indication. This type of data cannot be used for reservoir modeling study, however, the oil viscosity can be obtained at the reservoir conditions by using the Beggs and Robinson correlations,[9] 1975.

a. Calculation of dead oil viscosity, cp

$$Z = 3.0324 - (.02023 * API) \quad (2.18a)$$

$$Y = 10 ** Z \quad (2.18b)$$

$$X = Y/(T_r ** 1.163) \quad (2.18c)$$

$$VISD = (10 ** X) - 1 \quad (2.18d)$$

b. Calculation of live oil viscosity, cp.

The gas-oil ratio for heavy oil fraction is usually not reported because the gas-oil ratio is very hard to measure. Therefore, the gas-oil ratio is estimated for heavy oil fraction by using Chew and Connally correlation chart (Figure 2.7).

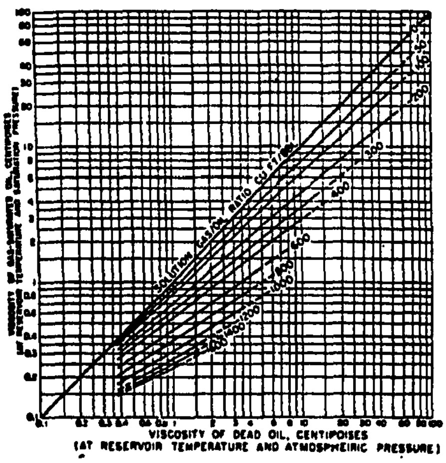


Figure 2.7 Chew and Connally Correlation Chart
(From Crafts & Hawkins)

$$\text{Ratio (R)} = \frac{\text{Reported Viscosity}}{\text{Dead Oil Viscosity (VISD)}} \quad (2.19)$$

If $R \leqslant 0.7$ set GOR = 200

If $0.7 < R < 0.8$ set GOR = 100

If $0.8 < R < 0.9$ set GOR = 50 and

If $R \leqslant 0.9$ set GOR = 2

A = 10.715/(GOR + 100) ** .515 (2.20a)

B = 5.44/(GOR + 150) ** .338 (2.20b)

VISO = A * (VISD ** B) (2.21)

where:

VISD = dead oil viscosity, cp
VISO = live oil viscosity, cp
GOR = gas-oil ratio
API = oil gravity
T_r = reservoir temperature, ^oF

X,Y,Z,A,B, are constants for correlation

2. Estimation of fuel concentration:

In the absence of other data, fuel concentration can be estimated by using correlation equations developed by Chu[13] from the actual field data:

$$C_f(Lb/Cf) = -.12 + .00262h + .000114K + 2.23S_o + .00242\ Kh/\mu_o - .0001897Z - .0000652\mu_o \quad (2.22)$$

3. Estimation of air-fuel ratio and air-sand ratio:

Since this oil recovery/volume burned chart is plotted with South Belridge crude, the same crude oil combustion tube results are used for the calculations (Williams et al.,[59] 1980).

Gas composition: CO(wt %) 1.1

CO_2(wt %) 15.2

O_2(wt %) 0.2

N_2(wt %) 83.2

Hydrocarbon ratio:

$$H/C = \frac{4x(.2658N_2\%-CO_2\%-O_2\%-.5CO\%)}{(CO_2\% + CO\%)} \qquad (2.23)$$

$= 1.513$

Air-fuel ratio (scf/lb):

$$AFR = \frac{479.7\ N_2\%}{(CO_2\%+CO\%)\ (12+H/C)} \qquad (2.24)$$

$= 181.2$ scf/lb

Air-sand ratio (Mscf/acre-ft):

$$ASR = AFR \times C_f \times 43.56 \qquad (2.25)$$

4. Cumulative air requirement (MMscf/acre-ft) is also calculated by using Chu's correlation equation.

$$CAI = 4.72+.03656h+9.996S_o+.000691K \qquad (2.26)$$

5. Oil recovery/volume burned method is applied to evaluate the performance of in-situ combustion process.

a. Since the oil recovery can be interpreted as the intercept and minimum deviation of the curve, equation (B-5) is written as equation (2.27).

$$Rec\ (\%) = 100x + (y)\ (MD) \qquad (2.27)$$

Oil-in-place (BBL/acre-ft) before the process is estimated as:

$$N_{pi} = \frac{7758 \times S_o \times \phi}{B_{oi}} \quad (2.28a)$$

where B_{oi} is assumed as 1 for heavy oil.

And the fuel burned (BBL/acre-ft) can be calculated in the following equation

$$FB = C_f \times \frac{43,560}{350} \quad (2.28b)$$

Then, the net recovery (bbl/acre-ft) is obtained in equation 2.28c after subtracting the fuel burned oil-in-place N_{pi} :

$$Reo = N_{pi} - FB \quad (2.28c)$$

Also, the cumulative production (Mbbl) can be calculated as follows:

$$N_p = \frac{(Rec\%) \times (Reo) \times (A) \times (h)}{100} \quad (2.28d)$$

And the current air-oil ratio (AOR) and cumulative AOR (Mscf/bbl) are calculated in equations 2.29a, b, c:

$$\text{Current AOR} = \frac{ASR}{\frac{dRec\%}{dV_B} \times Reo} \quad (2.29a)$$

$$AOR = \frac{ASR}{Slope \times Reo} \quad (2.29b)$$

$$\text{Cumulative AOR} = CAI \times 1,000 / N_p \quad (2.29c)$$

b. Assuming 55% aerial sweep and 5-acre inverted 5-spots flooding pattern, the author estimates the injection rate, production rate, injection pressure, and production time in the following calculations:

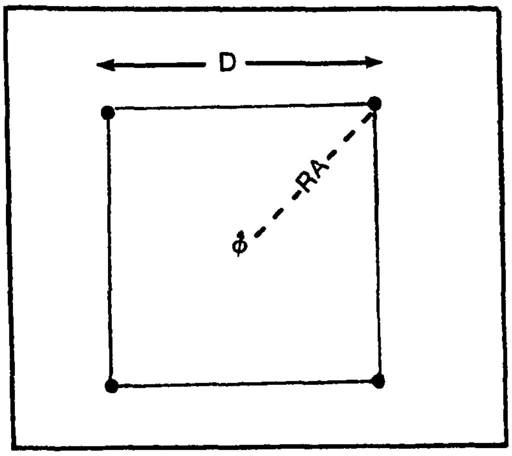


Figure 2.7 Inverted 5-spots flooding pattern

The flooding area Ap is given 5-acre and the radius is calculated in equations 2.30a, b:

$$D = \sqrt{5 \times 43{,}560} = 466.7 \text{ ft} \quad (2.30a)$$

$$RA = \sqrt{2 \times (D/2)^2} = \sqrt{2 \times (466.7/2)^2} = 330 \text{ ft} \quad (2.30b)$$

And the air requirement (scf/cf) is estimated as:

$$A = \frac{(CAI)(1{,}000)}{43{,}560} \quad (2.31)$$

The maximum initial injection (Mcf/D) rate can be calculated as:

$$q_{max} = (i_D)x(A)x(V_i)x(RA)x(h) \quad (2.32)$$

The dimensionless flow rate i_D is obtained as 4.77 for 55% aerial sweep; the corresponding initial air flux (V_i) is obtained as 0.125 ft/D of burning front advance. Both parameters are the experimental results from potentiometric model studies[71].

Then the maximum production rate can be obtained by assuming the producing rate is about the same rate as oil displacement. Therefore, the actual producing rate(B/D/well) can be calculated for an individual well in one pattern:

$$q_{prod} = \frac{q_{max}}{4(AOR)} \tag{2.33}$$

The production time (days) required for the process can also be estimated:

$$t = \frac{CAI}{q_{max}} \times 1{,}000 \tag{2.34}$$

The maximum injection pressure can be calculated after the time required to reach maximum injection rate is obtained. The time (days) can be estimated in equation (3.35a):

$$t_1 = \frac{q_{max}}{2hAV_{max}^2} \text{, days} \tag{2.35a}$$

where:

$V_{max} = 0.5$ ft/D ,

which is also estimated from the potentiometric model (Wilson et al.,[71] 1966)

The radial flow injection pressure has developed as follows:

$$P_{max}^2 = \left\{ P_w^2 + \left(\frac{q_{max} \mu_a T_f}{0.703 \ Kah} \right) \left[\ln \left(\frac{RA^2}{r_w \ V_{max} t_1} \right) - 1.238 \right] \right\} \quad (2.35)$$

The detail derivation of the above equation is shown in the Appendix B, see equation B-10. The maximum pressure P_{max} can be obtained by substituting the parameters into the equation 2.35.

where:

μ_a = 0.0186cp for air
K_a = 25 md for air
r_w = 0.276 ft for wellbore radius
T_f = formation temperature ^oF

2.4.3 Projection of the pilot test results to the whole reservoir

An inverted 5-spot, 5-acre pattern pilot test was simulated in the performance model. The results include cumulative production, cumulative air-oil ratio, air requirement and design parameters such as injection rate, injection pressure, and production rate. The design parameters remain the same if the design pattern is not going to change for the entire reservoir. If the flood pattern is changed, then the simulation model will have to be modified slightly.

The results of the pilot is encouraging. We would like to have this 5-acre flood pattern extended for the entire reservoir. The design parameters remain the same because we also consider the reservoir to be in a homogeneous condition. The cumulative production, cumulative air-oil ratio and air requirement need to be evaluated for the entire reservoir. The best way to evaluate the entire reservoir is by projecting the pilot test results.

a). Evaluate the possible number of flooding patterns:

Inverted 5-spot, 5-acre pattern has one injection well per each pattern; therefore, we can obtain the total number of injection wells such as:

$$Iinj = \frac{\text{Entire reservoir area, acres}}{\text{5-acre}} \tag{3.36}$$

b). Project the cumulative production, air-oil ratio, and air requirement.

The cumulative production per pattern is

$$N_p = Rec \times Reo \times A_p \times h/100 \tag{2.28}$$

and the entire reservoir can be evaluated as:

$$TN_p = N_p \times \text{number of patterns}$$

$$= N_p \times Iinj \tag{2.37}$$

Similarly, air-oil ratio is evaluated as:

$$TAOR = \frac{V_B \times ASR \times Iinj}{TN_p \times 100} \text{ (Mscf/bbl)} \tag{2.38}$$

and air requirement is evaluated as:

$$TCAI = \frac{(TAOR \times TN_p \times Iinj)}{1{,}000} \text{ (MMscf)} \tag{2.39}$$

Where:

V_B = vol. burned, %
ASR = air-sand ratio, Mcf/acre-ft
TN_p = cumulative production for the active reservoir, bbls
TAOR = air-oil ratio for the entire reservoir, Mscf/bbl
TCAI = air requirement for the active reservoir, MMscf
Iinj = no. of injection patterns

The author searched through the latest publications about the in-situ combustion process field reports, and 35 in-situ combustion process field cases were selected from the literatures[2, 35]. Only 32 field cases passed the screening criteria in the in-situ combustion performance model. The pilot test of each field case was projected to the whole reservoir evaluation. A list of the reservoir evaluations is attached in Appendix B.

2.5 Validation of In-Situ Combustion Performance Model

1. The curve-fitting procedure is used to interpolate the oil recovery/volume burned method developed from the actual field test and laboratory test results. This model used the crude oil sample for the oil recovery/volume burned method fitting the heavy oil reasonably well because the South Belridge Field Crude (API = 15^o) is at the mid-range of the heavy oils.
2. The performance model acts as a high efficiency process design. Therefore, the purpose of this performance model can be used for the process evaluation. The process design parameters are obtained instead of the

inherited bad field report data.

3. From those 35 selected field reports, only 32 field cases passed the screening criteria for the in-situ combustion process. The process parameters are calculated daily but the results are printed in the monthly records. The process monthly parameters form the data base which is input into the regression analysis procedures for the objective functions formulation.

4. Since the oil recovery/volume burned method is developed from the dry forward combustion process, the process evaluation is limited only to dry forward combustion. In this way, we can have a unique process evaluation for all the reservoirs.

The in-situ combustion performance model is outlined in the following flowchart (Figure 2.8). This performance model is the same program listing as the steam drive performance model shown in Appendix A.

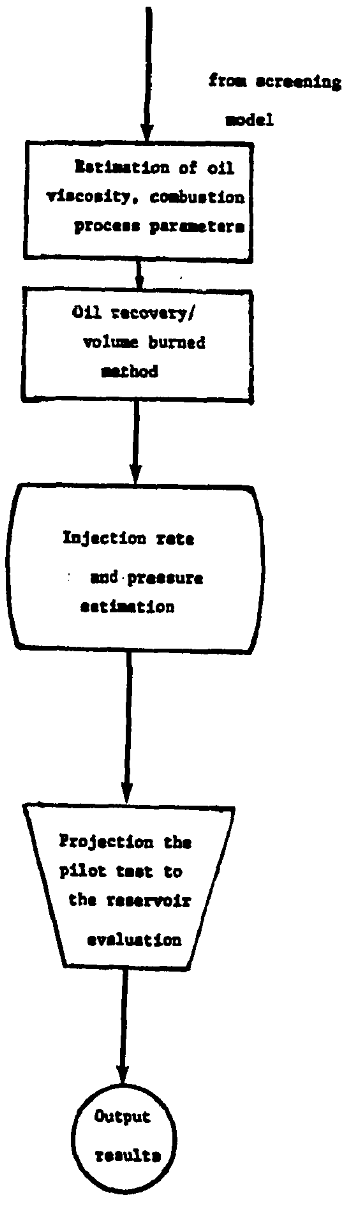


Fig. 2.8 Flowchart for in-situ combustion model

2.7 Petroleum Data System Data Applications

The Petroleum Data System (PDS) is a modern computer information system designed to store a large amount of petroleum-related information for the U.S. and Canada. Developed and maintained by the Office of Information System Programs, University of Oklahoma, the PDS consists of 12 data bases, each consisting of many kinds of oil- and gas-related data. It also contains data and parameters on fields and pools in average or aggregate values. It does not contain information from individual wells, with the exception of discovery well data. Furthermore, the PDS data includes crude oil analysis, gas analysis, brine analysis, reserves, listing of production, and information on federal offshore leases. In general, PDS data are nonproprietary information on geology of reservoirs, reservoir characteristics, status of reservoir, fluid production type, and fluid properties. This information was gathered from the following sources:

1. International Oil Scouts Associations's Review
2. Journal publications of the SPE, AAPG, and other professional groups.
3. Annual state regulatory agency reports, such as the Texas Railroad Commission, and the Oklahoma Corporation Commission
4. The State Geologists Reports.
5. The Canadian Provinces Conservation Boards
6. The Canadian Gas Conservation Boards
7. Federal Power Commission

8. Federal Energy Administration
9. US Department of Energy
10. US Geological Survey
11. Bureau of Mines Reports
12. Others

In this dissertation, the author used only the data files from data bases such as TOTL and SECR. The TOTL data base consists of the U.S. oil and gas data files. The files provide publicly available information for all fields and reservoirs. Data elements contained in the records may include identification of fields and reservoirs by name and code, location, and present producing status. Geological and engineering data may consist of the name and age of the producing formation, discovery method, trap type, drive lithology, depth, acreage, spacing, thickness, porosity, permeability, gravity, pressure, and temperature. The author requested a list of PDS files relating to those 100 steam drive field reports and 40 in-situ combustion field reports from the Oil and Gas Journal Annual Production Reports,[2] 1982 and SPE Improved Recovery Report,[35] 1975-1981. With the help of those PDS files, 45 steam drive field cases and 35 in-situ combustion field cases were manually validated and screened for the thermal recovery pilot test candidates. In addition, the author requested some files from the SECR data base to confirm the reservoir conditions after the waterflooding, e.g., fracture, corrosion, and sand problems.

The major portion of this research work is done on minicomputers, such as VAX 11/780 and PDP 11/70 at Engineering Computer Network (ECN). All the FORTRAN programming, error editing, data analysis, and word processing were done on the ECN cathod-ray-tube (CRT) terminal. The only opportunity to access the mainframe IBM computer is by using the SAS package and its graphic applications. The author found of accessing the ECN system with a CRT terminal to be fast, convenient and economical. The great growth of the minicomputer and microcomputer makes computer research easier than before.

III. REGRESSION MODELING OF THE THERMAL PROCESSES

3.1 Introduction

Performance modelings of two processes do not lend themselves to simple analytical expressions in terms of the process variables, as required by most mathematical optimization techniques. In order to acquire simplified and analytical expressions, known as objective functions in optimization terminology, four different terms were selected. These expressions are best described the process: oil recovery, air injection rate, air injection pressure, and oil production rate for the in-situ combustion process. Similarly, we can select oil recovery, steam injection rate, steam injection pressure, and oil production rate for steam drive process.

One approach to incorporating the functional equations of the process relationships into simplified and analytical expressions is by using regression analysis. Regression analysis formulates the objective functions in a better form than correlations. The advantage of using regression over correlation is that the regression method gives numerical estimates that are suitable for use in predicting future values of the dependent variable with knowledge of the independent variable. The exact functional equations of process relationships in regression analysis are rarely deduced theoretically. They are usually determined empirically. The simplest functional equation is a linear equation, which is the easiest to estimate and apply. Two criteria should be considered in choosing functional equations:

i) We should rely upon the reservoir engineering theory as much as possible in choosing functional equations.

ii) A good model should always have good predictive power.

The following two sets of regression models are formulated for the in-situ combustion process and the steam drive process. In the in-situ combustion model, about 12 different variables are considered for the independent variables. The oil recovery, injection rate, injection pressure, and production rate are dependent variables. All the above variables are simulated process parameters. Thus, the regression model is characterized by having four functional equations. The equations in a system are interdependent, such that dependent variables from one eouation appear as regressors in other equations.Then, the ordinary least squares estimates can be inconsistent. Researchers (Pindyck et al.[58], 1976; and, Theil[64], 1971) working with econometric models have developed several techniques to produce consistent estimators for this kind of model. A similar regression model was formulated for the steam-drive process as well. A flow chart outlines the scheme of the modeling stages which is shown in Figure 3.1.

This phase of work was accomplished by using a general purpose statistical computer library package known as the Statistical Analysis System (SAS). The author used the SAS package for statistical analysis because all the procedures available in SAS may be used interactively. The advantages of using the SAS can be enhanced for the following reasons (Winters[72], 1982):

i) The powerful macro and other programming capabilities make the SAS usable as a programming language in addition to statistics.

ii) It has an excellent graphics capacity for both data exploration and data reporting.

This chapter is written in three sections according to the statistical analysis procedures: variables selection procedures, problems of linear regression analysis procedures, and system regression analysis procedures.

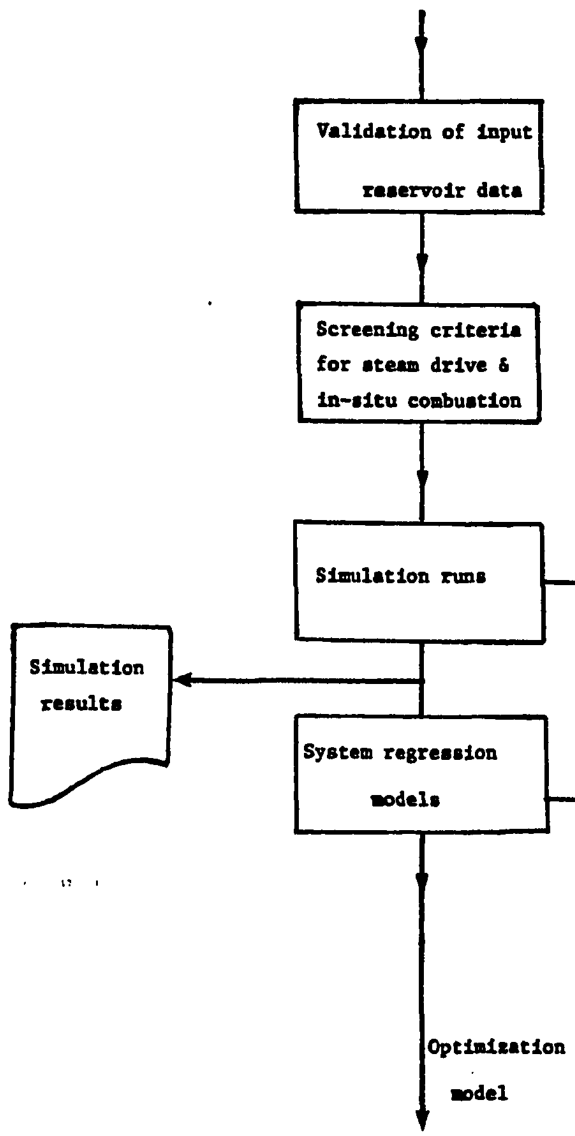


Fig. 3.1 Scheme of the modeling stages

3.2 Variables Selection Procedures

The variables selection procedures are important procedural steps for the formulation of the regression equations. The regression equations are usually empirical. The equations would be well "formulated" if they are based on reservoir engineering principles. Regression equations are preferable in the linear functions. However, regression modeling is a complex process and several statistical problems have to be cleared up before we can be sure of the validation of the regression equations (Freund et al.[27], 1981). The formulations of the regression equations can be achieved with different statistical analysis procedures.

3.2.1 RSQUARE procedure

The selected parameters for the independent variables are closely related to the dependent variable in the engineering relation. The RSQUARE procedure performs all possible regressions for one dependent variable and also for a collection of independent variables, printing the R-square value for each model.

i) In the steam drive regression model, the different equations can be formulated as follows:

The oil recovery (REC) includes the oil-steam ratio

(ROS), production rate (QNP), and oil viscosity (VISO) terms in the regression equation. These three variables are included in all the model combinations. The thermal efficiency (EH), oil saturation porosity (PIS), steam temperature (TS), and some other independent variables may also relate to the oil recovery.

The formulation can be programmed in the SAS as follows:

```
PROC RSQUARE DATA = ORIGINAL;
  MODEL REC = ROS QNP VISO TS VS EH NP TRS PIS
              /INCLUDE= 3;
```

The final formulation includes ROS,QNP,VISO,TS,EH, and PIS at 72% R-square.

Similarly, the steam injection rate (QINJ) dependent variable includes the cumulative steam injection (VS), injection pressure (PINJ), cumulative production (NP), oil steam ratio (ROS), transmissibility (TRS), oil saturation porosity (PIS), and other parameters as the independent variables. From the RSQUARE procedure, QINJ can be formulated with VS, PINJ, NP, ROS, TRS, and PIS at 86% R-square. The oil producing rate (QNP) is formulated with EH, ROS, REC, TS, and PIS as independent variables 97% R-square. Finally, the injection pressure (PINJ) can be formulated, from the RSQUARE procedure, with TS, QINJ, VS, and REC as indenpentent variables at 99% R-square.

ii) In the in-situ combustion regression model, the different equations can be formulated as follows:

The oil recovery (REC) is also closely related to air-oil ratio (AOR), oil producing rate (QNP), oil viscosity (VISO), and fuel burned (FB). These four variables are included in all the model combinations. The cumulative air requirement (CAI) and cumulative production (NP) also relate to the oil recovery. The formulation can be programmed in the SAS as follows:

```
PROC RSQUARE DATA ORIGINAL;
     MODEL REC = AOR QNP VISO FB CAI NP
                 /INCLUDE = 4;
```

The final formulation includes AOR,QNP,VISO,FB,CAI at 98% R-square.

Similarly, the air injection rate (QINJ) can be related to injection pressure (PINJ), cumulative production (NP), cumulative air requirement (CAI), air-oil ratio (AOR), air-sand ratio (ASR) and oil viscosity (VISO). From the RSQUARE procedure, QINJ can be formulated as PINJ, NP, CAI, AOR, ASR, and VISO as independent variables at 73% R-square. The oil producing rate (QNP) can be formulated, from the RSQUARE procedure, with VB, REC, FB, PINJ, VISO and NP as independent variables at 79% R-square. Finally, the air injection pressure (PINJ) can be formulated with QINJ, REC and CAI as independent variables at 53% R-square.

The RSQUARE procedure gives a general idea of what variables should be selected for the linear equations based on the engineering principles. The best combination of the independent variables has to be refined in the STEPWISE procedure. However, the RSQUARE is very useful when we want to investigate the general behavior of many regression equations (SAS User's Guide[61], 1979).

3.2.2 STEPWISE procedure:

STEPWISE is most helpful for statistical analysis because it can give you insight into the relationships between the independent variables and the dependent response variables. STEPWISE uses the selection strategies in choosing the variables for the models it considers. Also, when STEPWISE evaluates a model, it prints a complete report on the regression. In this procedure, there are several selection strategies available (SAS User's Guide): forward selection (FORWARD), backward elimination (BACKWARD), stepwise (STEPWISE), maximum R-square improvement (MAXR), and minimum R-square improvement (MINR). But, the author only applied STEPWISE, MAXR and BACKWARD selection strategies since three selection strategies were sufficient to make an intelligent decision on the regression equations.

The maximum R-square improvement (MAXR) technique, developed by James H. Goodnight (SAS User's Guide), is considered superior to the STEPWISE technique, and is almost as good as all possible regression. Unlike the

BACKWARD and STEPWISE techniques, this method does not settle on a single equation. Instead, it looks for the "best" equation.

The BACKWARD selection strategy is a backward elimination technique. It starts with all the variables, then each step removes the least significant variable until all variables are significant at the limit to stay. The STEPWISE selection strategy is the forward and backward technique. It starts out and acts like the FORWARD method. However, as each variable is entered, the procedure does a backward elimination of any variables that have become non significant. The author uses the results of these two techniques as additional references, with the MAXR technique.

In the steam drive process, three selection strategies were used in coordination to find the "goodness-of-fit" of the regression equations. The final regression equations are listed as follows:

Oil recovery (REC): (85% R-square)

= f(ROS,QNP,VISO,VS,TS)

Steam injection rate (QINJ): (86% R-square)

= f(NP,VS,PINJ,ROS,VISO,TRS,PIS)

Oil production rate (QNP): (99% R-square)

= f(EH,ROS,REC,NP,VS,VISO,TRS,PIS)

Injection pressure (PINJ): (93% R-square)

= f(REC,VS,VISO,TS,ROS,NP)

The formulation is also agreeable for RSQUARE procedure prediction.

In the in-situ combustion regression model formulation, the procedures are the same as the steam drive regression model formulation. The in-situ combustion regression models formulation again is based on the process mechanism. Since the RSQUARE, MAXR and other procedures interpretations are similar to the steam drive regression modeling, the author prefers to summarize the interpretations as follows:

Oil recovery (REC): (97% R-square)
=f(AOR,QNP,VISO,FB,CAI)

Air injection rate (QINJ): (73% R-square)
=f(PINJ,NP,CAI,AOR,ASR,VISO)

Oil producing rate (QNP): (80.3% R-square)
=f(VB,REC,PINJ,CAI,VISO,NP)

Injection pressure (PINJ): (52.5% R-square)
=f(QINJ,REC,CAI,VISO,VB,NP,QNP)

The above formulations are generally true, but they are not free from statistical problems; such as multicollinearity and outliers. These problems can be handled through the procedure REG which is discussed in the next section.

3.3 Problems of Linear Regression Analysis Procedures

In the last section, the formulation was based on the reservoir engineering principle and most of the variables were included in the regression model. However, a simple regression equation is always desirable because too many variables could cause statistical problems in the regression equations; such as the multicollinearity and outliers. These problems arise when a regressor variable is nearly a linear combination of other regressors, then the parameter estimate for it is not stable. A small perturbation of the data can lead to a large change in the estimates. When the data are not adequate to estimate the variables in the equation very precisely, we have two choices:

i). add more data, or,

ii) fit fewer variables in the equation.

For the first choice, it is almost impossible to collect more data because of the availability of the enhanced oil recovery field data, and the additional data will worsen the outlier problem. Therefore, we try to fit fewer variables into the model.

In the steam drive regression model, some of the variables are dropped from the equations if these variables are linear combinations of other regressors. The oil recovery (REC) is a linear combination with oil saturation porosity (PIS); therefore, (PIS) is dropped from the oil recovery regression equation. The oil recovery (REC) can be further tested with procedure (REG) such as:

```
    PROC REG DATA = NEW1;
    ID OBS;
         MODEL REC           = ROS QNP VISO TS EH/ PIR CLI
                          CLM TOL VIF COLLIN INFLUENCE;
         OUTPUT OUT
                   OUT  =  CP=PRED L95=L95  U95=U95
                                            R=RESID;
```

Similarly, the steam injection rate (QINJ), injection pressure (PINJ), and oil producing rate (QNP) are being modified in the formulations.

To diagnose collinearity, we go through the printout to see if any of the last few comments have very high condition indices, since the condition index is a measure of how depleted each component is. If two or more variables account for a high proportion of their variance on the same weak component, then this is where the collinearity problem lies. The condition index of over 7,000 and the loading of over 99.9% of the variance is strong evidence for diagnosis of collinearity. Luckily, we do not have such a high condition index in any of the regression equations after the modification. Therefore, the new steam drive regression model is established as follows:

Oil recovery:	REC =f(ROS,QNP,VISO,TS,EH)
Steam injection rate:	QINJ =f(VS,NP,PINJ)
Oil producing rate:	QNP =f(EH,ROS,TS,NP,VISO)
Injection pressure:	PINJ =f(REC,VS,VISO,TS,NP)

In the in-situ combustion process, a similar treatment is applied for the regression equations formulations. The REG procedure is also used for checking out the statistical problems such as multicollinearity and outliers. Since a similar explanation can be applied for the in-situ combustion statistical problems, a simplified version is written for the formulation:

Oil recovery: REC =f(AOR,QNP,VISO,FB,CAI)

Air injection rate: QINJ =f(PINJ,NP,CAI,AOR,ASR,VISO)

Oil producing rate: QNP =f(VB,REC,FB,PINJ,VISO,NP)

Injection pressure: PINJ=f(QINJ,REC,CAI,VISO,VB,NP,QNP)

For all the above regression equations, none of the variance inflation and condition index are significantly large, and they fall out of the range limits. Furthermore, the performance models have been screened through the input data. Therefore, there are no significant outliers in the steam drive process.

However, the formulations are not completed for both processes because some of the dependent variables in the equations are also the independent variable in other regression equations. This relationship among the variables will accumulate statistical errors. Therefore, the simultaneous equations regression technique has to apply for statistical analysis. This regression technique will be discussed in detail in the next section.

3.4 System Regression Analysis Procedures

From the RSQUARE, STEPWISE and REG procedures, we were only covering the formulation of the linear regression equations. The accuracy of prediction has not been considered. In this particular regression system, the model's dependent variables are also the independent variables of other regression equations; therefore, the interdependent relationships are established among the equations. These relationships cause more serious regression errors . Therefore, the regression equations in one system, such as the steam drive process, have to run simultaneously. The system regression modeling is always used in economic statistical analysis; hence, this regression modeling is called econometrics.

In the SAS package, the SYSREG procedure (SYStems REGression) is the regression technique; but this procedure has to be supplemented with other analytical procedures. Therefore, all the regression analysis procedures have to go through a number of steps.

3.4.1 Sorting the data by different timesteps

Since the performance models of two processes are being run in 12-month timesteps, the regression models are formulated for different timesteps. In this step, the models are formulated for different timesteps such as:

```
    DATA TIME1;
      SET ORIGINAL:
         IF TIME = 1 THEN OUTPUT TIME1;
    DATA ORIGM
      (RENAME = (VISO=Z1  EH=Z2  ROS=Z3  QINJ=Z4  QNP=Z5
         PINJ=Z6  REC=Z7  NP=Z8  VS=Z9  TS=Z10  TRS=Z11
              PIS=Z12));
                  SET TIME1;
```

3.4.2 Normalize all the variables into same magnitude

We begin our regression analysis by considering the units of all the variables. In Table 3.1, the steam drive parameters are listed out in the mean value.

Table 3.1 Mean of steam drive parameters

VARIABLE	LABEL	MEAN
R1	VISCOSITY(CP)	383.875909
R2	THERMAL EFF.(%)	98.727273
R3	OIL STEAM RATIO	0.670000
R4	STEAM INJ RATE(B/D/W)	992.727273
R5	PROD RATE(B/D)	650.929545
R6	INJ PRESS.(PSIA)	562.755227
R7	ULT RECOVERY(%)	23.454545
R8	CUM OIL PROD(MBBL)	39185.746136
R9	VOL STEAM REQD(MCF)	337517.272727
R10	STEAM TEMP(DEG F)	444.913409
R11	TRANSMISSIBILITY	2201.490000
R12	POROSITY*OIL SAT	2304.628409

The values have several degrees of magnitude difference. For example, mean value of volume steam required(MCF) is 1,000,000 difference for oil-steam ratio (B/B). It is necessary to put them into the same magnitude before we do the regression analysis; otherwise, there will be significant figure problems in the final results.

```
IF _N_ =1 THEN SET STDM:
  SET ORIGM:
     ARRAY ORIGI3  (I) R1-R13;
        ARRAY MEA13 (I)  M1-M13;
           ARRAY STDM13 (I) S1-S13;
             ARRAY ZVAL13 (I) Z1-Z13;
           DO I=1 TO 13;
        ZVAL13=(ORIG13-MEA13)/STDM13;
     END;
```

All the regression equations intercepts were being minimized to such a degree that they can be removed from the equations. The advantage is that they have no intercepts because the objective functions cannot have constant values in the equations; otherwise, the optimized results could be very misleading.

3.4.3 System Regression Modeling Technique

One system of simultaneous equations is used to model the behavior of each thermal recovery process. The SYSREG (SYStems REGression) is specialized in handling the linear system of equations. Like the other regression procedures, SYSREG estimates parameters in linear models by least squares. When there is a system of simultaneous equations for modeling the behavior of a process (Maddala[40], 1977), the dependent variables from one equation appear as regressors in other equations. Ordinary least squares (OLS) estimates can be inconsistent. Therefore, the three-stage least squares method is used.

In the system modeling, the independent variables are known as exogenous and the dependent variables are known as endogeneous. Since some of the variables are inter-dependent, the exogenous and endogenous variables are formulated into groups as in the steam drive process:

```
PROC SYSREG OUTEST=OPS;
BLOCK QNP QINJ REC TS = ROS VISO TS VS NP
                        TRS EH PIS REC QINJ QNP PINJ;
   PRODRATE:
      MODEL QNP=EH VISO TS REC PIS;
   STEAMINJ:
      MODEL QINJ=VS NP TRS;
   RECOVERY:
      MODEL REC=QNP ROS NP VISO PIS;
   INJPRESS:
     MODEL PINJ=TS VISO VS TRS;
```

A similar system model can be built for the in-situ combustion process:

```
PROC SYSREG OUTEST=OPS;
BLOCK REC QINJ QNP PINJ=VISO FB CAI NP AOR ASR
                         VB REC QINJ QNP PINJ PIS TRS;
   RECOVERY:
      MODEL REC = AOR PIS FB CAI;
   INJRATE:
      MODEL QINJ=PINJ VISO CAI NP ASR TRS PIS AOR;
   PRODRATE:
      MODEL QNP=VB REC PINJ CAI VISO NP;
   PRESSINJ:
      MODEL PINJ=CAI VISO VB AOR NP QNP TRS;
```

The results of the regression modeling are very encouraging. The weighted R-square for the steam drive process modeling system turned out to be in the 89% to 97% range and the weighted R-square for the in-situ combustion modeling was found to be in the 80% to 99.9% range.

3.4.4 Graph plotting of the regression models

Regression statistics are computed under the assumption that the model is correctly specified. However, this is not always true unless we have some means to check the accuracy of the models. The residuals show what remains after we tried to account for the behavior of the response with the model. When the data does not fit the model very well, the residuals show how the model failed. Sometimes the regression statistics indicates highly significant estimates, but a look at the residuals will reveal the deficiencies of the fit.

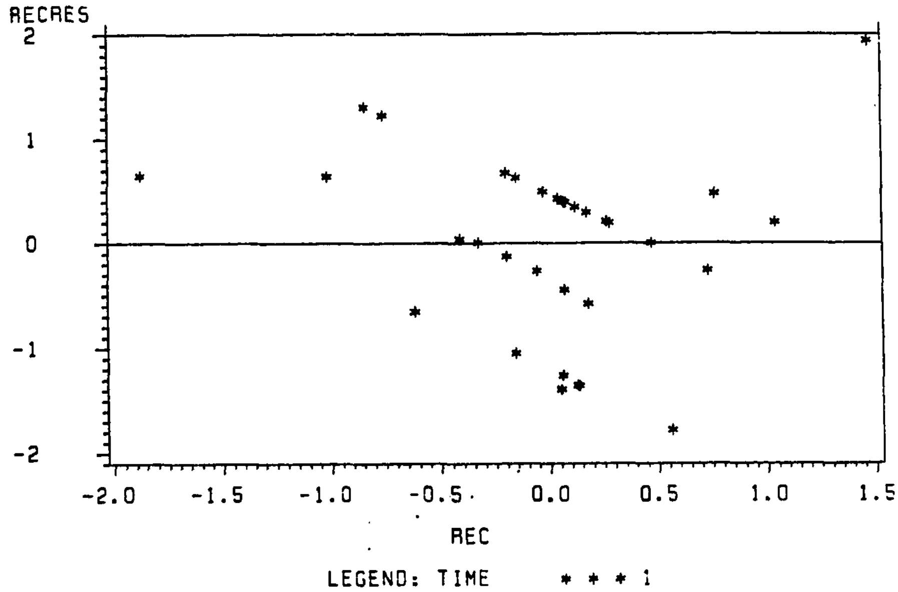
For example:

```
    PROC GPLOT;
       PLOT QNPRES*QNPHAT=TIME/VPOS=22 HPOS=100 VREF=0
                        HAXIS=-1.5 TO 1.5 BY .1;
         SYMBOL1 I=NONE V=STAR
              TITLE1  .C=5  .H=2  .F=TITALIC  RESIDUAL
                        VALUE VS PREDICTED VALUE;
```

In the in-situ combustion process, the residual value versus the predicted value plots indicate the regression equations have a reasonable fit, i.e., the residual values are distributed along both sides of the zero horizontal axis. (shown in Figure 3.2 and Figure 3.3). Similar residuals plot patterns show in each of the different timesteps.

In the steam drive process, the residuals plots are also satisfactory (Figures 3.4 and 3.5). However, the steam injection rate and injection pressure residual plots are shown in special distribution trends. The injection rate is in an extremely narrow range, i.e., about 1,000 B/D for different timesteps. Therefore, a narrow trend for residual values is found for regression. The narrow range in the dependent variable does not actually affect the prediction, which was proved both in the prediction plot and the prediction calculation in the next section. The injection pressure residuals plot shows that a quadratic term may need to be included in the regression equation, because the exponential term and error function were used in the performance steam drive model. Since the prediction is reasonably acceptable, the quadratic term is not necessarily improving the prediction. Therefore, this quadratic term is neglected and the regression equation easily included into the system regression analysis. These steam drive residuals plots are similar for each of the timesteps.

IN-SITU COMBUSTION PROCESS
RESIDUAL VALUE VS PREDICTED Z-VALUE



OIL RECOVERY RESIDUAL PLOT

RESIDUAL VALUE VS PREDICTED Z-VALUE

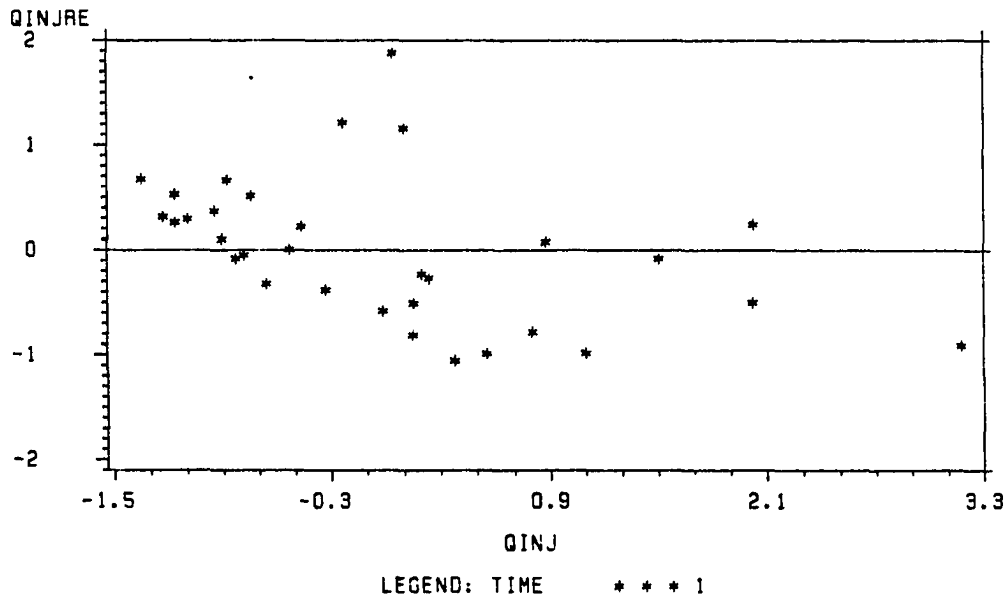
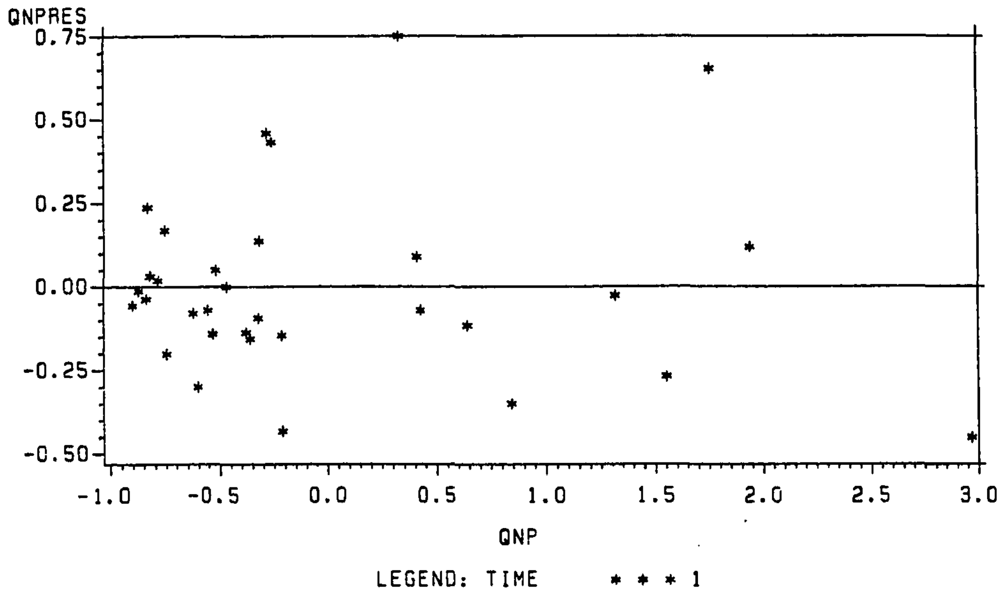


FIG 3.2 INJECTION RATE RESIDUAL PLOT

IN-SITU COMBUSTION PROCESS
RESIDUAL VALUE VS PREDICTED Z-VALUE



PRODUCTION RATE RESIDUAL PLOT

RESIDUAL VALUE VS PREDICTED Z-VALUE

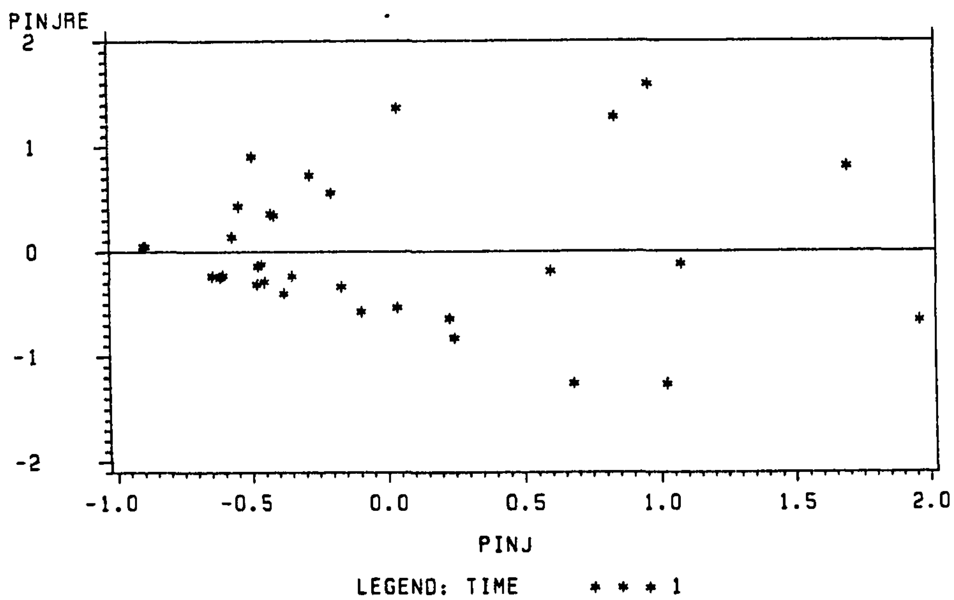
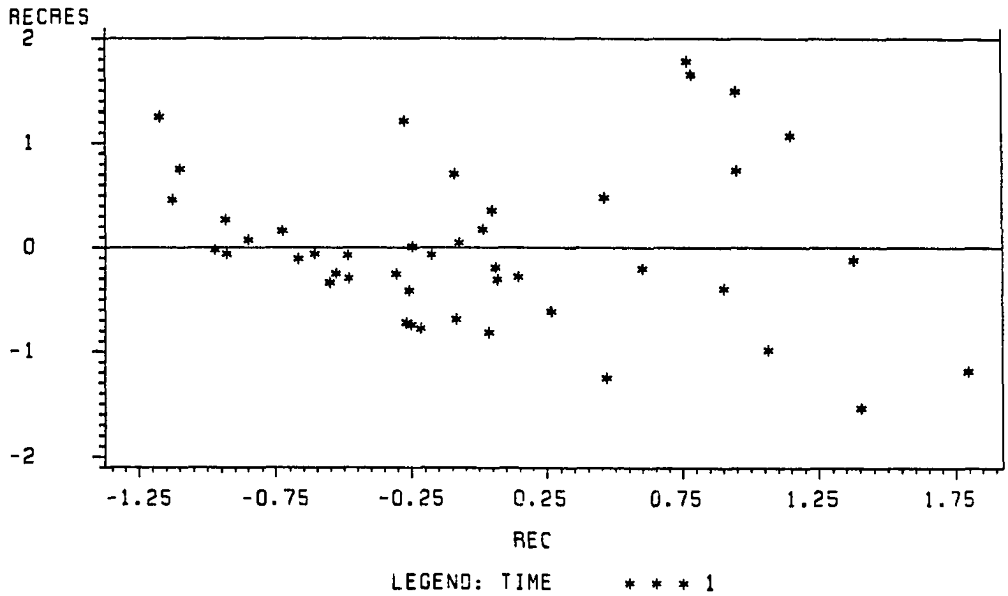


FIG 3-3 INJECTION PRESSURE RESIDUAL PLOT

STEAM DRIVE PROCESS

RESIDUAL VALUE VS PREDICTED Z-VALUE



OIL RECOVERY RATE RESIDUAL PLOTS

RESIDUAL VALUE VS PREDICTED Z-VALUE

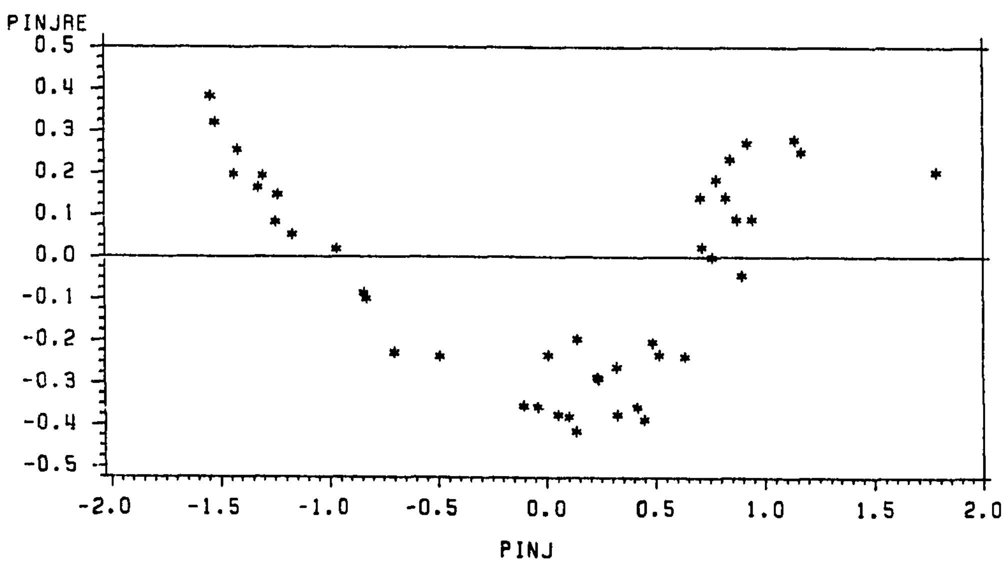
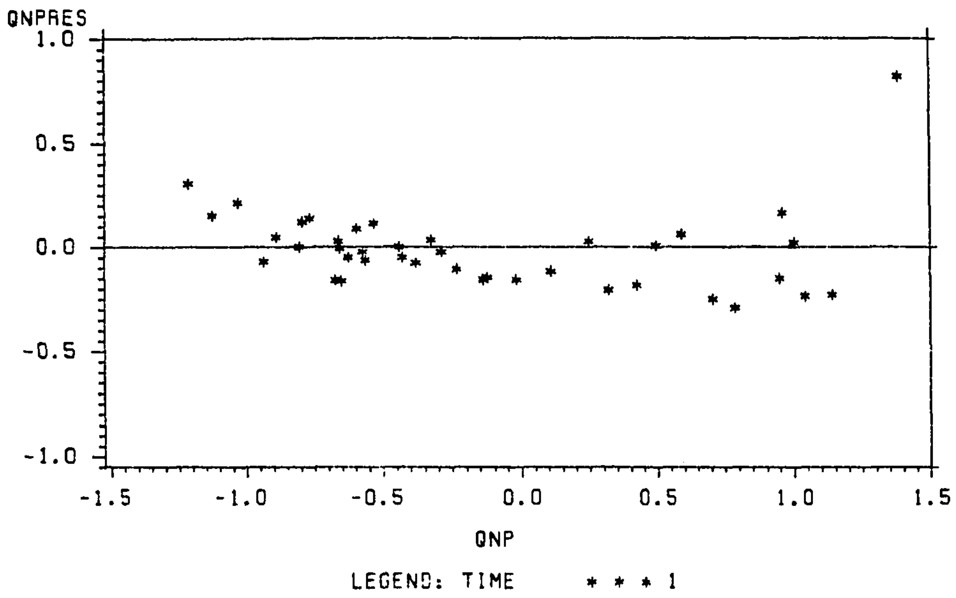


FIG 3-4 INJECTION PRESSURE RESIDUAL PLOT

STEAM DRIVE PROCESS
RESIDUAL VALUE VS PREDICTED Z-VALUE



PRODUCTION RATE RESIDUAL PLOTS

RESIDUAL VALUE VS PREDICTED Z-VALUE

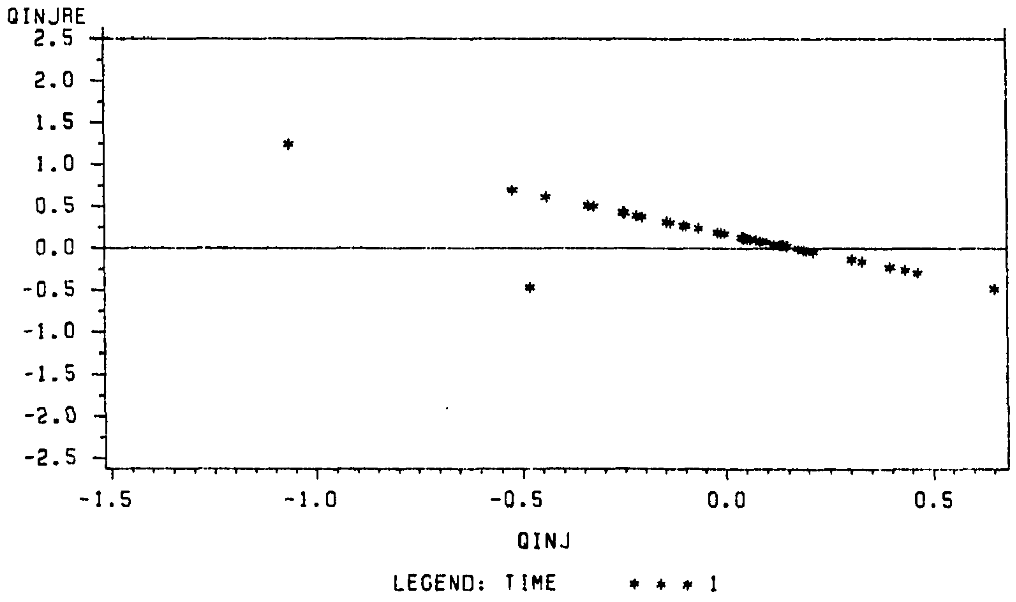


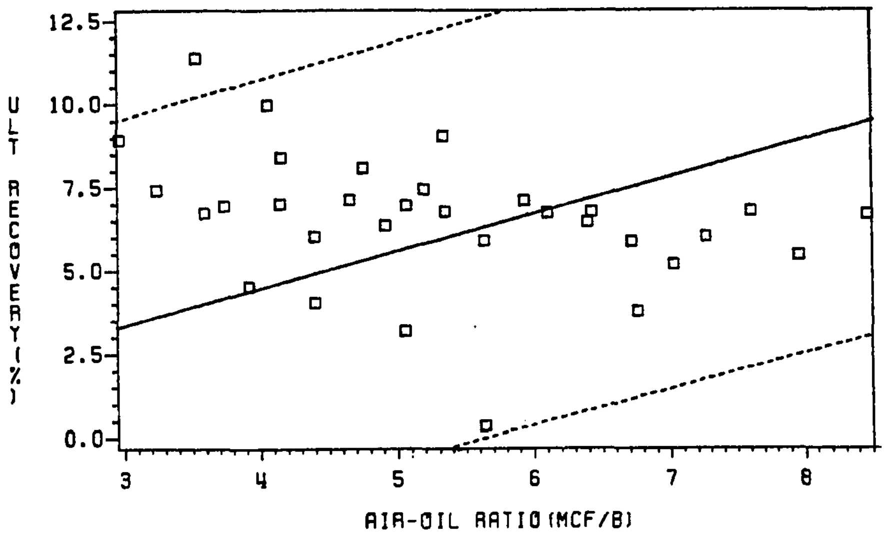
FIG 3-5 INJECTION RATE RESIDUAL PLOTS

In a simple linear regression, we can plot the predicted values against the independent variable and judge the fit by looking at the plot. In multiple regression, this is not possible since the data are scattered in more than two dimensions of the plot. Therefore, we can do a 95% confidence limits partial plot of the predicted value versus the predominate independent variable in the regression model, e.g., oil producing rate versus volume burned in the in-situ combustion process. The SAS program is written for both processes, such as in-situ combustion process:

```
PROC GPLOT;
   PLOT QNPHA*VB/VPOS=22 HPOS=100;
SYMBOL1  I=RLOCLI95  V=SQUARE;
        TITLE1  .C=NONE  .H=2  .f=TITALIC  PRODRATE
                          VS VOL BURNED;
FOOTNOTE.M=(26,35).C=NONE .F=TITALIC WITH  95
                          CONFIDENCE LIMITS;
```

The partial prediction plots are good for the in-situ combustion process (Figures 3.6 and 3.7). The predicted values are within 95% confidence limits. In the steam drive process, the partial prediction plot for steam injection rate is abnormal. The cause for this was explained in the residuals plot, as the dependent variable is in a very narrow range. Therefore, a z-value injection rate is plotted versus volume of steam required indicating the prediction does fall within 95% confidence limits. (The steam drive prediction plots are shown in Figures 3.8 and 3.9).

IN-SITU COMBUSTION PROCESS
WITH 95 PERCENT CONFIDENCE LIMITS



RECOVERY VS AIR OIL RATIO

WITH 95 PERCENT CONFIDENCE LIMITS

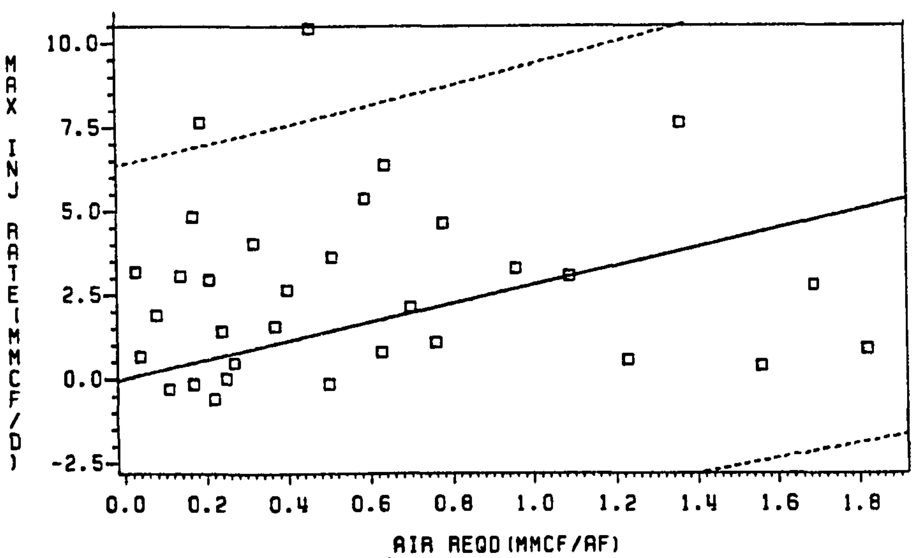
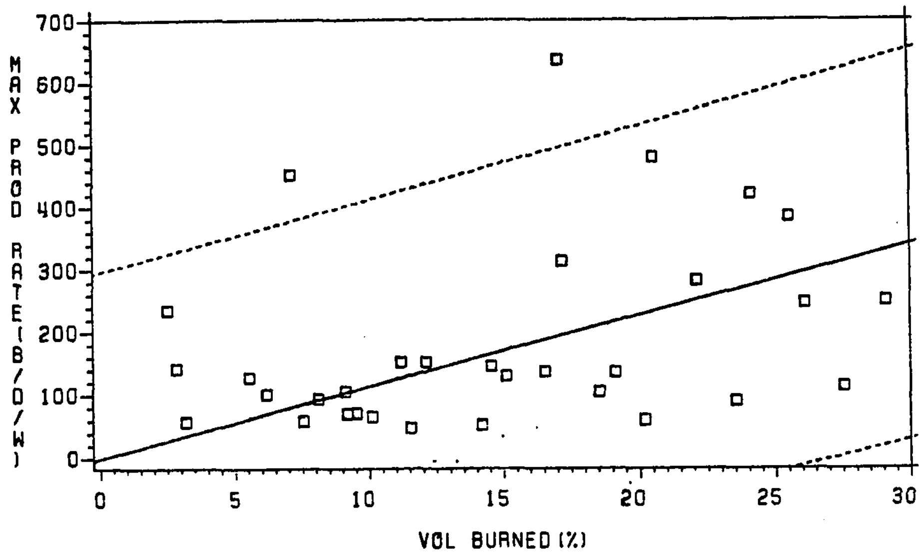


FIG 3-6 INJECTION RATE VS CUM AIR REQD

IN-SITU COMBUSTION PROCESS
WITH 95 PERCENT CONFIDENCE LIMITS



PRODUCTION RATE VS VOLUME BURNED

WITH 95 PERCENT CONFIDENCE LIMITS

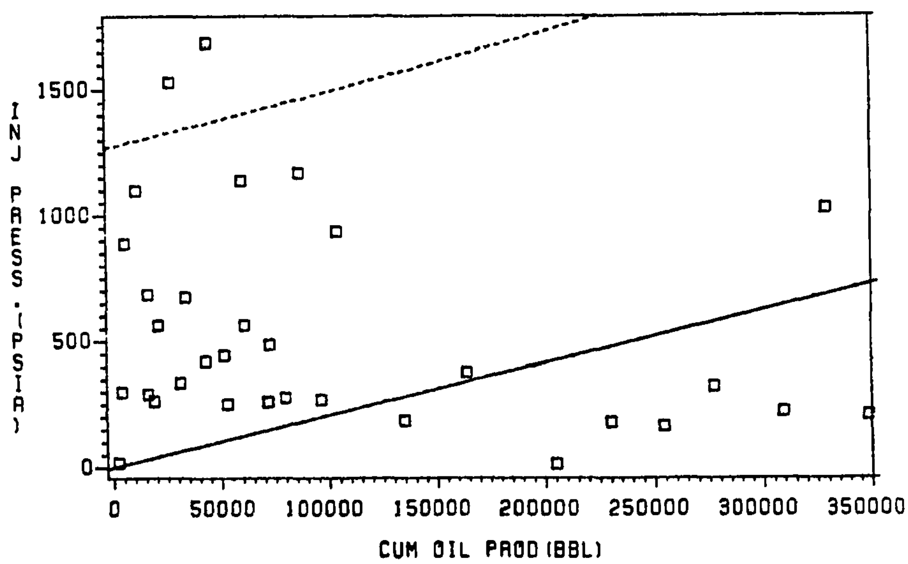
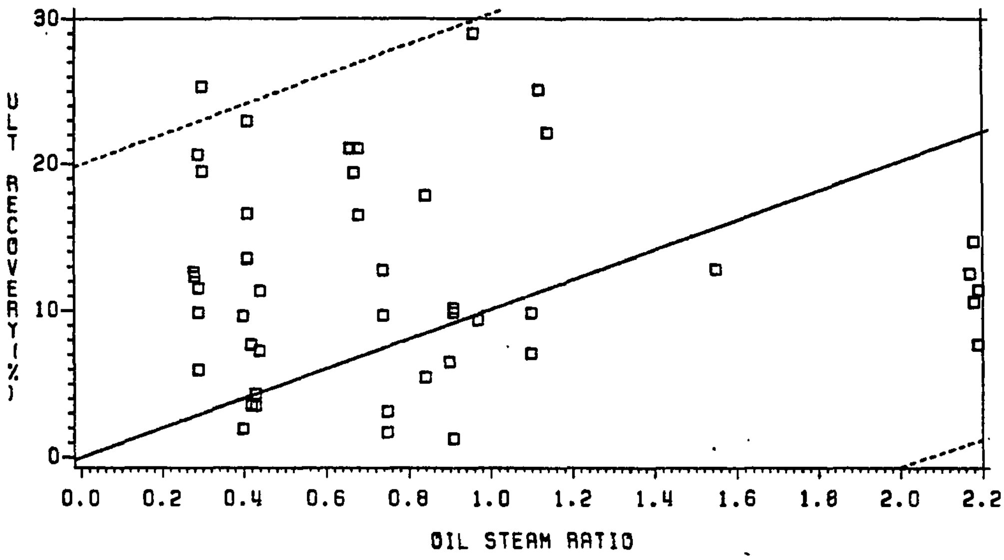


FIG 3·7 INJECTION PRESS VS PRODUCTION

STEAM DRIVE PROCESS
WITH 95 PERCENT CONFIDENCE LIMITS



RECOVERY VS OIL-STEAM RATIO

WITH 95 PERCENT CONFIDENCE LIMITS

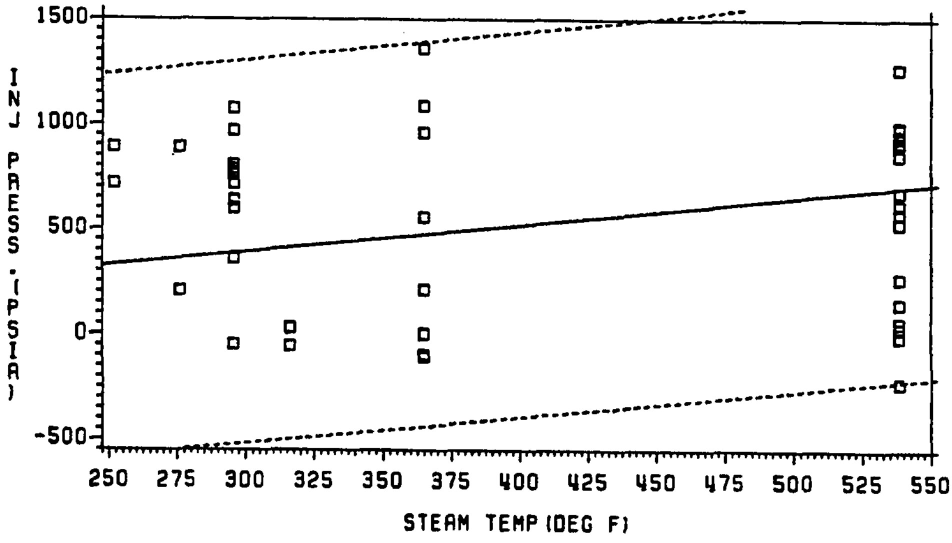
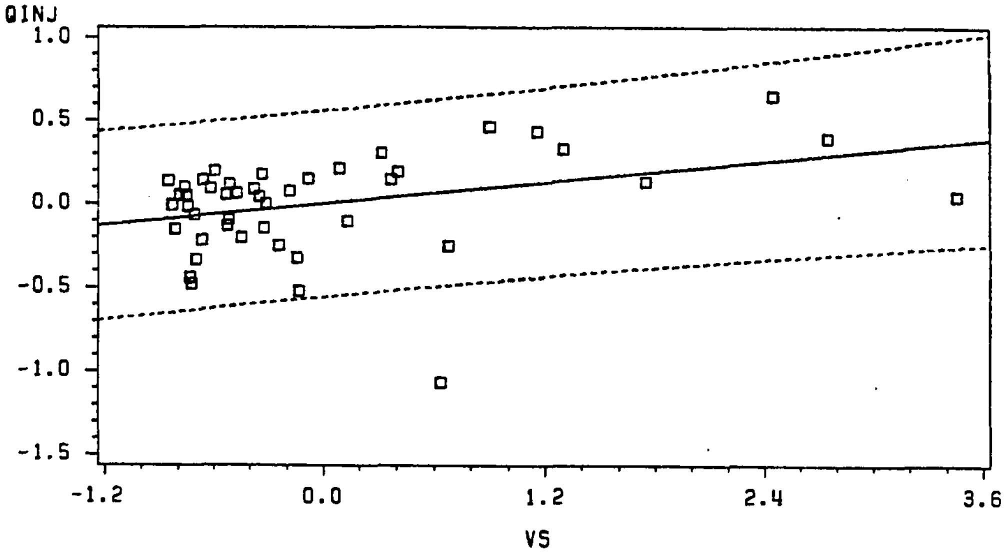


FIG 3-8 INJECTION PRESSURE VS STEAM TEMP

STEAM DRIVE PROCESS
WITH 95 PERCENT CONFIDENCE LIMITS



INJECTION RATE VS STEAM INJED

WITH 95 PERCENT CONFIDENCE LIMITS

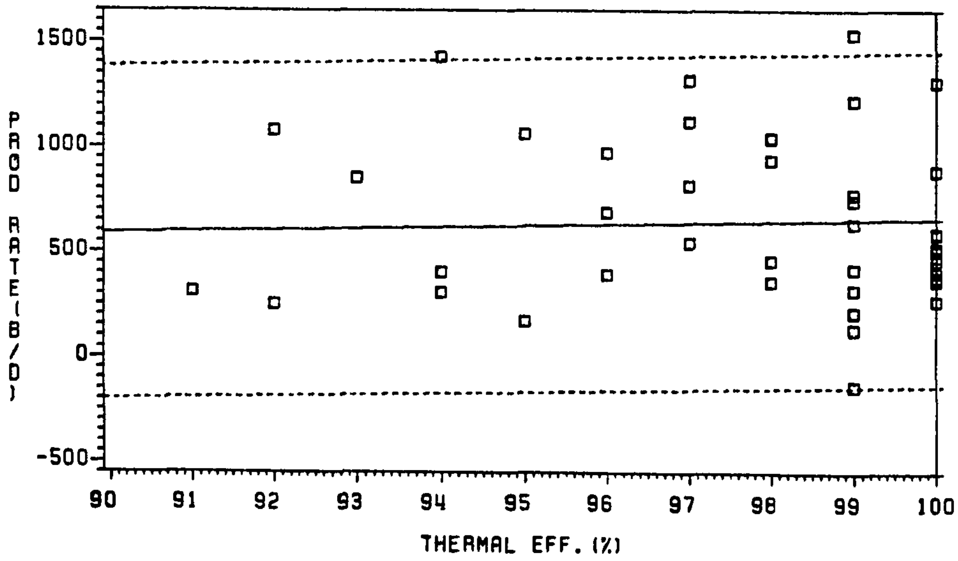


FIG 3-9 PRODUCTION RATE VS THERMAL EFF

3.4.5 Use of the actual input values to do prediction

This procedure is actually used to do predictions in all the regression equations. In this case, we can visualize how good our models can be.

In the SAS modeling procedures (SAS Users' Guide), there is a SIMLIN procedure to do predictions by simulation. However, this procedure does not suit our purpose because the procedure uses the simulated results which accumulated the prediction errors.

In this dissertation, the SAS' powerful macro capability is used to program the prediction algorithm as follows:

i) Reset all the regression equation's coefficients into an array, and strip off the unnecessary columns from the array. Then, the coefficients of the variables are picked up from the array and dataset.

```
DATA NUMERIC;
     SET OPS(FIRSTOBS=9);
     DROP  _TYPE_  _MODEL_  _SIGMA_;

DATA FIELDS;
  FORMAT SERIES E10.;
   ARRAY ALLPARMS(P)
     PINJ QINJ REC CAI VISO ASR VB AOR NP FB
     ONP PIS TRS INTERCEP;
   SET NUMERIC;
     DO P=1 TO 14;
       SERIES = ALLPARMS;
```

```
OUTPUT; END;
    DROP PINJ QINJ REC CAI VISO ASR VB AOR NP
         FB QNP PIS TRS INTERCEP;

DATA PARMS:
  SET FIELDS;
   IF SERIES=. OR SERIES=-1.0 THEN DELETE;
     DATA OUTPARM;
       FORMAT P1-P29 E10.;
          ARRAY OUTPARMS(Q) P1-P29;
       DO OVER OUTPARMS;
          SET PARMS;
       OUTPARMS=SERIES;
     END;
          DROP Q P SERIES;
```

ii) Those coefficients are substituted into the original regression equations formulated.

```
DATA FINAL;
  IF _N_ =1 THEN SET OUTPARM;
   SET ECOM;
     RECHAT = P1*CAI +P2*AOR + P3*FB +P4*PIS;
              RECRES= REC - RECHAT;
     QINJHA = P6*PINJ + P7*CAI +P8*VISO +P9*ASR +
              P10*AOR +P11*NP +P12*TRS +P13*PIS;
              QINJRE = QINJ - QINJHA;
     QNPHAT = P15*PINJ +P16*REC +P17*CAI +
              P18*VISO +P19*VB +P20*NP;
              QNPRES = QNP - QNPHAT;
     PINJHA = P22*CAI +P23*VISO +P24*VB +P25*AOR
              +P26*NP +P27*QNP +P28*TRS;
              PINJRE = PINJ - PINJHA;
```

iii) Convert the normalized values back into the original values.

```
DATA REVERSE;
     IF _N_=1 THEN SET STDM;
          SET FINAL:
           ARRAY ORIG13(I) R1-R13;
            ARRAY MEA13(I) M1-M13;
             ARRAY STDM13(I) S1-S13;
               ARRAY   ZVAL13(I)   RECHAT   AORHAT
               QNPHAT  FB  CAI  NP  PINJHA  VISO  VB
               PIS TRS ASR;
```

```
DO I=1 TO 13;
  ORIG 13=(ZVAL13*STDM13) + MEA13;
    END;
```

A similar program was written for the steam drive process.

3.4.6 Check the time serial of the regression models

In the performance models, the process parameters were being estimated in continuous timesteps, and the results were only printed out in 12 timesteps for a one-year period. Therefore, there is actually one-month variation in each timestep which could cause time serial problem in the regression models. The AUTOREG procedure estimates parameters in regression models when the data is a time series and the error term is an autoregressive process. Therefore, the AUTOREG procedure can be used to check the possible time serial problem in the regression models. The SAS program is written for this purpose for the in-situ combustion process as :

```
PROC AUTOREG DATA=AUTO;
     MODEL REC = AOR QNPHAL VISO FB CAI NP/NLAG =13
                    BACKSTEP;
     MODEL QINJ=PINJHL NP CAI ASR VISO/NLAG=13
                    BACKSTEP;
     MODEL QNP=VB RECHAL PINJ CAI VISO NP/NLAG=13
                    BACKSTEP;
     MODEL PINJ=QINJAL RECHAL CAI VISO VB NP
                         QNPHAL/NLAG=13 BACKSTEP;
```

A similar program was also written for the steam drive processs. The program options are specified as:

NLAGF=13 specified the order of autoregressive process. Here we specify 1/3 of one-month time which is long enough to check the problem. In the steam drive process, the injection pressure regression equation shows that the first time lag standard derivation is significant which is consistent with the residuals plot in section 3.4.4. This deviation indicates that a quadratic term may be needed to improve the time serial change. Since only the first time lag has this problem, we do not need to put in an extra term for improvement. Similarly, the in-situ combustion process' oil recovery regression equation shows that the first time lag standard derivation is significant which also can be neglected. All the other equations standard deviations are zero in all time lag. BACKSTEP requests that AUTOREG remove autoregressive parameters if they are not significant.

The AUTOREG procedure indicates that there is no time serial problem in the regression models for both processes. Therefore, the regression models are "good" enough for the objective functions in the optimization models. The algorithms of the regression model building are outlined in the following flow chart (Figure 3.10).

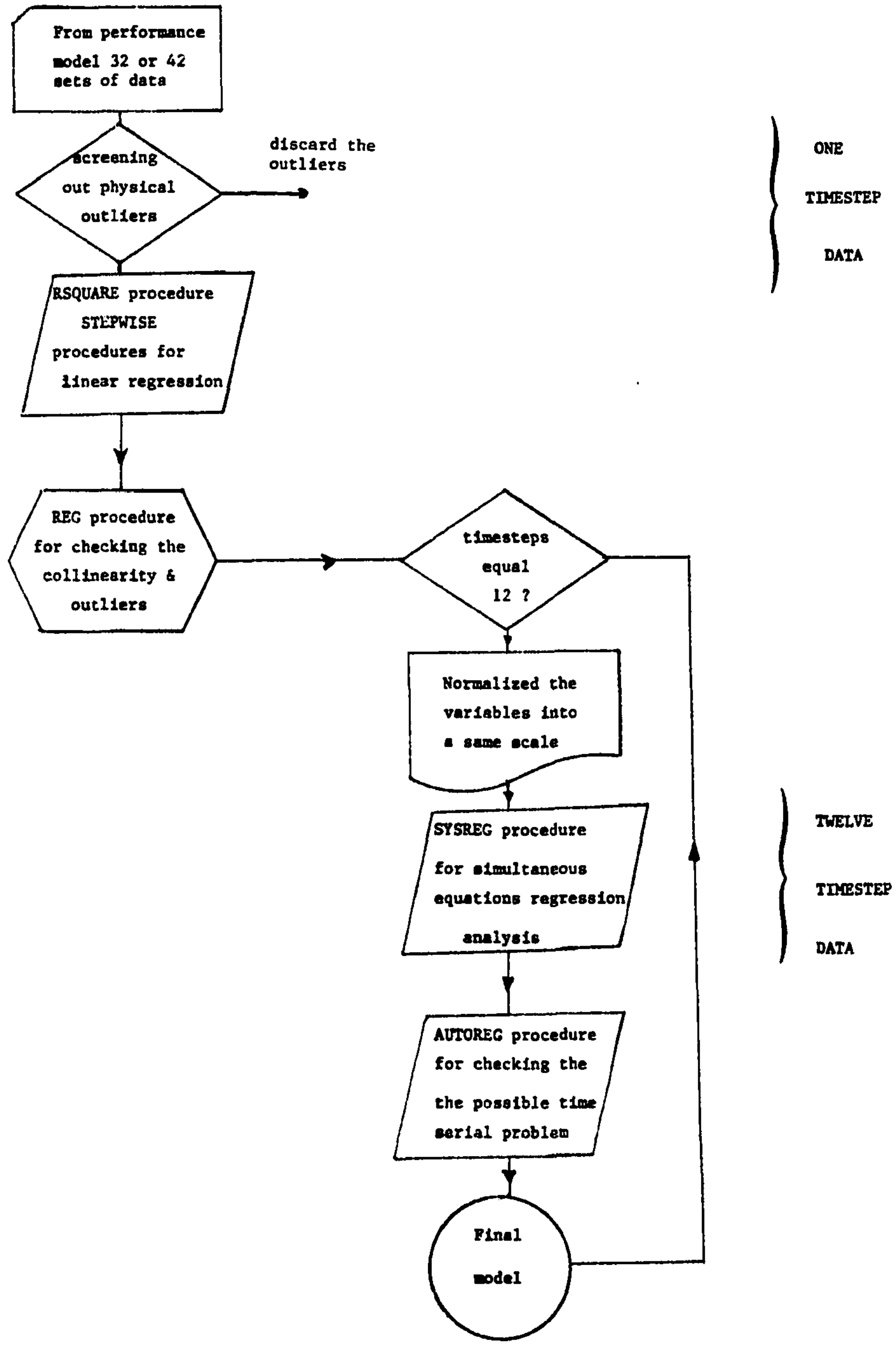


Fig. 3.10 Algorithms of regression model building

3.4.7 One Timestep Regression Modeling Results

From the previous sections, the regression models are shown to be the best-fitted formulations. They can be used for further applications, such as objective functions for the optimization model. In Table 3.2, the parameter estimates are in the normalized z-values.

Table 3.2 Third Timestep Regression Results

MODEL: RECOVERY
DEP VAR: REC

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	2.75899E-15
R001.QNP	1	0.247291
R001.ROS	1	0.573287
VISO	1	0.044587
PIS	1	-0.556212

MODEL: STEAMINJ
DEP VAR: QINJ

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	5.57917E-16
VS	1	0.178807
NP	1	-0.197262
TRS	1	0.086283

MODEL: CILPRCDN
DEP VAR: QNP

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	-3.41528E-15
EH	1	0.219517
VISO	1	-0.035888
R001.TS	1	-0.481235
REC	1	0.338109
PIS	1	0.537767

MODEL: INJPRESS
DEP VAR: PINJ

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	-2.07179E-15
R001.TS	1	0.961326
VISO	1	0.056363
VS	1	0.048218
TRS	1	-0.029626

MODEL: RECOVERY
DEP VAR: REC

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	2.80893E-15
AOR	1	-0.918565
PIS	1	-0.684917
FB	1	0.044559
CAI	1	0.348810

MODEL: INJRATE
DEP VAR: QINJ

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	-3.52674E-17
R001.PINJ	1	-0.031246
VISO	1	0.032501
CAI	1	0.751532
NP	1	0.220271
ASR	1	-0.032422
TRS	1	0.063542
PIS	1	-0.00400793
AOR	1	0.046543

MODEL: PRODRATE
DEP VAR: QNP

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	3.45970E-16
VB	1	0.139276
R001.REC	1	-0.160397
R001.PINJ	1	-0.043903
CAI	1	0.085703
VISO	1	0.029948
BP	1	0.933218

DEP VAR: PINJ

VARIABLE	DF	PARAMETER ESTIMATE
INTERCEPT	1	-7.11364E-16
CAI	1	-0.583858
VISO	1	0.236990
VB	1	0.677206
AOR	1	0.012519
BP	1	0.462549
R001.QNP	1	-0.094701
TRS	1	0.713179

Those parameter estimates are being used as the coefficient constants in the regression equations. Note that all the intercepts are negligibly small and they are being excluded from the equations.

In-situ Combustion Process:

Oil recovery: REC = -0.918565AOR - 0.684817PIS + 0.044559FB + 0.348810CAI

Injection rate: QINJ = -0.031246PINJ + .032501VISO + .751532CAI + .220271NP - .032422ASR + .063542TRS - .0040079PIS + 0.046543AOR

Production rate: QNP = 0.138276VB - 0.160397Rec - .043903PINJ + .085700CAI + .029948VISO + 0.933218NP

Injection pressure: PINJ = -0.583858CAI + .23699VISO + .677206VB + .012519AOR + 0.462549NP -0.094701QNP + 0.713179TRS

Steam Drive Process:

Oil recovery: Rec = 0.247291QNP +0.573287ROS + 0.044587VISO - 0.556212PIS

Injection rate: QNP = 0.178807VS - 0.197262NP + 0.086283TRS

Production rate: QNP = 0.219517EH - 0.035888VISO - 0.481235TS +0.338108REC +0.537787PIS

Injection pressure: PINJ = 0.961326TS + 0.056363VISO + 0.048218VS - 0.029626TRS

This timestep is only used as an illustration. Total 12 sets of regression equations will be used as the objective functions for the optimization model.

IV. OPTIMIZATION MODEL FORMULATION FOR HEAVY OIL RECOVERY

4.1 Introduction

The term "heavy oil" usually implies crude oil having an API gravity of 25^o or less (Dietzman[18], 1965; and, Farouq Ali[25], 1974). However, semi-solid hydrocarbons (e.g., bitumen in tar sands, asphalt, etc.) are excluded in this category. The author only considers those heavy oils which are mobile at reservoir conditions, as established by some primary and secondary productions. Therefore, crude oils have viscosities between 100 to 10,000 cp at the original reservoir temperature, frequently referred to as "heavy oils."

Due to the high viscosity of heavy oils at the lower temperature, crude oil pumping, lifting, and pipeline transportation are common problems. A mixture of crude with water or diluents has been found to be of some benefit. Heavy oils have very little gas in solution but often contain above average amounts of sulfur, metals, and asphalt. For example, the U.S. crudes in the $20\text{-}25^o$ API range contain 0.1 to 4.17 percent sulfur by weight.

Canadian crudes (20^{o}API and below) contain about 3.0 percent sulfur. Venezuelan crudes (Orinoco Tar belt crudes 15^{o} API or below) contain 25 percent sulfur, vanadium, and nickel (Farouq Ali[25], 1974). Both high sulfur and metal contents pose problems in refining (McKie,[45] 1982).

Despite the above problems, the heavy oil reserves are one of the great potential fossil fuel resources, both in the U.S. and worldwide. In the U.S., over 2,000 heavy oil reservoirs occurring in 1,500 fields and in 26 states were catalogued in 1965. By 1980 production of heavy oil had reached about 170,000 B/D and an estimated 30 billion recoverable barrels were still current (Time, April 28,[63] 1980). In 1982, the author collected about 100 steam drive and 40 in-situ combustion field case reports in the US (Oil & Gas Journal Annual Production Reports[2], 1982; and, Meyer et al.,[46] 1982). Among the oil producing states, California has the largest heavy oil reserves (53.64 billion bbls) and Texas is second (30.57 billion bbls). Other states having significant reserves are Louisiana (6.39 billion bbls), Wyoming (5.28 billion bbls), Arkansas (5.0 billion bbls), and Oklahoma.

Venezuela is another country which has a large heavy oil reserve (Alcocer[1], 1980). For example, Orinoco Tar belt is considered to be one of the largest heavy oil accumulations in a single place in the world. The estimated oil in place would be greater than 700,000 million barrels, with an oil gravity range between 8°API and 14.5°API. Canada and Romania also have large heavy oil reserves. In-situ combustion pilot field tests were reported successful in Suplace de Baracau field, Romania (Philip et al.,[51] 1983).

4.2 Basic considerations for thermal recovery process design

Because of the low mobility of heavy oils, the primary and secondary recovery of such oil is low. In the case of a typical 25°API crude, the primary recovery would be 5-10 percent, which may be increased to about 15 percent by waterflooding. Waterflooding is usually very inefficient in heavy oil reservoirs. The breakthrough recovery is low (about 300 to 350 bbl/ac-ft for a 65 cp oil), and following breakthrough, the water cut increases rapidly to values of 90-98 percent.

It is apparent that the principle obstacle in heavy oil recovery is the high viscosity. Any reduction in viscosity will increase the oil mobility, leading to an increase in the oil cut. Viscosity can be lowered most effectively through the application of heat - the higher the oil viscosity, the greater the rate of viscosity reduction as recovery processes are the major recovery methods. The main heavy oil recovery methods, as well as the approximate API gravity ranges of applicability, are as follows:

Cyclic Steam Stimulation	$<15^{o}$ API
Steam Drive	12^{o}-25^{o}API
Hot Waterflood	20^{o}-25^{o}API
In-Situ Combustion	8^{o}-36^{o}API

In this dissertation, the author chooses only steam drive and in-situ combustion techniques for the model for on three reasons.

i) Both processes may be frontal drive processes; therefore, the mechanism can be implemented in the optimization model on an equal basis.

ii) Steam drive and in-situ combustion are the most popular thermal recovery processes being applied in the field. The optimization model is worthwhile as it can be used for comparison and analysis.

iii) Since the steam drive and the in-situ combustion are the more popular thermal processes used in the field, the large number of field cases can be used for a sufficient number of regression analysis and design study.

In the steam drive process design, consideration of viscosity reduction is the key factor for the success of the process. The principal mechanisms at work in steam drive which cause high recovery are:

1. Thermal expansion of oil in place.

   Steam carries heat into the formation and the crude oil expands in the porous rock.

2. Viscosity reduction.

   Crude oil with a reservoir viscosity of 1,000 cp at $100^{O}F$ could have a reservoir viscosity of about 50 cp at a temperature of $200^{O}F$. Thus, viscosity can be reduced by a factor of about 1,000 by increasing reservoir temperature.

3. Steam distillation.

   Thermal distillation causes the lighter fraction crude oil to flow easily out of the reservoir rock.

4. Mobility control.

   At higher temperature, the oil viscosity and relative permeability characteristics are changed; therefore, a better mobility control can be obtained from the steam drive.

The steam injection rate and pressure are the important designed parameters. The oil recovery and the oil production rate are the measurement of the process efficiency. These four designed parameters are formulated into the regression equations which are being used in the multi-criteria optimization model.

In the in-situ combustion process design consideration, fuel deposition is the key factor for the success of the process. The fuel content determines the combustion of the flame front throughout the formation. The principle mechanisms at work in the in-situ combustion that cause higher recovery are:

1. Effect of pressure on fuel deposition.

   Increasing the pressure was to increase the fuel consumption as the kinetics of the process indicates oil sand burns vigorously at a higher pressure, even at the same air injection rate.

2. Effect of air injection rate on burning velocity.

   The rate of advance of the combustion front was found to be approximately proportional to the air flux. If the burning velocity is dropped below one foot per day at a low injection rate, the combustion front is suspected of not being able to sustain.

3. Effect of air injection on oxygen consumed.

   As the air injection rate is increased to exceedingly high values, a smaller percentage of the oxygen is utilized. However, at fairly low rates the oxygen consumption is frequently quite high. This undoubtedly reflects the kinetic of combustion since the high rates provide short residence times and prevent the oxygen from being utilized efficiently.

Again, the air injection rate and pressure are the important designed parameters. The oil recovery and the oil production rate are the measurement of the process efficiency. These four designed parameters are formulated into the regression equations which are being used in the multi-criteria optimization model.

4.3 Application of Optimization Programming Technique

The optimization programming technique is applied to the thermal recovery process for on the following reasons:

1. To minimize the deviations of the designed parameters evaluated from the performance models; e.g. injection rate, injection pressure, production rate and oil recovery. In this way, we can also check the feasibility of process parameters for a particular reservoir.

2. To develop analytical solutions relating the profit of a recovery process to the designed parameters. Therefore, we can have a complete overview of the successful application of the process to a particular reservoir.

3. To compare both processes based on deviation from designed parameters, feasibility of process parameters, and

profit gained from each process for a particular reservoir is feasible for both steam drive and in-situ combustion processes.

For this optimization model, multiple objective functions are involved in an optimization technique. This technique is capable of handling decision problems which deal with multiple objective functions. In the conventional programming methods, the objective function has to be unidimensional either to maximize profits (effectiveness) or minimize cost (sacrifice). This dimensional limitation of the objective function sometimes does not fit the actual engineering design problem. This multi-criteria optimization model meets the design requirements. Often, ultimate design requirements set by management are achievable only at the expense of other minor design requirements. Thus, there is a need to establish a hierarchy of importance among these incompatible requirements so that the lower order requirements are considered only after the higher order requirements are satisfied.

a) Priority ranking for the in-situ combustion process

Priority 1 (P_1): Although only the higher recovery efficiency is expected, an exact achievement at each timestep is a sensible indication of this goal, i.e., $-d_1^+ + d_1^-$.

Priority 2 (P_2): Higher oil production rate increases the revenue for the process and thus higher production rate is desirable. We have maximum production rate as the design parameter. Therefore, we can only have underachievement of oil production, i.e., minimize the positive deviational variable ($-d_2^+$).

Priority 3 (P_3); The injection rate for the process is a direct indication of the rate of fuel burning in the formation. Overachievement of the air injection rate is desirable, i.e., minimize the negative deviational variable ($+d_3^-$).

Priority 4 (P_4): Higher injection pressure is a direct indication of the additional cost to the process. Therefore, it is always desirable to have injection pressure underachieved to the design goal, i.e., minimize the positive deviational variable ($-d_4^+$).

Priority 5 (P_5): Maximize the profit. Therefore, an overachievement is always desirable, i.e., minimize the negative deviational variable ($+d_5^-$).

b) Priority ranking for the steam drive process

The priority ranking is similar to the steam drive process, e.g, P_1, P_2, P_5 priorities. Steam generation is the major cost, but the injection pressure is not essential to cost. We consider these two goals in a different aspect than in the in-situ combustion process.

Priority 3 (P_3): The steam injection rate is the major cost of this process; therefore, underachievement of the steam injection rate is desirable. This goal is set differently from the in-situ combustion process. i.e. minimize the positive deviational variable ($-d_3^+$).

Priority 4 (P_4): Steam injection pressure is just high enough to be injected into the formation. Therefore, overachievement of injection pressure is tolerable as long as the pressure does not cause fracturing in the formation. i.e., minimize the negative deviational variable ($+d_4^-$).

4.3.1 Multi-criteria Optimization Technique:

In the early 1960's, Charnes and Cooper[12] presented an approach to the solution of linear decision models having more than a "single" objective. Their work and that of others (Lee,[39] 1972; and, Ijiri,[34] 1965) have resulted in a systematic methodology known as goal programming for solving linear, multiple objective problems wherein preemptive priorities are associated with the objectives. This method is capable of handling decision problems which deal with a main objective function, multiple goal objective functions (also known as goal constraints), and all the real constraints.

In addition to the treatment of multiple incommensurable objectives, preemptive goal programming is distinctly different from the conventional programming technique. In this programming technique, instead of trying to maximize or minimize the objective criterion directly, we try to minimize deviational variables among the goals objective functions which we can actually achieve within the given real constraints. Here, we set the deviational variables into one main objective function. Then, we minimize those undesirable deviational variables in the main objective function:

$$\text{Minimization: } Z = P_1(d_1^- + d_1^+) + P_2 d_2^\pm + P_3 d_3^\pm + P_4 d_4^\pm + P_5 d_5^\pm$$

where:

The positive or negative deviational variable ($d^\pm$) will depend on overachievement or underachievement of the process parameter.

This optimization technique is illustrated in the following formulation for the steam drive and the in-situ combustion process.

4.3.2 Assumptions and Limitations

Assumptions are always necessary in the development of any viable model. This multi-criteria programming technique is no exception. In many ways, however, this technique is less constrained by assumptions than the conventional optimization techniques. The following assumptions are listed in order:

1) None of the priority levels are commeasurable and

so we establish preemptive priorities for each objective or group of objectives. As shown before that the highest priority is indicated by P_1, the next highest by P_2, and so forth. The notion of preemptive priorities holds that P_1 is preferred to P_2, regardless of any multiplier associated with P_2.

2) All decision variables are nonnegative. This assumption is necessary since the solution method employed can only consider nonnegative variables. This limitation is included in the program application which is illustrated in Appendix D.

The most apparent limitation is that the goal programming model simply provides the best solution under the given constraints and priority structure. Therefore, if management assigns incorrect priorities to various goals, the model solution will not provide the optimum solution, as is usually the case for any optimization model.

Since the thermal recovery models are simulated in ideal conditions, the optimization model will have to follow the same assumptions. In reality, there are some physical limitations for modeling. These physical modeling limitations are discussed in detail in the next chapter.

4.4 Multi-criteria Optimization Model Formulations

In the multi-criteria optimization model, there are two types of objective functions: main objective function and goal objective functions (or goal constaints). As shown before the main objective function minimizes deviational variables among goals objective functions. The main objective is formulated according to the number of goal objective functions. The goal objective functions are formulated either analytically or empirically. The profit equation is formulated analytically and process design parameters are formulated by using regression analysis. Both steam drive and in-situ combustion processes employ the same technique for the goal objectives formulations.

4.4.1 Profit Equation Formulation

In the steam drive process, the profit equation is formulated analytically, incorporating the gross profit and cost. The cost computations are classified in three types (Perry,[52] 1981):

1) General cost: This cost includes the traditional oil field development costs for drilling and completing wells, installing surface equipment, and operating the well. However, the enhanced oil recovery method only considers the developed reservoir or field; therefore,

this cost is assumed not to be of much importance or can be neglected.

2) Financial costs: The financial costs associated with any recovery project which are paid from production revenues are:

- o Royalties, severance, and other taxes
- o Windfall profit tax
- o State and federal income taxes
- o Return on captial.

Doscher and Ershaghi[20] (1978), noted that the financial costs are not considered in calcuations because these items are unique for all the projects and individual operations. Particularly, the EOR profit term is only used for comparative purposes.

3) Process costs: To determine whether the project will be economical, the costs specific to a steam drive operation need to be analyzed in detail. They include the following :

- o Steam generator operation and maintenance cost
- o Fuel cost for generating steam
- o Water supply and treatment costs
- o Pollution control equipment operation and maintenance cost

The process costs are the only costs included in the profit equation, therefore, the profit equation is formulated as:

Profit = Reveune - (Generator operation and maintenance cost) - (fuel cost) - (scrubber operating and corrosion cost)

Crude oil price	= \$35.5/bbl
Generator operating and maintenance cost	= \$0.1/bbl of steam injected
Fuel cost	= \$2.26/bbl of steam injected
Scrubber operation and maintenance cost	= \$0.2/bbl of steam injected

Therefore:

$$\text{Profit} = 35.5N_p - 0.1VS - 2.26VS - 0.2VS \quad (4.1a)$$

$$\text{Profit} = 35.5N_p - 2.56VS \quad (4.1b)$$

where:

N_p = cumulative oil production, bbls

VS = steam injected, bbls

The oil recovery, oil production rate, steam injection rate, and steam injection pressure equations are obtained from regression equations for the steam drive model.

Similarly, the profit equation of the in-situ combustion operation can be formulated as:

Profit = Revenue - (compressor operation and maintenance cost) -(compressor energy cost) -(oil treatment cost) -(field operating cost)

Crude oil price	= \$35.5/bbl
Compressor operation and maintenance cost	= \$0.10/Mcf of cumulative air injection
Compressor energy cost	= \$0.50/Mcf of cumulative air injection
Oil treatment cost	= \$3.25/bbl of cumulative oil produced
Field operating cost	=\$0.075/Mcf of cumulative air injection

Therefore:

$$\text{Profit} = 35.5N_p - 100CAI - 500CAI - 3.25N_p - 75CAI \quad (4.2a)$$

$$\text{Profit} = 32.25N_p - 675\ CAI \quad (4.2b)$$

where:

N_p = cumulative oil production, bbls

CAI = cumulative air injection, MMscf/acre-ft

4.4.2 Formulation of the Process Design Equations

In the Chapter III, the author has illustrated the validation of those regression equations. The regression equations are best fitted linear functional equations. Therefore, the equations can be used as the goal objective functions.

Since the regression equations are different for both steam drive and in-situ combustion processes, the equations are listed according to the individual process. The author also uses the third timestep for illustration:

Steam drive process goal objective functions

Oil recovery G_1 Rec $= 0.247291X_6 + 0.573287X_{10} + .044587X_2 - 0.556212X_5 + d_1^- - d_1^+$

Production rate $G_2 = 0.219517X_8 - 0.197262X_7 + 0.481235X_9 + 0.338108X_4 + 0.537787X_5 + d_2^- - d_2^+$

Injection rate $G_3 = 0.178807X_8 - 0.197262X_7 + 0.086283X_9 + d_3^- - d_3^+$

$$\text{Injection pressure } G_4 = 0.961326X_3 + 0.056363X_2 \; 0.048218X_8 - 0.029626X_9 + d_4^- - d_4^+$$

In-situ Combustion goal ojective functions

$$\text{Oil recovery } G_1 = -0.918565X_9 - 0.684817X_2 + 0.044559X_3 + 0.348810X_4 + d_1^- - d_1^+$$

$$\text{Production rate } G_2 = -0.031246X_5 + 0.032501X_{12} + .751532X_4 + .220271X_6 - .032422X_7 + .063542X_8 - .0040079X_2 + .046543X_9 + d_2^- - d_2^+$$

$$\text{Injection rate } G_3 = -.031246X_5 + .032501X_{12} + .75153X_4 + .220271X_6 - .032422X_7 + .063542X_8 - .0040079X_2 + .046543X_9 + d_3^- - d_3^+$$

$$\text{Injection pressure } G_4 = -0.583858X_4 + .23699X_{12} + .677206X_{10} + .012519X_9 + .462549X_6 - .094701X_{11} + 0.713179X_8 + d_4^- - d_4^+$$

The above equations only represents one timestep and there are another 11 timesteps, which can be represented in a matrix form.

The real constraints are the processes parameters obtained from the performance model results (Appendix C).

4.4.3 General form of Model Formulation

The oil recovery, oil production rate, air injection rate, and air injection pressure equations are obtained from the regression equations and the profit equations is formulated analytically. Then the optimization model can be formulated for the steam drive process and the in-situ combustion process. Since the main objective function, goal objective functions (or goal constraints) and real constraints are different for the two processes, the optimization model for each process has to formulate individually:

(i) Steam drive process: (General form)

Goal objective functions

Oil Recovery $G_1: \beta_1 = k_{11}X_6 + k_{12}X_{10} + k_{13}X_2 + k_{14}X_5 + d_1^- - d_1^+$ (4.3)

Production Rate $G_2 : \beta_2 = k_{21}X_1 + k_{22}X_2 + k_{23}X_3 + k_{24}X_4$ $k_{25}X_5 + d_2^- - d_2^+$ (4.4)

Injection Rate $G_3 : \beta_3 = k_{31}X_8 + k_{32}X_7 + k_{33}X_9 + d_3^- - d_3^+$ (4.5)

Injection Pressure $G_4 : \beta_4 = k_{41}X_3 + k_{42}X_2 + k_{43}X_8 + k_{44}X_9 + d_4^- - d_4^+$ (4.6)

Profit $G_5 : \beta_5 = k_{51}X_7 - k_{52}X_8 + d_5^- - d_5^+$ (4.7)

Main objective function

Minimization: $Z = P_1(d_1^- + d_1^+) + P_2d_2^+ + P_3d_3^+ + P_4d_4^- + P_5d_5^-$ (4.8)

Real constraints

$$X_1 \le \lambda_1$$
$$X_2 \le \lambda_2$$
$$X_3 \le \lambda_3$$
$$X_4 \le \lambda_4$$
$$X_5 \le \lambda_5$$
$$X_6 \le \lambda_6$$
$$X_7 \le \lambda_7$$
$$X_8 \le \lambda_8$$
$$X_9 \le \lambda_9$$
$$X_{10} \le \lambda_{10}$$

Where β_1 = oil recovery efficiency,%
β_2 = oil production rate, B/D
β_3 = steam injection rate, B/D
β_4 = steam injection pressure, psia
β_5 = profit, dollars
λ_1 = thermal efficiency, %
λ_2 = oil viscosity at reservoir conditions, cp
λ_3 = steam temperature, ^{o}F
λ_4 = oil recovery, %
λ_5 = oil saturation porosity
λ_6 = oil production rate, B/D
λ_7 = cumulative oil production,bbl
λ_8 = steam required, bbl
λ_9 = transmissibility
λ_{10} = oil steam ratio, bbl/bbl

(i) In-situ combustion process: (General form)

Goal objective functions

Oil Recovery G_1: $\delta_1 = k_{11}X_9 + k_{12}X_2 + k_{13}X_3 + k_{14}X_4 + d_1^- - d_1^+$ (4.9)

Production Rate G_2: $\delta_2 = k_{21}X_{10} + k_{22}X_1 + k_{23}X_5 + K_{24}X_4 + k_{25}X_{12} + k_{26}X_6 + d_2^- - d_2^+$ (4.10)

Injection Rate G_3: $\delta_3 = k_{31}X_5 + k_{32}X_{12} + k_{33}X_4 + k_{34}X_6$ $k_{35}X_7 + k_{36}X_8 + k_{37}X_2 + k_{38}X_9 + d_3^- - d_3^+$ (4.11)

Injection Pressure G_4: $\delta_4 = k_{41}X_4 + k_{42}X_{12} + k_{43}X_{10} + k_{44}X_9$ $k_{45}X_6 + k_{46}X_{11} + k_{47}X_8 + d_4^- - d_4^+$ (4.12)

Profit G_5: $\delta_5 = k_{51}X_6 - k_{52}X_4 + d_5^- - d_5^+$ (4.13)

Main Objective

Minimization $Z = P_1(d_1^- + d_1^+) + P_2d_2^+ + P_3d_3^- + P_4d_4^+ + P_5d_5^-$ (4.14)

Real constraints

$$x_1 \leq \zeta_1$$
$$x_2 \leq \zeta_2$$
$$x_3 \leq \zeta_3$$
$$x_4 \leq \zeta_4$$
$$x_5 \leq \zeta_5$$
$$x_6 \leq \zeta_6$$
$$x_7 \leq \zeta_7$$
$$x_8 \leq \zeta_8$$
$$x_9 \leq \zeta_9$$
$$x_{10} \leq \zeta_{10}$$
$$x_{11} \leq \zeta_{11}$$
$$x_{12} \leq \zeta_{12}$$

where:
δ_1 = oil recovery efficiency, %
δ_2 = oil production rate, B/D
δ_3 = air injection rate, Mscf/D
δ_4 = air injection pressure, psia
δ_5 = profit, dollars
ζ_1 = oil recovery efficiency, %
ζ_2 = oil saturation porosity
ζ_3 = fuel burned, bbl/acre-ft
ζ_4 = cumulative air injected, MMscf/acre-ft
ζ_5 = air injection pressure, psia
ζ_6 = cumulative oil production, B/D
ζ_7 = air-sand ratio, Mcf/acre-ft
ζ_8 = transmissibility
ζ_9 = air-oil ratio, Mcf/bbl
ζ_{10} = volume burned,%
ζ_{11} = oil production rate, B/D
ζ_{12} = oil viscosity at reservoir condition, cp

In the general formulations, those process parameters β_i, δ_i, γ_i, ζ_i will be transfered from the performance model parameters. The coefficient is obtained from the regression equations; the coefficient constants are subjected to change if the input data is different. The actual application of these two general formulations will be demonstrated in the field case studies.

This multi-criteria programming technique can also be applied in linear integer and nonlinear models (Ignizio[76], 1978). The application of this technique depends on the functional equations used for the goal objective functions. In this thermal process optimization model, all the goal objective functions are linear functions.

V. THE APPLICATIONS OF THE OPTIMIZATION MODEL AND THE FIELD CASE STUDIES

In this chapter, the optimization model applications in two field cases and the sensitivity analysis for each case will be illustrated.

Oklahoma fields were selected for the field case studies. The same performance model for generating the thermal recovery process parameters for the optimization model has applied. The Sho-vel-tum SE Pauls Valley and Loco fields were selected for the case studies. However, the reservoir in Sho-vel-tum field did not pass the screening criteria in the performance model. The computer printout of three reservoirs in those fields is shown in Appendix C. There are detailed publications about S.E. Pauls Valley and Loco fields (Elkins et al.,[22] 1972; and, Martin et al.,[42] 1968). The optimization model can validate the model with actual field results.

5.1 Heavy Oil Recovery in Oklahoma

In 27 counties of Southern Oklahoma (shown in Figure 5.1a), heavy crude oil accumulations are found primarily in sandstone as well as found in limestone and conglomerate. Geological eras of the formations are Permian and Pennsylvanian. The principal primary producing mechanisms are solution-gas expansion, waterflood, and combinations of the two. Net thickness of the reservoirs ranges from a few feet to about 140 feet. Known depths range from about 100 to 9,700 ft; however, 53 of the 125 reservoirs reported are at depths less than 3,000 ft. Therefore, most of the reservoirs are good for steam drive according to the process screening criteria (Dietzman,[18] 1965). The in-situ combustion process is certainly a good choice. Actually, Oklahoma was the first state to experience the in-situ combustion process in Jefferson County in 1953.

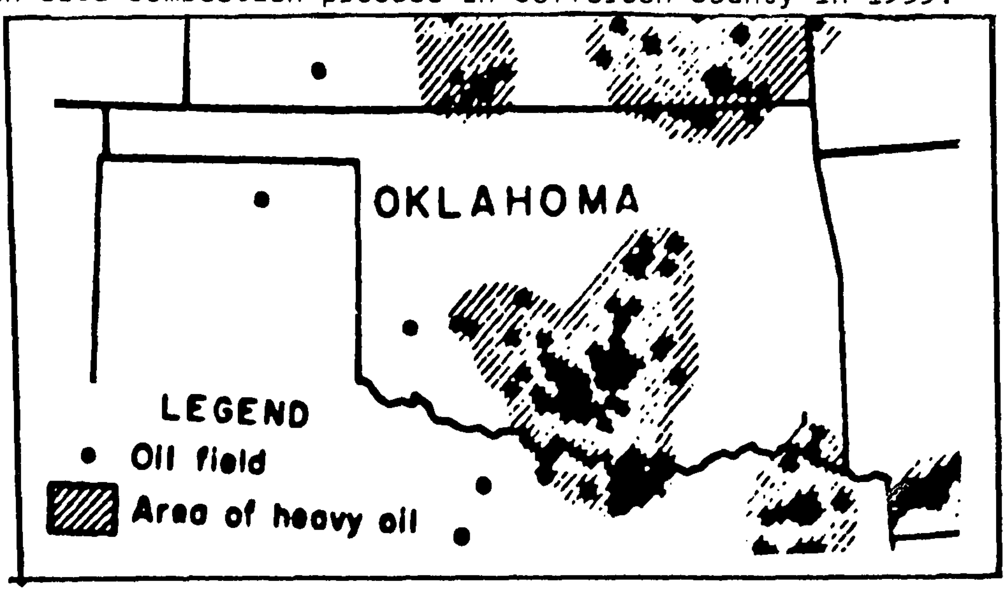


Figure 5.1a Heavy oil reserve in southern Oklahoma

usts 1953, the first experimental in-situ combustion process in Oklahoma was conducted independently by two separate companies, Sinclair Oil Co. and Magnolia Petroleum Co. The method proposed by Magnolia Petroleum Co. was developed with the idea of producing heavy oils in the 10^{0} to 25^{0}API. The Sinclair Oil Co. method was applied for higher API gravity oils, i.e. 30^{0} to 40^{0}API.

Mobil (formerly Magnolia Petroleum Co.) conducts the in-situ combustion pilot project at Pontotoc Test Sand, in Jefferson and Stephens counties. Their summary of experiences is listed as follows:

Research 5-spot - 40 ft between wells - 195 ft deep
18.4^{0}API Oil - 5,000 cp at BHT
Highly instrumented and controlled
Injectivity increased at 150 PSI
Conformance good but directional
51% of oil recovered from pattern
20% of pattern volume was burned clean
Results checked lab predictions

Mobil also ran another in-situ combustion pilot at Cox Penn Sand unit, in Carter County, but no report was available this pilot. Sinclair had two pilots of the in-situ combustion runs at Delaware-Childers, Nowata County. Both tests were run in 1949, and the total increased oil recovery was estimated at 34,971 bbl and 11,106 bbls. In 1960, Sinclair reran the in-situ combustion process for a watered-out reservoir. The summary of pilot test is listed as follows:

In-situ combustion process technically feasible
Air only for watered-out reservoir
Inverted 2.2-acre 5-spot 33°API oil
High injection rates and pressures
Delayed response due to high gravity reservoir
Good conformance

The operation was discontinued because of delayed response in the time frame of the project (Martin,[43] 1968).

Sohio also did an experimental in-situ combustion pilot in S.E. Pauls Valley, in Gravin County. Conoco operated in Loco field, in Jefferson County for some years. Conoco tried hot waterflood for a pilot test and then ran a steam drive pilot in Loco field. The author chooses the last two field cases as the field case studies in this dissertation because both fields have more detailed publications of the field test results (Martin,[42] 1968; and Elkins, et al.[27], 1972). The details of these two field cases are discussed in the next two sections.

5.2 Case Study 1: SE Pauls Valley Field, Oklahoma

5.2.1 Field History:

The Southeast Pauls Valley Field, Garvin County, Oklahoma, producing from the Oil Creek Sand at a depth of 4,300 ft., was discovered in March, 1955. The oil is very viscous (7,000-8,000 cp API) and the operating problems have been severe. By 1968, it was apparent that ultimate oil recovery by natural water drive was going to be less than 5% of the oil-in-place. Therefore, the thermal recovery method was considered to apply for the field.

The Oil Creek Sand reservoir is a faulted anticlinal nose with a 100-ft. oil column covering some 325 acres as outlined on the structure map in Figure 5.1. The reservoir temperature is found to be 110^{o}F and the pressure has been maintained at about 1,800 to 1,900 psi.

From the core analysis, porosity averaged 31%, oil saturation 57%, and water saturation 15%. Permeabilities of these 8 samples ranged from 878 to 2,505 md. The reservoir data does not indicate how thick each producing zone is, therefore, a high permeability and a low permeability case were studied. Given the above reservoir parameters, oil-in-place is initially calculated to be 1,370 bbl/acre-ft. An experimental in-situ combustion process was suggested for this field.

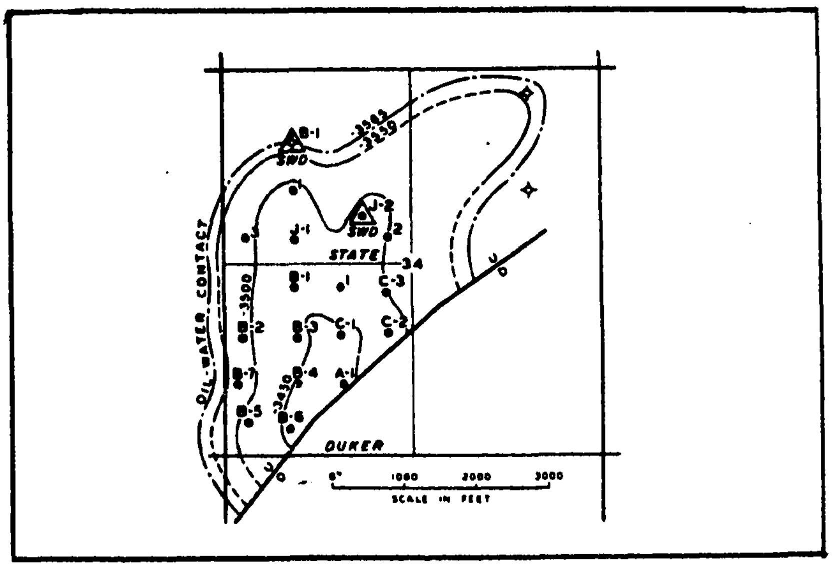


Figure 5.1 Structure, top of oil creek sand
(From Elkins et al.)

5.2.2 Experimental in-situ combustion process

Sohio Petroleum Co. and Morgan Guaranty Trust Co. conducted two experimental in-situ combustion processes in this field. From January through November, 1969, air was injected below the oil-water contact in an edge well as a partial evaluation for the feasibility of using a peripheral in-situ combustion process. In October, 1970, they ignited a structurally high well with the entire 100-ft sand column saturated with oil. Air injection into this well was continued through January, 1972. The net oil sand isopach oil creek sand and test wells map is shown in Figure 5.2.

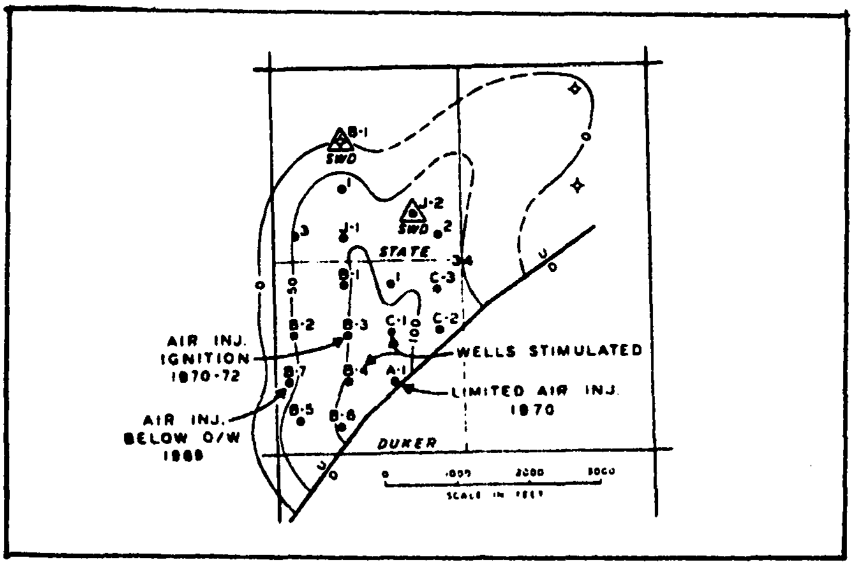


Figure 5.2 Net oil sand isopach oil creek sand (From Elkins et al.)

Starting on January 10, 1969, air was injected into water-sand below the oil-water contact in an edge well, Duker B-7, at rates of 500-800 Mcf/day at surface pressures of 1,800 to 2,400 psi. By mid-April, after injection of some 45 MMcf of air, breakthrough occurred in four offset wells. Three of the wells, Duker B-3, B-5, and B-6 were flowing successfully with the help of sucker-rod pumping. In October, 1969, with air injection into Duker B-7 continuing, the volume of gases produced by Duker B-5 and B-6 increased significantly. In addition, both wells went substantially to 100% water production. The test was terminated on November 17, 1969, after a cumulative 156 MMcf of air was injected.

On August 2, 1970, air injection was started in Duker A-1 at the rate of 200 to 300 Mcf/D at surface pressure up to 3,000 psi. This well showed a limited air intake capacity even after the wellbore cleanup. Therefore, facilities were arranged for injection into Duker B-3. On October 7, 1970, 450 MMcf of air was injected at about 1,700 psi surface pressure. Severe channelling to other producing wells was found in this injection well.

The overall performance of the in-situ combustion test is summarized in Figure 5.3. Oil production increased from 100-170 B/D during the first 9 months of 1970, before ignition of Duker B-3 on October 1, to a peak rate of 401 B/D in March, 1971. It declined to 285 B/D in January, 1972, just before air injection was terminated. During the 16 months of air injection into Duker B-3, the field produced 149,000 bbl of oil, average 310 B/D. For the total project period, the air-oil ratio averaged 6 Mcf/bbl.

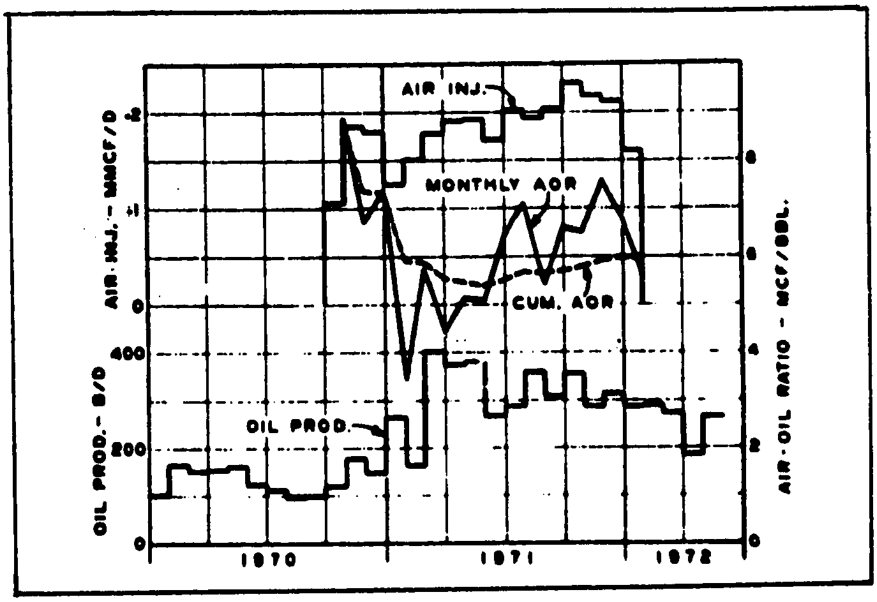


Figure 5.3 In-situ combustion pilot performance (From Elkins et al.)

After these two field tests, the engineers evaluated the possibility of project expansion. In their concluding remarks, they suggested an expansion of the in-situ combustion process despite the usual severe channelling and high operating cost during that time. One additional factor favored the expansion, the intake capacity of the single air injection well. They commented :

"Injectivity calculations indicated the air injection rate probably could be doubled or tripled with surface injection pressure not exceeding 2500 psi. If this would cause other wells to flow at a similar air-oil ratio, total field oil production rate might be doubled or tripled."

5.2.3 Optimization model applications and sensitivity analysis

The above quotation provides a good basis for the multi-criteria optimization model to evaluate the injection pressure, injection rate, and production rate for the in-situ combustion process. The detailed input reservoir parameters and the performance model results are listed in Appendix C. The multi-criteria programming technique is programmed in FORTRAN. The program listing and user's guide to the in-situ combustion pilot are shown in Appendix D. Since the published literature has not indicated different permeability producing zones, this pilot was evaluated on high and low permeability cases.

a) High permeability case: permeability = 2,500md

Optimization model results:

Table 5.1 Process Achievement for 2,500md

Timestep (month)	Prof ($)	P_{inj} (psi)	q_{inj} (MMcf/D)	q_{np} (B/D)	Rec (%)
1	41039.76	594.54	2.70	184.82	12.86
2	80914.61	539.43	2.70	173.22	20.24
3	119785.70	539.43	2.70	162.52	25.96
4	157735.50	492.31	2.77	155.49	31.30
5	194757.28	492.31	2.79	145.90	32.23
6	230891.00	437.00	3.02	140.06	33.86
7	266120.43	451.33	3.42	133.64	34.06
8	300551.30	461.35	2 96	128.58	38.87
9	334176.90	470.39	2.79	122.92	42.74

where:

Prof = profit, dollars

P_{inj} = injection pressure, psi

q_{inj} = injection rate, MMcf/D

q_{np} = production rate, B/D

Rec = oil recovery, %

The work of the optimization model usually is not completed when the multi-criteria programming technique has been successfully applied to identify the optimal solutions. The parameters used in the model are just the estimates from the performance model for a prediction of future conditions. The data obtained to develop these estimates are often rather crude and the process parameters may even represent overestimates, such as the maximum injection pressure and injection rate.

The sensitivity analysis of the decision variables can be performed in two aspects:

1) The goal objective functions are formulated as the regression equations, and the coefficients for each parameter are constant. The input parameters have to readjust themselves in order to achieve the predictive power of each regression equation. The readjustments of the decision variables form the feasible region for the model.

2) The physical model is simulated in different timesteps. Some of the decision variables vary throughout the timesteps, e.g., oil recovery, cumulative air injection, cumulative oil production, air-oil ratio, volume burned, and oil producing rate. The optimization model feasible region may vary in different timesteps; therefore, some of the decision variables are obtained for the feasibility of the modeling.

The multi-criteria programming technique forms the feasible region with the input parameters as the real constraints. Some of the real constraints have to readjust as the basic variables for the feasible region. Then the basic variables and some other real constraints are used as the decision variables for the optimization model. The basic decision variables are obtained for this particular model as follows:

Table 5.2 Basic Decision Variables for 2,500md

Timestep (month)	q_{np} (B/D)	CAI (MMcf)	q_{inj} (MMcf/D)	FB (B/AF)	PIS (%-%)	VISO (Cp)	VB (%)	P_{inj} (psi)
1	360.36	.33	5.52	299.50	2937.10	303.66	13.52	759.73
2	338.18	.57	5.52	252.86	2997.40	329.63	14.52	759.73
3	318.30	.79	5.52	232.26	3054.60	358.80	15.52	759.73
4	328.63	1.15	6.08	233.21	3116.10	429.96	16.52	698.56
5	308.40	1.41	6.08	237.26	3059.13	414.50	20.52	698.56
6	317.60	1.76	6.44	235.10	3043.50	407.16	24.52	633.70
7	315.96	1.95	6.60	231.95	3008.84	405.67	28.52	638.12
8	134.26	2.25	6.98	242.23	3013.78	416.24	31.52	632.31
9	128.16	2.55	7.02	245.17	3103.81	405.02	32.31	575.59

where:

q_{np} = production rate, B/D
CAI = cumulative air injected, MMscf/acre-ft.
q_{inj} = injection rate, MMscf/D
FB = fuel burned, B/acre-ft
PIS = oil saturation porosity
VISO = oil viscosity, C_p
VB = volume burned, %
P_{inj} = injection pressure, psi

b) Low permeability case: permeability = 878md

The other reservoir parameters are the same for the high permeability case. The pilot pattern is an inverted 5-spot in 5-acre spacing.

Optimization model results:

Table 5.3a Process Achievement for 878md

Timestep (month)	Prof ($)	P_{inj} (psi)	q_{inj} (MMcf/D)	q_{np} (B/D)	Rec (%)
1	41039.78	635.04	2.70	184.82	11.88
2	80783.87	599.43	2.70	173.22	21.95
3	118479.30	589.30	2.70	162.52	25.20
4	157188.40	580.31	2.98	155.49	28.10
5	191631.28	539.45	3.14	145.90	28.95
6	213602.73	537.00	4.33	140.06	32.20
7	266996.95	585.60	2.99	133.64	39.31

Table 5.3b <u>Basic Decision Variables for 878md</u>

Timestep (month)	P_{inj} (psi)	FB (B/AF)	CAI (MMcf/AF)	PIS (%-%)	VB (%)
1	978.95	284.17	0.33	3382.71	13.52
2	978.95	250.99	0.57	3497.99	14.52
3	978.95	219.99	0.79	3571.47	15.52
4	894.56	226.45	1.15	3440.01	20.52
5	894.56	227.49	1.41	3341.36	25.52
6	835.27	230.52	1.76	3295.84	30.52
7	861.03	236.08	1.95	3237.85	35.52

From the results of the decision variable in both processes,(Tables 5.2 and 5.3) the injection pressure is considerably higher for the low permeability case (861-979 psi) than the high permeability case (575-759 psi). The different injectivity of pressure is due to the tighter formation for the low permeability case. Two pressure ranges are plotted on a consolidated graph (Figure 5.4) for comparison. The process achievements show a closer range of injection pressure for both cases, but the injection pressure is still higher for low permeability case.

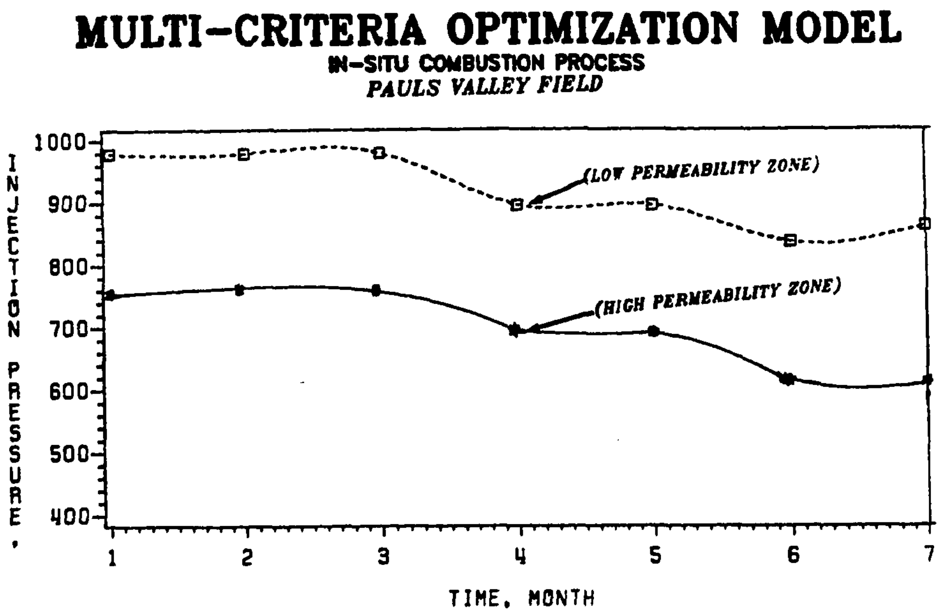


Fig. 5.4 Injection pressure for high, low permeability cases.

The oil saturation porosity, PIS, is usually used for EOR screening purposes because this term indicates a basic idea of oil-in-place. For the low permeability case, the PIS term has a relatively higher value which gives a lower oil recovery than the high permeability case. Therefore, the oil recovery is relatively lower for low permeability case; the oil recovery for two different cases are plotted in Figure 5.5.

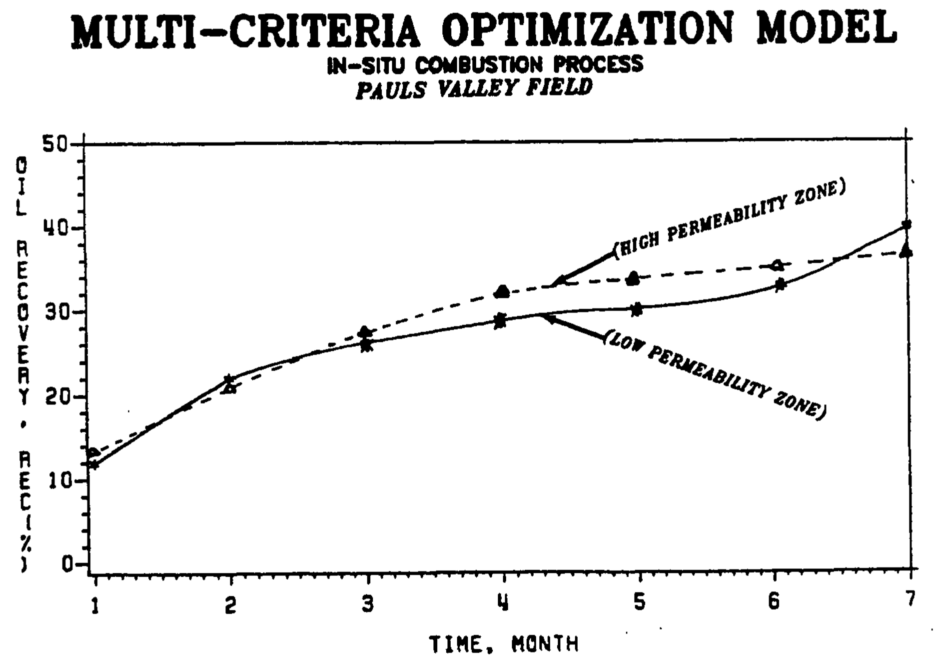


Fig. 5.5 Oil recovery for high, low permeability case.

Since the profit is based on the production rate, injection pressure, and injection rate, the profit is relatively lower for the low permeability case, i.e., $266,996.95 as compared to $334,176.90.

5.2.4 Steam drive process for S.E. Pauls Valley:

The screening criteria of the performance model has indicated a steam drive process for the pilot test in S.E. Pauls Valley field. The reservoir parameters are the same parameters used for the in-situ combustion process. Both high permeability and low permeability producing zone case studies are simulated for the steam drive process. The multi-criteria optimization model is also applied for both cases and the results are almost identical except that of the oil recovery. Therefore, the results are listed in a consolidated table as follows:

Table 5.4 Process Achievement for High, Low Permeability

Timestep (Month)	Prof ($)	P_{inj} (psi)	q_{inj} (B/D)	q_{pp} (B/D)	high k Rec (%)	low k Rec (%)
1	-1195536.3	1088.14	993.11	644.15	24.41	21.47
2	-1017656.3	1084.14	992.73	747.37	46.85	40.97
3	- 840099.4	1088.69	992.43	609.97	52.78	43.96
4	- 662876.6	1098.20	990.88	632.37	65.00	53.26
5	- 485971.7	1169.34	986.79	645.07	69.64	54.97
6	- 309386.8	1174.53	984.00	550.52	72.70	55.12
7	- 133146.3	1184.32	981.74	484.39	77.71	57.21
8	+ 42822.4	1212.79	979.05	468.05	82.34	58.93

Table 5.5 Basic Decision Variables (Both cases)

Timestep (Month)	EH (%)	VS (BBLS)
1	99.82	449450.13
2	99.64	450459.91
3	99.46	451469.94
4	99.28	452480.16
5	99.11	453490.06
6	98.93	454500.00
7	98.75	455509.88
8	98.58	456520.02

Since both process achievement parameters are almost identical, except oil recovery, a consolidated graph is plotted for the oil recovery in Figure 5.6. The oil recovery is considerably higher because the steam injection increases the injectivity of the process.

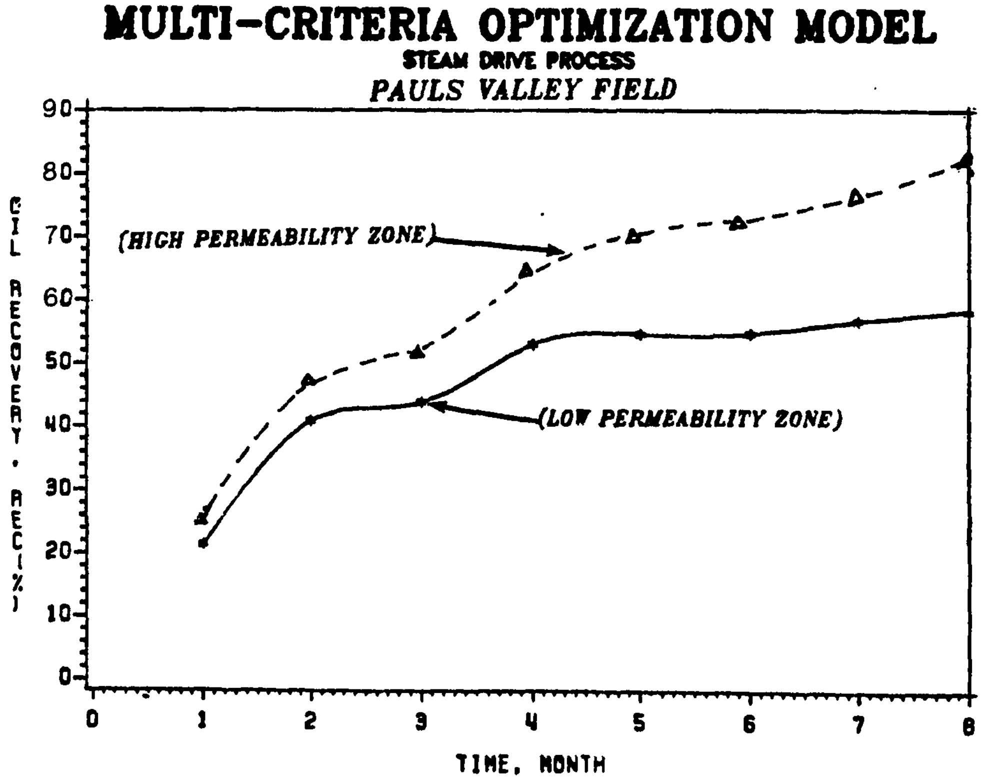


FIG 5-6 OIL RECOVERY VS TIME

As shown in Figure 5.7, the negative profit for the steam drive process indicates a failure in comparison with the in-situ conbustion process. This is due to the fact that the steam drive has a relatively high injection rate (avg. 990 B/D) and a high injection pressure (avg. 1,100 psi) for the process.

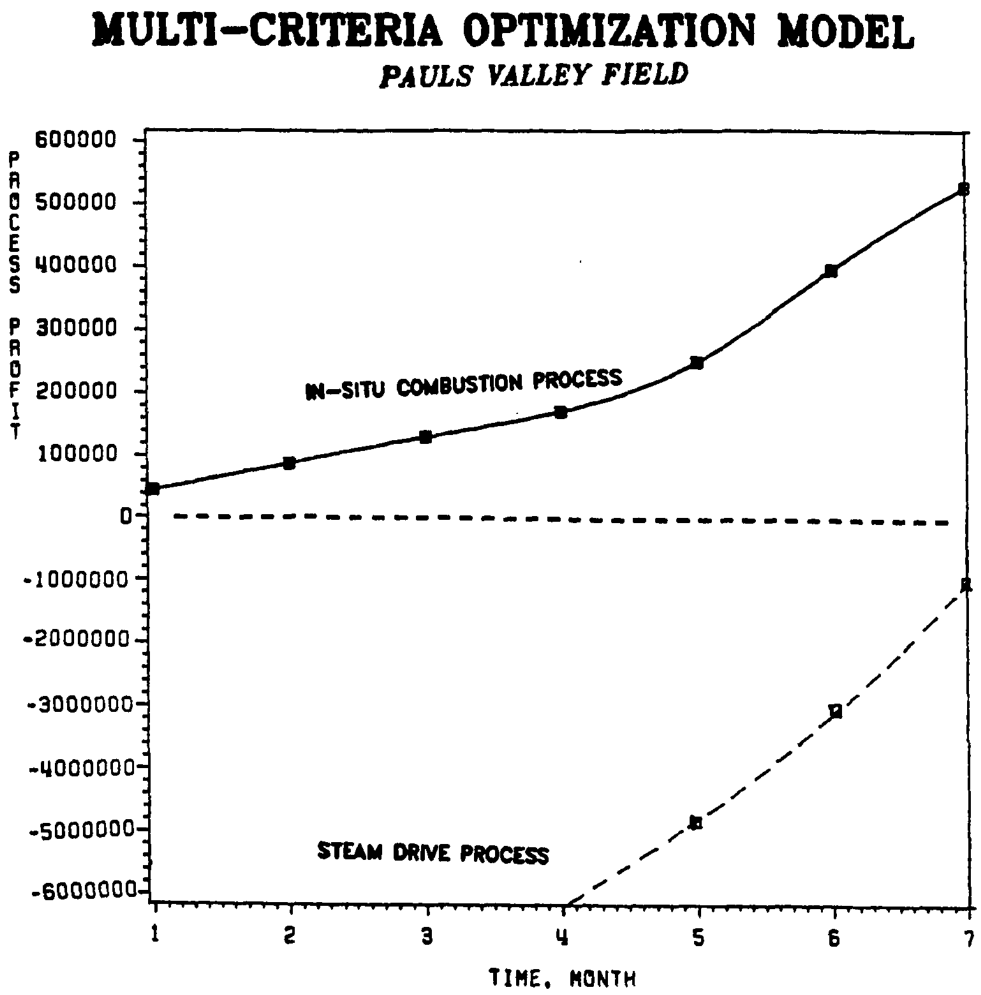


FIG 5.7 PROCESS PROFIT VS TIME

5.2.5 Discussion of field case study 1

1) In the high permeability and low permeability cases, the in-situ combustion process injection pressure is kept well below 2,500 psi as suggested by Elkins et al.,[22] (1972). Actually, the injection pressure achievement for the low permeability case is about 860-980 psi which is higher than the high permeability case (Tables 5.2, 5.3). This is because the tight formation has a limited capacity for injectivity.

2) The in-situ combustion process depends on the amount of air injected for combustion to form the hot front pushing the viscous oil out. The volume burned and fuel deposit are the factors which decide on the air injection rate. The optimum injection rate is about 2.7 MMcf/D for high and low permeability cases (Tables 5.1, 5.3). In the last four months, the injection pressure climbs up because of a higher consumption of oxygen for sustaining the combustion.

3) The success of the in-situ combustion process relies on the higher oxygen content for sustaining the combustion front to drive the oil out of the producing well. The low permeability has an advantage of sustaining the combustion better than the higher permeability case. The oil recovery is slightly higher for the high permeability case than for the lower

permeability case because an easier flow is found in the high permeability formation.

5) For Pauls Valley Field, the screening guide also recommends the steam drive process. The multi-criteria optimization model is able to tell the differences in the advantages of conducting an in-situ combustion process in this field.

a) The 1,100 psi injection pressure has to be sustained at a high injection rate for the steam drive process. The higher pressure for generating steam is costly and dangerous.

b) The steam injection is usually more costly than air injection. A 990 B/D steam injection rate puts a substantial cost on the steam drive process which results in a negative profit for most of the process time (Table 5.4).

c) The producing rate is almost double for the steam drive process. However, this oil production is usually a mixture of oil with water for the steam drive process. A higher producing rate would mean a higher cost for de-eumulsifiers.

d) According to a DOE survey on EOR (Johnson,[36] 1982), the steam drive process obtains a higher oil recovery than the in-situ combustion process. The steam drive process improves injectivity, the oil recovery is proved to be 20-30% higher than the in-situ combustion model (Tables 5.1, 5.3, 5.4).

The higher cost of the steam generation gives a negative profit for the steam drive process. Therefore, we would still consider using the in-situ combustion process in the S.E. Pauls Valley Field. (Figure 5.7)

5.3 Case Study 2: Loco Field, Oklahoma

5.3.1 Field History

Loco field is located in Southern Oklahoma, Ardmore Stevens County, Oklahoma. A waterflood was in operation on the Ida Billy lease when Continental Oil Co. obtained the Loco properties. However, the conventional waterflood was well past its economic limit for a reservoir containing 600 cp 20.8^{o}API viscous oil.

Conoco initiated a hot waterflood test in 1961 in order to obtain technical information and operating experience. The test was conducted on a 2 1/2-acre pattern that was part of a 20-acre conventional water-flood pilot area (shown in Figure 5.8). Hot water provided water injectivity increases of 200 to 400 percent. The final results showed that the hot waterflood increased oil recovery.

5.3.2 Loco Field (Hot Waterflood in Ida Billy Lease):

Summary of hot waterflood pilot experience:

Table 5.6 Ida Billy Reservoir Parameters Core Analysis

Porosity	= 25.6%
Oil saturation	= 58.1%
Water saturation	= 31.6%
Gas saturation	= 10.3%
Formation volume factor	= 1.05

Core Analysis Data

Sand	Depth (ft)	thickness (ft)	K(md)	S_o (%)	S_o bbl/AF	S_w Core	S_w Log
Upper	529-36	8	3065	47.3	1068	28.9	32
Lower	537-41	5	1733	44.4	980	39.4	60
Over-all	529-41	13	2553	46.2	1032	32.9	43

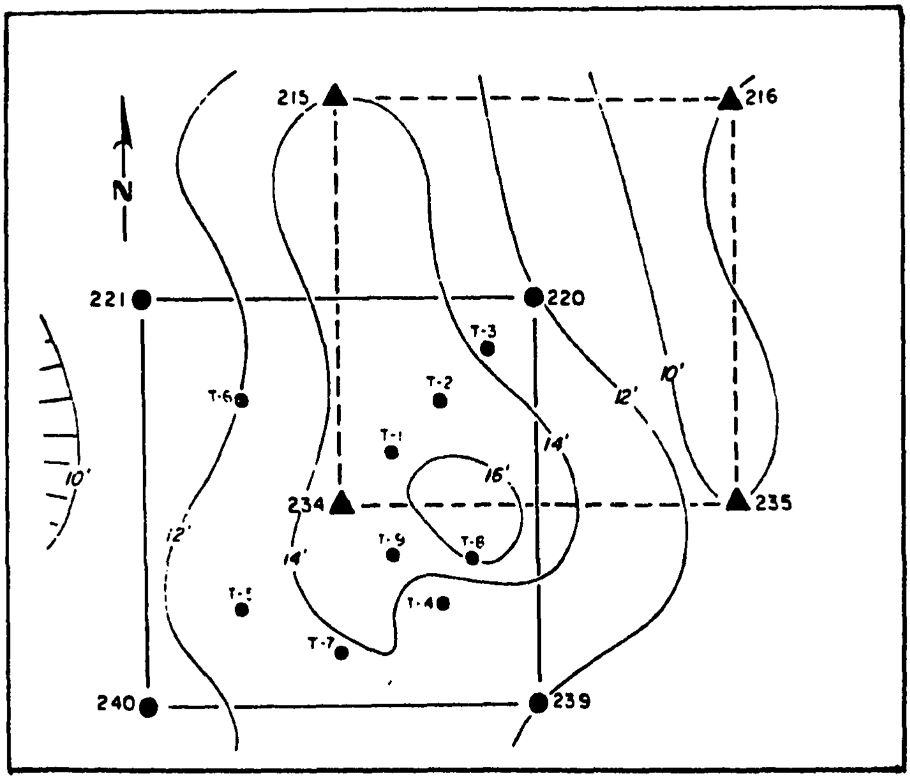


Figure 5.8 Pilot patterns, Loco hot water drive
(From Martin et al.)

The fresh water supply comes from nine fresh water wells.

The fresh water analysis is listed as:

Total dissolved solids, ppm	= 1,410
Specific gravity @ 78^{o}F	= 998
Calcium, ppm	= 10
Magnesium, ppm	= 18
Chloride, ppm	= 260
Sulfate	= None
Carbonate	= None
Bicarbonate, ppm	= 730

Description of the hot water flood process:

- o Hot water injectivity increase from 200 to 400%
- o 75% of the pattern was affected by heat
- o 60% of the injected heat was lost to over/underburden zones
- o Severe channeling across the lower portion of the oil-sand through zones of relatively high water saturation
- o "plugging off" the injection well because the injected water may have been contaminated with clay particles
- o Tertiary oil production from the pilot pattern area was 3,896 bbl or about 156 bbl/acre-ft
- o water-oil ratio is found to be 34:1

Process data:

Volume hot water injected	= 178,887 bbl
Hot water injectivity	= 4.0 BWPD/psi
Cumulative oil production	= 3,896 bbl (12/61-7/62)
Oil recovery(saturation)	= (46-35) = 11% = 156 bbl/acre-ft
Profit	= $123,464.24
Hot water injection rate (average)	= 500 BWPD (shown in Fig. 5.9)

Production rate for wells #221,239,240 is shown in Figure 5.9.

Average production rate/well = 280 B/D

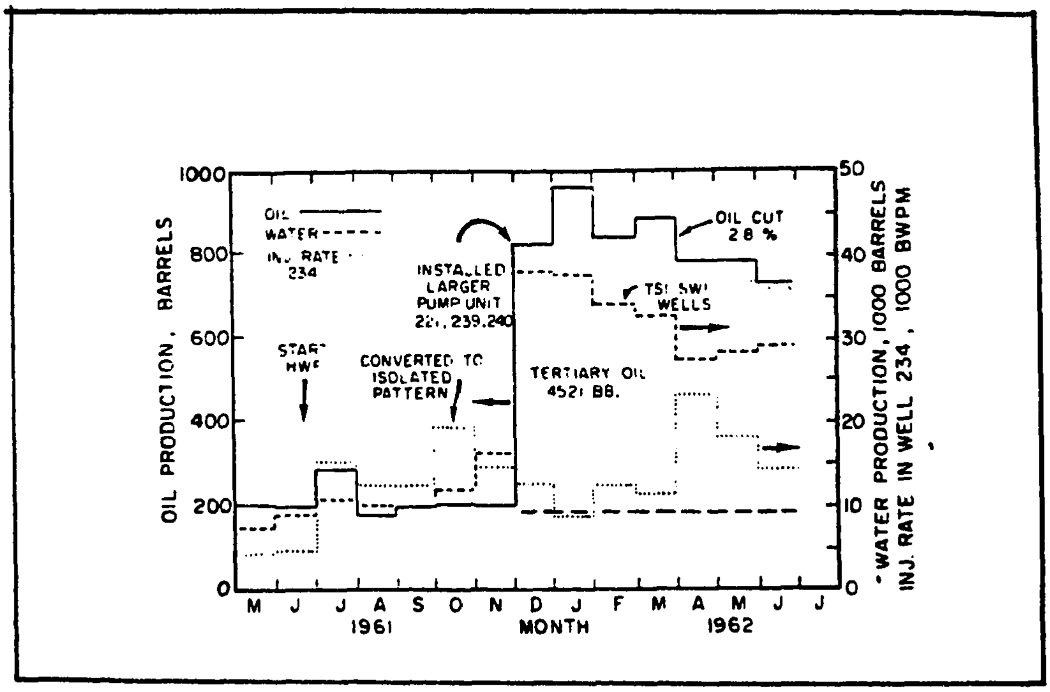


Figure 5.9 Monthly average production history and monthly average injection rate (From Martin et al.)

Process conclusive remarks:

(i) Heat produced additional oil from this watered-out reservoir

(ii) Heat increased water injectivities. This is a good indication that the heat will decrease oil viscosity substantially.

(iii) Wellbore heat losses were tolerable at 526 ft with injection rates of 500 to 600 BWPD, and with low-pressure gas in the casing-tubing annulus.

(iv) The injected water channeled through zones of high water saturation and some of the injected water reached the producing wells two months or more ahead of the heat front.

(v) Producing WOR's were very high.

(vi) The hot waterflood drive enhanced the incremental oil recovery of 156 bbl/acre-ft indicating that the steam drive is the potential enhanced oil recovery method.

5.3.3 Loco field (Steam drive process and in-situ combustion process)

In early 1970, Conoco planned a full-scale steam drive project in the Loco field. In 1982, Gas and Oil Journal Annual Production Report[2], the project consisted of 24 injection wells, 43 producing wells in a area of 90 acres. The details of the project will be disucssed in the steam drive section.

Summary of thermal processes description:

i) The same reservoir parameters are listed in the hot waterflood pilot test.

ii) The 5-acre pattern chart is assumed to be part of a 20-acre conventional waterflow pilot area.

iii) Since the steam drive is assumed to conduct at the same pilot pattern as the hot waterflood. There are several process parameters that remain the same as in the hot waterflood process, as follows:

- 75% of the pattern was affected by heat
- 60% of the injected heat was lost to over/underburden zones
- severe channeling across the lower portion of the oil-sand through zones of relatively high water saturation

Optimization model results:

a) Steam drive process

Table 5.7 Process achievement in Loco Field

Timestep (months)	Prof ($)	P_{inj} (psi)	q_{inj} (B/D)	q_{np} (B/D)	Rec (%)
1	18,300.8	829.57	993.11	644.15	20.54
2	118,093.1	801.19	992.73	650.93	40.04
3	247,489.2	940.88	992.43	609.97	58.10

b) In-situ combustion process:

Table 5.8 Process achievement in Loco Field

Timestep (Month)	Prof ($)	P_{inj} (psi)	q_{inj} (MMcf/D)	q_{np} (B/D)	Rec (%)
1	15,375.73	539.43	4.98	184.82	6.87
2	30,315.37	539.43	4.97	173.22	14.26
3	58,945.65	539.43	4.99	162.52	19.89
4	98,939.02	492.31	5.07	155.49	25.39
5	123,786.07	492.31	5.11	145.90	31.46
6	148,433.93	437.00	5.26	140.06	36.98
7	169,553.48	451.33	5.24	133.64	37.99
8	190,655.35	422.79	5.33	128.58	46.69
9	220,324.72	467.18	5.10	122.92	51.53
10	238,897.82	422.85	5.60	128.11	53.70

Table 5.9 Basic Decision Variables in Loco Field

Timestep (Month)	TRS (md-ft/cp)	VISO (cp)
1	1,050.52	395.68
2	1,050.52	372.50
3	1,050.52	373.79
4	1,030.50	414.18
5	1,030.48	408.72
6	942.09	406.30
7	846.87	421.20
8	795.02	437.41
9	671.40	496.18
10	691.19	428.97

where:
TRS = transmissibility, (kh/μ)

From the results of process achievement (Tables 5.7, 5.8), we find both processes are very similar in terms of the final profit and oil recovery; i.e., $238,897.82 profit and 54-58% recovery. The injection pressure, injection rate, and production rate will be discussed in the later section. In the in-situ combustion process (Table 5.9), the decision variables indicate heat lost to - the formation becoming apparent because the viscosity increases as the temperature drops. Therefore, the transmissibility decreases to the flow when the oil is getting thicker in the formation.

5.3.4 Discussion of Case Study 2

1) In early 1970, Conoco planned on a full-scale steam drive project in the Loco Field. Fresh water is always the first consideration of the steam generation because

water treatment adds a substantial cost to the project (Fincher,[26] 1969). Conoco drilled nine fresh water wells for hot waterflood; but the wells could not provide enough fresh water for the entire project. Therefore, Conoco actually built a fresh water reservoir for fresh water supply.

A small pilot in-situ combustion process was conducted in 1963 and the project was abandoned for safety reasons (Martin, 1975).

2) The Loco is an old field; many wells have been drilled in all the area. Channeling is a severe problem. Steam leaks in the injection wells and, in some old wells, are very common. The producing formation is 500 ft. deep. The optimized steam injection rate maintains at 992 B/D throughout the project. The optimized injection pressure is kept in the range of 800 to 950 psi ; i.e., a higher injection rate and a lower injection pressure give a better result.

For the same reasons, the optimized air injection pressure is kept at 420-540 psi and a higher injection rate of 4.9-5.60 MMscf/D for the in-situ combustion pilot.

3) The sensitivity analysis of input parameters has been done and the parameters do not affect the feasibility of the optimization model in general. The injection pressure and production rate show a slight change

throughout the process; the injection rate is increased to about 992 B/D and it remains steady throughout the process. This steam drive pilot project is an accelerated project of the hot waterflood. The average production rate will be 635 B/D in three months (Table 5.7). The steam generator is a portable one which can be moved around in the whole field. The steam driving period runs about 3 to 5 months in the Loco Field. The movable steam generator has the advantage of accomplishing the accelerated project as designed in the optimization model. The project life is about 10 months for the in-situ combustion pilot which is three times longer than the other one (Table 5.8). Therefore, the increasing steam injectivity can accelerate the process considerably.

4) The optimum production rate (avg. 638 B/D or 160 B/D/well) is higher than the reported average production rate (100 B/D) in the Loco Field (Gas & Oil Journal Production Report,[2] 1982). The production is being pumped off by using sucker rod pumps. The oil is both viscous and low in gas content. Therefore, the collection system is characterized as having a relatively smaller oil-gas separator and a large de-emulsifier for adding chemicals which may increase the project operating cost.

The production rate is 128-185 B/D for the in-situ combustion process. This production rate does not consist of hot water production as in the steam drive process. If we consider 30% oil cut for the steam drive production, the actual oil production rate is also turned out to be 130 B/D!

5) The steam drive process profit is $247,489.20 at the end of the drive (Table 5.7). This profit is a bigger economic gain than the hot waterflood $123,464.24. The steam drive cumulative oil production is 8,248 bbls which is double the hot waterflood of 3,896 bbls production. This double incremental production agrees with the profit gained.

The in-situ combustion process profit is $238,897.82 in ten months. As an accelerated project with a quicker rate of return, the steam drive process is a better choice.

A pilot steam drive process is being conducted in the deeper producing zone (D-deep) at 1,000 ft. depth. It may be too early to reach a conclusive result about the project (Oil and Gas Journal,[2] 1982).

5.4 Discussions

In general, the simplest model should be tried first, for additional accuracy is apt to require additional cost and time. The performance model simulates the thermal process and the multi-criteria programming optimizes the outcomes; however, the modeling assumed ideal conditions.

The model is not a specialized model tailored for any production problems, e.g., fracture, corrosion, sand, and channeling. If any of these problems arise during production, the engineer will consider shutting-in the well and may suggest a work-over job. Models that takes into account such uncertainties are called "stochastic." Formulation of a model in stochastic terms poses another fundamental question: What is meant by an optimum solution in the face of uncertain outcomes? In other words, the uncertainties introduced in the stochastic model effectively present a guaranteed solution. In Bentsen and Donohue's paper[8] (1969), the authors discussed the idea:

> "The problem is not in finding a means for comparing policies, taking into account the possible fluctuation of outcomes, but rather to find a unique measure. It develops that there is no one method that can be considered "best". However, it has become a generally accepted procedure to use some average of the possible outcomes as a measure of the value of a policy. This particular average possesses an important invariant property - linearity - that greatly simplifies the functional equations describing the process. As a consequence of this property, future decisions can be based solely upon the present state of the system, independent of the past history of the process."

A stochastic model required considerably more computation and memory storage in the computer.

However, the author suggests a stochastic model could be a good research topic provided a bigger computer system is available

By the same token, there is another problem posing on the expansion of the model. This model uses the reservoir data which is an average data point. The author only used the average data point on a single injection well of the inverted 5-spot and simulated the production well process parameters. Evidently, the reservoir heterogeneity could only be simulated by using a number of wells' data and their pressure and production history, etc. The author suggests that the well-to-well data base will be used when the computer simulation group works on the modeling.

VI. SUMMARY AND CONCLUSIONS

6.1 Summary of Modeling

The modeling concept has began with a pilot test applied to a reservoir evaluation, and this concept is the usual evaluation procedure being used by the oil companies. In fact, the engineers carefully design a pilot and collect the process parameters from these wells or from the observation wells. The process parameters can perform any type of reservoir evaluation when the pilot is successfully run. The given reservoir parameters are only a single representation; therefore, the inverted 5-spot pilot test is designed. Then, the given data has been applied to the injection well and the four producing wells respond from the process performance model, which generates the process parameters. These process parameters can be considered the same as the actual pilot test has been conducted in the field.

Therefore, the performance model has been carefully designed. In the performance model, a screening criteria is set for both steam drive and in-situ combustion processes. The criteria screens through the undesirable candidates and validates the potential pilots for evaluation. The performance model consists of two individual process models; namely, the Marx and Langenheim steam drive model and the oil recovery/volume burned in-situ combustion model. In the steam drive model, the author included Van Lookeren's sweep efficiency approach for maximum injection rate and pressure, and also included the Mandl-Volek refinement on the hot water bank. This steam drive model is a good simulation for most of the reservoir cases (i.e., the problem is reasonably resolved for the Marx and Langenheim solution for thin layer formation modeling). In the in-situ combustion model, the author applied the oil recovery/volume burned method which is a result of both field and experimental tests. The relationship is generalized on a graph with oil recovery versus volume burned and a prediction can be made by curve-fitting on those curves. The inverted 5-spot pilot test is selected for this process, and a radial flow equation is used for the calculation of air injection pressure and injection rate.

The performance model has been used to simulate 42 steam drive and 32 in-situ combustion field cases and generates both process parameters for regression analysis.

The current process parameters provide a good foundation for regression modeling.

Regression modeling is employed to formulate the objective functions for the optimizaion model. Several SAS regression analysis procedures have been used in the modeling: RSQUARE, STEPWISE, MAXR, and BACKWARD. These procedures formulate the basic terms for the dependent variables such as oil recovery, injection rate, injection pressure, and production rate. These regression equations were screened through by the REG procedure to get rid of outliers and collinearity problems. The accuracy of prediction has also been considered for those equations. In this particular regression system, the model's dependent variables are also the independent variables of some other regression equations; therefore, interdependent relationships are established among the equations. Those relationships can cause more serious regression errors. The SYSREG regression models are confirmed with a 95-99% weighted R-square. The residual plots further reveal that the equations are reasonably fit and most of the prediction points fall within the 95% confidence limits. The AUTOREG further checks the possibility of time serial problems which are not significant in the regression modeling for both processes. Regression analysis formulates objective functions and they can be used for the optimization model with confidence.

In the S.E. Pauls Valley and Loco fields case studies, the performance model has been used again to evaluate the process parameters optimization model. Those process parameters are substituted as constants into the objective functions obtained from regression analysis. The multi-criteria objective functions have been successfully applied in the optimization model.

6.2 Conclusions

1) This model indicates that a bridge has been successfully built between the engineering aspect and decision-making aspect. In the engineering aspect, optimized oil recovery, injection rate, injection pressure and production rate are obtained from the multi-criteria optimiztion model. An engineer can simply assign those optimized parameters as the designed requirement. In the decision-making aspect, the process profit is optimized with the preemptive priorities of engineering parameters. The profits of each process can be compared and the engineer can reject the uneconomical proposal.

In the field case studies, these two aspects were demonstrated very well. In S.E. Pauls Valley field, the screening criteria suggested both the steam drive and the in-situ combustion process could be applied. The performance model has also simulated both processes as if they are promising. The multi-criteria programming technique minimizes the deviational variables and evaluates the achievement of each goal. In the in-situ combustion process, the high permeability case could possibly be better because a lower air injection pressure is applied (avg. 450-540 psia compared to 580-630 psia). The process achieves a higher oil recovery (43% compared to 39%) and yields a much higher profit, i.e., $334,176.90 as compared to $270,000.00!

The steam drive process, in Pauls Valley Field, is unfavorable both in the engineering and economic aspects. The achievement indicates the production rate has to "jack-up" 600 to 770 B/D which is unusual for such heavy crude. The profit is a very great loss in comparison with the other process. Apparently, this candid evaluation of both processes could never be achieved with only the performance model!

Conoco operated the Loco field as early as the 1950s. This field has a reputation for shallow but fresh water sand (Suchard,[62] 1983), and so is a good candidate for either steam drive or in-situ combustion processes. Since the hot waterflood proved an increase in injectivity, Conoco decided on a full-scale steam drive project. From the optimization model solutions, the steam evidently boosts up the injectivity substantially. As a result, the injection pressure is doubled; and the production rate is pushed up to 5 times higher (640 B/D compared to avg. 150B/D). Although the in-situ combustion pilot also has performed reasonably well in this field, the steam drive pilot is an accelerated process, i.e., 3 months compared to 10 months. The steam drive process has a quicker rate of return with a higher profit.

Therefore, the steam drive process is a favourable choice. This fact confirms with Conoco abandonment the in-situ combustion pilot in this field. The process safety and environmental pollution were also problems.

2) The steam drive model has proved two basic effects for oil recovery and production:

a) decreasing the oil viscosity,

b) increasing the injectivity.

But, the in-situ combustion has only the effect of decreasing oil viscosity. The increasing injectivity effect usually enhances a higher oil recovery for the steam drive process. In the S.E. Pauls Valley field , there is only a slightly higher oil recovery in high permeability zone for the in-situ combustion process (Figure 5.5). However, a comparatively higher oil recovery results in the steam drive process (Figure 5.6) than in the in-situ combustion process for the same high permeability zone. In the Loco field, the injectivity effect of the steam drive is even more apparent that the process is much more accelerated, leading to a quicker return in the investment.

3) In this model, the optimized design parameters and the profit decision analysis are obtained simultaneously. Due to the unidimensional limitation of the linear programming, the engineering optimization applications are usually not practical. This multi-criteria optimization model has proved to be a more practical engineering application. The injection pressure, injection rate, and production rate are the design parameters; the oil recovery and profit are the decision analysis. The optimization model can also be applied in most engineering design. This easy application has been illustrated in the field case studies (Appendix D).

Furthermore, the multi-criteria optimization model also has the advantage of small size. The model only needs 35k core memory for storage and execution in the minicomputers. With a slight modification, the program could be executed comfortably with a 48k Apple computer or any other desktop microcomputer.

4) A one-dimensional performance model has been successfully applied for screening and evaluating both the steam drive and in-situ combustion processes. In the model, the screening criteria, the Marx and Langenheim

solution and oil recovery/volume burned method, are incorporated as the basics which are supplemented with other theories in order to prefect the deficiencies, such as thick layer and frontal drive mechanism.

5) In thermal processes regression modeling, series SAS procedures have been successfully used to formulate the equations, and REG procedure checks out the possible outliers and collinearity. The SYSREG procedure has been applied to formulate the regression equations simultaneously in one system; the regression models are confirmed with weighted R-square 95-99% for both processes. This system regression technique has been intelligently adopted in the engineering application.

6) This work has demonstrated the successful application of PDS data for the reservoir evaluation. An inverted 5-spot pilot design has been used for the thermal recovery performance evaluation. The pilot results can be projected on the entire reservoir. The minicomputers VAX 11/780 and PDP 11/70 were used for this research work. The computer programs can be executed on any desktop microcomputer with a slight modification in the programs. The use of a stochastic and well data may prove to be a more realistic approach; however, it is not the purpose of this research.

NOMENCLATURE

A = entire reservoir area, acres

AE = area sweep efficiency, fraction

AOR = air-oil ratio , Mcf/bbl

AR = vertical conformance factor, radial flow case

ASR = air-sand ratio, Mcf/ acre-ft

API = oil gravity, ^{o}

CAI = cumulative air injection, MMscf/acre-ft

c_o, c_w, c_r = heat capacity with respects to oil, water and rock

CN_p = projected total production of a whole reservoir, bbls

D = thermal diffusivity of cap rock ($K_h/\rho c$), ft^2/D

FB = fuel burned, B/acre-ft

GOR = gas-oil ratio

h = pay thickness, ft

h_n = net pay thickness, ft

H_{wv} = latent heat of vaporization at P_s, T_s, Btu/lb.

H_{ws} = the enthalpy of wet steam at P_s, T_s, Btu/lb.

H_{wr} = the enthalpy of saturated liquid at P_s, T_s, Btu/lb.

H_t = the specific enthalpy of steam P_i, T_i at reservoir conditions

Iinj = no. of injection patterns

i_{s2} = maximum allowable steam injection rate, B/D

i_{s1} = initial steam injection rate, B/D

k_h = thermal conductivity, Btu/ft-hr-^{o}F

k_s = permeability of steam, md

m_s = steam injection rate, B/D/pattern

N_p = cumulative production, bbls

PIS = oil saturation porosity

Prof = profit, dollars

P_{inj} = injection pressure, psi

P_1 = initial injection pressure, psia

P_2 = increamental injection pressure, psia

P_s = steam injection pressure, psia

q_{inj} = injection rate, MMcf/D

q_{np} = production rate, B/D

q_o = production rate, B/D

Rec = oil recovery, %

R_{os} = oil-steam ratio, bbl/bbl

t_c = production time peroid, days

TAOR = air-oil ratio for the entire reservoir, Mscf/bbl

TCAI = air requirement for the active reservoir, MMscf

TN_p = cumulative production for the total reservoir, bbls

ΔT = temperature difference, ^oF

T_r = reservoir temperature, ^oF

T_s = $115.1P_s^{8.225}$, ^oF

TRS = transmissibility, (kh/μ)

X_i = steam quality, fraction

$\overline{X}_i$ = steam quality at the sandface, fraction

VISD = dead oil viscosity, cp

VISO = live oil viscoisty, cp

V_B = volume burned, %

VTSW = vertical sweep efficiency, fraction

V_s = total steam injection rate, B/D

ϕ = porosity, fraction

$(\rho c)_{R+F}$ = heat capacity of fluids saturated rock, Btu/ft^3-^oF

$(\rho c)_{ob}$ = heat capacity of overburden rock, Btu/ft^3-^oF

ρ_s = $5.06\ e^{0.000359P_s} - 5$, lb/cu-ft

ρ_o = $\dfrac{141.5}{API + 131.5}\ 62.4$, lb/cu-ft

μ_s = $0.0000517T_s + 0.00049$, cp

Bibliography

1. Alcocer, A.C., "A Study of Diluent Fluids Associated with Crude Oil Viscosity in Orinoco Tar Belt, Venezuela," unpublished M.S. thesis, Univ. of Oklahoma, (1979)

2. "Annual Production Report, 1982", Oil and Gas J. (April 5, 1982), 139-153

3. Akindele, F., Senior Reservoir Engineer of Sohio Petroleum Oil Co., Dallas, Tx., Telephone conversation, (1982)

4. Aronofsky, J.S., and Lee, A.S., "A Linear Programming Model for Scheduling Crude Oil Production", J. Pet. Tech., (July 1958), 51-54

5. Asward, Z.A.R., "Optimization Techniques for a Multi-dimensional Drilling Model," unpublished Ph.D. thesis, Univ. of Oklahoma, (1980)

6. Baker, P.E., "Effect of Pressure and Rate on Seam Zone Development in Steamflooding, J. Pet. Tech., (Feb., 1973), 274-294

7. Burger, J.G., "Analysis Aids EOR Method Selection", Petroleum Engineer International, (Mar., 1982), 186-194

8. Bentsen, R.G., Donohue, D.T., "A Dynamic Programming Model of the Cyclic Steam Injection Process, " J. Pet. Tech., (Dec., 1969), 1582-1596

9. Beggs, H.D., Robinson, J.R., "Estimating the Viscosity of Crude Oil Systems", J. Pet. Tech., (Sept., 1975), 1140-1141

10. Buhima, I., Reservoir Engineer at Johnston-Macco Service Co., Houston, TX, private communication about well-testing data collection, (1982)

11. Carter, R.D., "Appendix to "Optimum Fluid Characteristics for Fracture Extension", by G.C. Howard and G.R. Fast, Drill and Prod. Prac., SPE, (1957), 267

12. Charnes, A., Cooper, W.W., "Management Models and Industrial Applications of Linear Programming," New York, John Wiley & Sons, Inc., (1961)

13. Chu, D., "A Study of Fireflood Field Project", J. Pet. Tech. (Jan., 1977), 111-120

14. Coats, K.H., "Use and Misuse of Reservoir Simulation", SPE Reprint Series, Numerical Simulation, (1975), 183-190

15. Crichlow, H.B., "Mathematical Models for the Design of Thermal Methods", Heavy Oil Recovery Symposium, Venezuela, (1974)

16. Cronquist, C., Secrest, E.L., and J.W. Jones, "A Computer Model for Comparative Economic Analysis of Enhanced Oil Recovery Projects", SPE/DOE 9818 presented in 2nd Joint Symposium of EOR, Tulsa, OK, (April 1981)

17. Crovelli, R., "Oil and Gas Resource Appraisal Methodology", PDS Advisory Meeting, Washington D.C., (1981)

18. Dietzman, W.D., Carrales, M., Jr., and C.J.Jirik, "Heavy Crude Oil Reservoirs in the United States: A Survey", Bureau of Mines Information Circular 8263, (1965)

19. Dietzman, W.D., Carrales, M., Jr., and C.J. Jirik, "Heavy Crude Oil Reservoirs in the United States: A Survey", USGS Circular 725, Washington D.C., (1975), 1-9

20. Doscher, T.M., Ershaghi, I., "Current Economic Appraisal of Steam and Combustion Drives", SPE 7073, presented in 5th SPE Symposium on Improved Oil Recovery Tulsa, OK, (1978)

21. Doscher, T.M., Osazuwa, S.O., G. Farhad, "Steam Drive Definition and Enhancement", J. Pet. Tech., (July, 1982), 1543-1545

22. Elkins, L.F., Morton, D., and W.A. Blackwell, "Experimental Fireflood in a Very Viscous Oil-Unconsolidated Sand Reservoir, S.E. Pauls Valley Field, Oklahoma", SPE 4086 paper presented in 47th Annual Fall Meeting of SPE, San Antonia, TX (Oct., 1972)

23. Farouq Ali, A.M., "Graphical Determination of Oil Recovery in a Five=Spot Steamflood", SPE 2900 presented in SPE Rocky Mt. Regional Meeting, Casper, WY (June, 1970)

24. Farouq Ali, S.M., "Marx and Langenheim"s Model of Steam Injection", Producers Monthly, (Nov., 1966)

25. Farouq Ali, S.M., "Secondary and Tertiary Oil Recovery Processes - Steam Injection", Interstate Oil Compact Commission, OKC, OK (1974), 134-182

26. Fincher, D.R., Hagist, F.L., and D.L. Gallaher, "How to Treat Feedwater on Steam Injection Projects," Reprinted from World Oil, Gulf Publishing Co., (1969), 83-88

27. Freund, R.J., Littell, R.D., "SAS for Linear Models", SAS Institute Inc., (1981), 42-45

28. Gates, C.F., Ramey, H.J., Jr., "Fluid Results of South Belridge Thermal Recovery Experiment," Trans. AIME (1958), 213, 236-244

29. Gates, C.F., Ramey, H.J., Jr., "A Method for Engineering In-Situ Combustion Oil Recovery Projects", J. Pet. Tech., (Feb., 1980), 285-294

30. Gomma, E.E., "Correlations for Predicting Oil Recovery by Steamflood", J. Pet Tech., (Feb, 1980), 325-332

31. Goodbread, D., Cronquist, D., "Data Validation by Using Computer Procedures," DOE report, (1981)

32. Grummick, J., Bavinger, B., "Cluster Analysis and the Field Test Data Base", PDS Advisory Meeting, Washginton, DC, (1981)

33. Hayes, H.J., "Enhanced Oil Recovery - An Analysis of the Potential for EOR from Potential Fields in the U.S. 1976 to 2000", National Petroleum Council, (1976), 12-20

34. Ijiri, Y., "Management Goals and Accounting for Control," Rand-McNally, Chicago, (1965)

35. "Improved Oil Recovery Field Reports", Society of Petroleum Engineers of AIME, Vol 1-5, (1975-1981)

36. Johnson, H.R., "Outlook for Enhanced Oil Recovery", presented at EOR Conference, New Orleans, LA, (Feb., 1982)

37. Jones, D., "An Application of Basin Analysis to Exploration Strategy Determination", PDS Advisory Meeting, New Orleans, LA, (1980)

38. Jones, J., "Steam Drive Model for Hand-Held Programmable Calculators", J. Pet. Tech., (Sept., 1981), 1583-1598

39. Lee. S.M., "Goal Programming for Decision Analysis," Auerbach Publishers, Inc., (1972)

40. Maddala, G.S., Economics, McGraw-Hill Book Co., (1977), p. 220

41. Mandl, G., Volek, C.W., "Heat and Mass Transport in Steam Drive Process", SPE Journal, (1969), 59

42. Martin, W.L., Dew, J.N., M.L. Powers and H.B. Steves, "Results of a Tertiary Hot Waterflood in a Thin Sand Reservoir", J. Pet. Tech., (July, 1968), 739-750

43. Martin, W.L., "In-Situ Combustion in Mid-Continent Reservoirs", SPE 2043, presented in SPE Regional Meeting, Oklahoma City, OK, (1968)

44. Marx, J.W., Langeheim, R.N., "Reservoir Heating by Hot Fluid Injection", Trans. AIME, 216, (1959), 312

45. McKie, J.W., "Heavy Oil: Its Significance for the U.S. Energy Balance", The Journal of Energy and Development, International Research Center for Energy and Economic Development, Univ. of Colorado, (Spring, 1982), 152-153

46. Meyer, R.F., and P.A. Fulton, "Toward an Estimate of World Heavy Crude Oil and Tar Sands Resources", National Tar Sands (Heavy Oil) Symposium, Lexington, Kentucky, (June, 1982)

47. Myhill, N.A., G.L. Stegemeier, "Steam-Drive Correlation and Prediction", J. Pet. Tech., (Feb., 1978), 173-181

48. Newman, C.H., "A Mathematical Model of the Steam Drive Process - Applications", SPE 4757, presented at the SPE 45th Calif Regional Meeting, Ventura, 1975.

49. Offeringa, J., R. Barthel and J. Weijdema, "The Interplay Between Research and Field Operations in the Development of Thermal Recovery Methods", Proceedings of 3rd European Symposium on EOR in Bournemouth, UK, (Sept, 1981), 527-541

50. "Petroleum Data System User's Guide", Information Systems Program Office, Energy Resource Center, Univ. of Oklahoma, (1980)

51. Philip, D.W., Moss, J.T., "Thermal Recovery Methods," PennWell Books, (1983). 146-205

52. Perry, C. W., "Economic of Enhanced Oil Recovery-Final Report," DOE report, (1981)

53. Pindyck, M. E., Roberts, E. S., and, D.L. Rubinfeld, "Econometric Models and Economic Forecasts", New York: McGraw-Hill, 1976

54. Ramey, H.J., Jr., "A Current Review of Oil Recovery by Steam Injection," Proc. 7th World Petroleum Congress, Vol. 3, 471-476

55. Romero, E., "Optimization of Steam Drive Processes by Geometric Programming", Stanford Univ., unpublished MS thesis (1974)

56. Rowan, G., and Warren, J.E., "A System Approach to Reservoir Engineering Optimum Development Planning," J. of Can. Tech., (July-Sept, 1967), Vol. 6, No. 3, 84-94

57. Saisasong, A., J.P. Yu, "Study of Distribution of Residual Oil Saturation by Statistical Methods," PDS Advisory Meeting, Washington, D.C., (1980)

58. Satman, M., Brigham, W., "Recovery Correlations for In-situ Combustion Field Projects and Applications to Combustion Pilots", J. Pet. Tech., (1980), 2132-2138

59. Shutler, N.D., Numerical Three-Phase Model of Linear Steam Flood Process," Soc. Pet. Eng. J., (June, 1969), 232-246

60. Soliman, M., Brigham, W., "Numerical Modeling of Thermal Recovery Process", DOE Report, (1981)

61. "SAS User's Guide", SAS Institute, 1979 Edition

62. Suchard, J., Engineer at Oil Compact Commission Office, OK, Private communication about the Oklahoma Oil field, (1983)

63. Time, April 28, (1980), p.45

64. Theil, H., "Principles of Econometrics", New York: John Wiley and Sons, 1971

65. Van Lookeren, J., "Calculation Methods for Linear and Radial Steam Flow in Oil Reservoirs," SPE 6788 presented in SPE 52nd Annual Meeting, (1977)

66. Van Poollen, "Enhanced Oil Recovery Manual", Penwell Publication Company, (1981)

67. Venkatesh, E.S., "Application of Petroleum Data System to Oil Field Evaluations," unpublished MS thesis, Univ. of Oklahoma, Norman, (1980)

68. Vogel, J.V., "Simplified Heat Calculations for Steamfloods", SPE 11219 presented in SPE 57th Annual Meeting, New Orleans, LA, (1982)

69. Williams, R.L., Ramey, H.J., Jr., S.C. Brown, S.K. Sangal, R. Raghaven, "An Engineering Economic Model for Thermal Recovery Methods", SPE 8906 presented in 50th California Regional Meeting, in Los Angeles, CA, (1980)

70. Wilson, L.A., Root, P.J., "Cost Comparison of Reservoir Heating Using Steam or Air", J. Pet. Tech, (Feb., 1966), 233-239

71. Wilson, L.A., Wygal, R.J., et al., "Fluid Dynamics During an Underground Combustion Process", SPE reprint No. 7, (1965), 87-95

72. Winters, J., Staff in the University of Oklahoma Computer Service, Drafts for TSO lecture notes, 1982

73. Yuen, M., Engineer of Core Laboratory, Dallas, TX, Telephone communication, (1981)

74. Fassihi, M. R., Gobran, B. D., and H. J. Ramey, Jr. "An Algorithm for Computing In-situ Combustion Oil Recovery Performance," DOE report, (1981).

75. Muskat M., "Physical Principles of Oil Production," International Human Resources Development Corp., Boston, MA. (1981), 688-715.

76. Ignizio J. P., "Goal Programming and Extensions", Lexington Book, Lexington MA (1978), 119-176

Appendix A

Thermal Process Screening Guide

Within the performance model, the author included an initial screening guide for the candidate reservoirs. In this case, the candidate reservoir has gone through an EOR screening procedure and missing data can be validated. The screening criteria (Hayes,[33] 1976) are listed as follows:

Screening guide for stream floods

a)	API gravity	≤ 25
b)	oil viscosity (cp)	> 20
c)	depth (ft)	< 5000 but > 200
d)	payzone thickness (ft)	≥ 20
e)	permeability (md)	≥ 20
f)	oil saturation	$> .50$
g)	min oil content (STB/AF)	> 500

Screening guide for in-situ combustion

a)	API gravity	≤ 25
b)	oil viscosity (cp)	> 20
c)	depth (ft)	< 5000
d)	payzone thickness (ft)	≥ 10
e)	oil saturation	$> .50$
f)	min oil content (STB/AF)	> 500

The screening method has been programmed in the main program.

Appendix A

Marx and Langenheim solution

This model was first introduced by Marx and Langenheim[44] in 1959 and was further clarified by Farouq Ali[24] in 1966. Although the authors did not discuss the basic assumptions upon which the model was formulated, they have implicitly assumed that the reservoir base and cap rock are geometrically, hydrologically and thermally homogeneous and isotropic, and that radial heat conduction can be ignored. In addition, they have assumed that only steam displaces the oil, without a hot water bank ahead of it, and that the fluids are incompressible.

cap rock, Tr
reservoir rock, Tr
base rock, Tr

Fig. A.1 Initial Temperature of reservoir, base and cap rock.

The figure above shows the reservoir base and cap rock at an initial temperature T_r. The thickness of the base and cap rock are assumed infinite. At time $t = 0$, heat is applied to the face of the reservoir rock and the temperature T_s is sustained. Consider the origin of the y coordinate to be at the contact between reservoir and cap rock. The differential equation which describes the heat flow in the y direction is given by:

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial y^2} \qquad (A.1)$$

The initial and boundary conditions are: $T(y,0) = T_r$ for $0 \leq y \geq \infty$; and $T(0,t) = T_s$, D is the thermal diffusivity of the cap rock (overburden) which is defined as $K_h/(\rho C)$,

where:

K_h = thermal conductivity, BTU/ft-hr°-F
ρ = density of the cap rock, lb/ft^3
C = specific heat of the cap rock, BTU/lb°-F

The solution to equation A.1 is given by:

$$T(y,t) = T_s - \frac{\Delta T}{2\sqrt{Dt}} \operatorname{erf}(x) \qquad (A.2)$$

where:

$$x = y^2/4Dt$$
$$\Delta T = (T_s - T_r)$$
$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

Equation A.2 gives the temperature at any point, y, in the cap rock, at any time t, following the application of sustained heat at the face of the reservoir rock. The heat H_t, conducted in the vertical direction, is given by:

$$H_t = -K_h\left[\frac{\partial T}{\partial y}\right]_{y=0}$$

or (A.3)

$$H_t = \frac{K_h \Delta T}{\sqrt{\pi D t}}$$

If a continuous supply of steam or hot water is injected into the reservoir, then the heat will propagate in the reservoir and hence, the area of the cap rock through which heat is lost will expand continuously with time. The following figure A.2 shows three stages of heat propagation, assuming no temperature gradients in the sand in the vertical direction, and that the temperature distribution is a step function. Figure A.2a also shows the heat wave occupying an area ΔA_1, at time $\tau = 0$

(a)

(b)

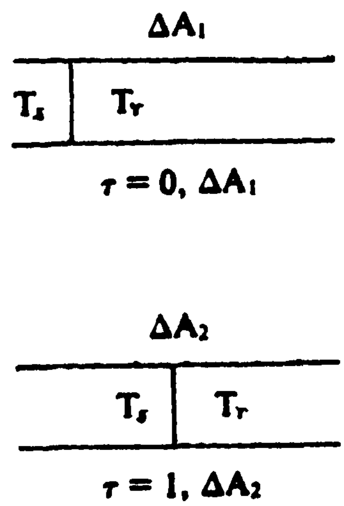


Fig. A.2a,b Progation of unit step heat wave (from Van Poolen[66])

(c)

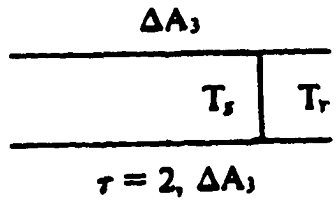


Fig. A.2c Propagation of unit step heat wave (from Van Poollen[66])

where:

τ = time step

t = total time since beginning of injection

$\tau < t$

From Equation A.4, it is evident that at time t, the heat loss to the cap rock is given by:

$$H_t = \frac{K_h \Delta T}{\sqrt{\pi D(t-0)}} \Delta A_1 \qquad \text{(A.4a)}$$

Fig. A.2b shows that at time $\tau = 1$, the heat wave occupies an area ΔA_2, then at time t, the total heat loss is given by:

$$H_t = \frac{K_h \Delta T}{\sqrt{\pi D(t-0)}} \Delta A_1 + \frac{K_h \Delta T}{\sqrt{\pi D(t-1)}} (\Delta A_2 - \Delta A_1) \qquad \text{(A.4b)}$$

Likewise, the total heat loss when the heat wave covers an area ΔA_3 Fig. A.2c is given by:

$$H_t = \frac{K_h \Delta T}{\sqrt{\pi D(t-0)}} \Delta A_1 + \frac{K_h \Delta T}{\sqrt{\pi D(t-1)}} (\Delta A_2 - \Delta A_1) + \frac{K_h \Delta T}{\sqrt{\pi D(t-2)}} (\Delta A_3 - \Delta A_2) \qquad \text{(A.4c)}$$

Therefore, as the heat wave travels in the reservoir, the total heat loss to the cap rock is given by:

$$H_t = \sum_{\tau=0}^{t} \frac{K_h \Delta T}{\sqrt{\pi D(t-\tau)}} (\Delta A_{\tau+1} - \Delta A_\tau) \text{ and } \Delta A_0 = 0 \qquad \text{(A.4d)}$$

Since in the limit $\Delta A_{\tau+1} - \Delta A_\tau = \frac{\partial A_\tau}{\partial \tau} d\tau,$

the above expression may be written as:

$$H_t = \int_0^t \frac{K_h \Delta T}{\sqrt{\pi D(t-\tau)}} \frac{\partial A_\tau}{\partial \tau} d\tau \qquad \text{(A.4)}$$

The above equation gives the total heat loss to the cap rock, and if the base rock has the same thermal conductivity, density and heat capacity as that of the cap rock, then the total heat lost to the base and cap rock combined would be twice that given by Equation A.5. The heat U utilized in heating the reservoir at time t is given by:

$$U = h \frac{dA}{dt} (\rho c)_{R+F} \Delta T \qquad \text{(A.5)}$$

where: h = thickness of the reservoir, feet

U = heat in heating the reservoir, Btu/hr

$(\rho C)_{R+F}$ = heat capacity of saturated rock, BTU/ft^3-^oF

Therefore, the rate of heat injected into the formation is given by:

$$M_s H_o = 2\int_0^t \frac{K_h \Delta T}{\sqrt{\pi D(t-\tau)}} \frac{\partial A}{\partial \tau} d\tau + (\rho c)_{R+F}\, h\, \Delta T \frac{dA}{dt} \qquad (A.6)$$

where:

H_t = specific enthapy of steam, Btu/lb
m_s = mass rate of steam injection, lb/hr .

Briefly, Equation A.7 states:

[The rate of energy injected] = [The rate of energy loss to cap and base rock] + [the rate of energy accumulation in the heated oil sand]

Laplace transformation is applied to obtain the heated area (Carter,[11] 1957):

$$A(t) = \frac{m_s H_t\, h(\rho c)_{R+F}\, D}{4K_h^2\, \Delta T}\, \xi_s / \theta \qquad (A.7)$$

where:

$$\xi_s/\theta = e^{\tau/\theta}\operatorname{erfc}\left(\sqrt{\tau/\theta}\right) + \frac{2\sqrt{\tau/\theta}}{\sqrt{\pi}} - 1 \qquad \text{(A.7a)}$$

and

$$\tau/\theta = \frac{4K_{h_{ob}}(\rho c)_{ob}\, t}{h^2(\rho c)^2_{R+F}} \qquad \text{(A.7b)}$$

which is the dimensionless time

H_t = the specific enthalpy of steam P_i, T_i at reservoir conditions

$H_t = X_i H_{wv} + H_{ws} - H_{wr}$, (BTU/lb)

h = pay thickness, ft

and the complementary error function is defined as:

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$$

PERFORMANCE MODEL FOR STEAM DRIVE AND IN-SITU COMBUSTION

```
$JOB
C *****************************************************
C      THIS IS A PROGRAM THAT USES PDS SUPPLIED DATA     *
C      AND REGENERATES A NEW FILE FOR DATA VALIDATION    *
C      THEN ,INITIAL SCREENING FOR THERMAL PROCESS       *
C      SELECTION FOR STEAM DRIVE OR IN-SITU COMBUSTION   *
C *****************************************************
       REAL*4 MS1,N,NP
       DIMENSION PRES(45),TEMP(45),ACRE(45),DEPTH(45),CROS(45),TS(45),
      1THICK(45),API(45),PERM(45),VISC(45),POR(45),TCAI(45),TCAOR(45),
      2WATSAT(45),RS(45),OILSAT(45),GASAT(45),EH1(45),ROS(45),TNP(45),
      3MS1(45),QO(45,30),PINJ(45),N(45),RECUT(45),VS(45),VISO(45),TRS(45
      4),ASR(45),CAI(45),VB(45),AOR(45),FE(45),NP(45),CAOR(45),CNP(45,30)
      5,QMAX(45),QNP(45),PMAX(45),QMA(45),REC(45),CF(45),PIS(45),NPR(45)
C
       COMMON / FNAME / STATE(24),CNTY(35),FIELD(40)
       COMMON /RESPAR / PRES, TEMP, ACRE, DEPTH, THICK, API,
      1         PERM,VISC,POR,WATSAT,OILSAT,GASAT,RS,PIS,TRS
       COMMON / FPARM / ORICRU, AGSCM, CUCRU
       COMMON / STEAMP/EH1,ROS,MS1,QO,PINJ,N,RECUT,VS,CNP,CROS,TS
       COMMON / INSITP/ VISO, ASR, CAI, VB, AOR, FE, NP, CAOR,
      1         QMAX, QNP, PMAX, QMA, REC, CF,TNP,TCAOR,TCAI,NPR
       DATA EPS5,EPS6/1.E-5,1.E-6/
       READ (5,99) M
       DO 800 I=1,M
       READ(5,100) STATE, CNTY, FIELD
       READ(5,150)
      1ORICRU,CUCRU,AGSCM,RS(I),GASAT(I),OILSAT(I)
       READ(5,200)
      2DEPTH(I),PERM(I),THICK(I),PRES(I),VISC(I),ACRE(I)
       READ(5,201)
      1TEMP(I),POR(I),WATSAT(I),API(I)
       WRITE(6,350)
       CALL PRINT(I)
       IF(ORICRU.LE.EPS6) ORICRU=EPS5
       IF(CUCRU.LE.EPS6) CUCRU=EPS5
       IF(AGSCM.LE.EPS6) AGSCM=EPS5
       IF(PRES(I).LT.EPS6) PRES(I)=EPS5
       IF(TEMP(I).LT.EPS6) TEMP(I)=EPS5
       IF(ACRE(I).LT.EPS6) ACRE(I)=EPS6
       IF(DEPTH(I).LT.EPS6) DEPTH(I)=EPS5
       IF(THICK(I).LT.EPS6) THICK(I)=EPS5
       IF(API(I).LT.EPS6) API(I)=EPS5
       IF(VISC(I).LT.EPS6) VISC(I)=EPS5
       IF(PERM(I).LT.EPS6) PERM(I)=EPS5
       IF(POR(I).LT.EPS6) POR(I)=EPS5
       IF(OILSAT(I).LE.EPS6) OILSAT(I)=EPS5
       IF(WATSAT(I).LE.EPS6) WATSAT(I)=EPS5
       IF(GASAT(I).LE.EPS6) GASAT(I)=EPS5
C
C      CALCULATION OF SOME MISSING DATA
C
       IF(TEMP(I).LE.EPS5) TEMP(I)=60.+.02*DEPTH(I)
       IF(PRES(I).LE.EPS5) PRES(I)=.5*DEPTH(I)
       IF(ORICRU.LE.EPS5) ORICRU=7758.*POR(I)*OILSAT(I)
       IF(GASAT(I).LE.EPS5) GASAT(I)=(1.-OILSAT(I)-WATSAT(I))
       IF(VISC(I).GE.EPS5) GOTO 300
       CALL LIQVIC(I,TEMP,API,PRES,VISC,RS)
   300 CONTINUE
       WRITE(6,370)
```

```
      CALL PRINT(I)
C
C     SCREENING GUIDELINE VALUES FOR STEAM DRIVE PROCESS
C
      IV1=0
      IV2=0
      IF(API(I).LE.25. .AND.
     1VISC(I).GE.20. .AND.
     2DEPTH(I).GT.200. .AND.
     3DEPTH(I).LE.5000. .AND.
     4PERM(I).GT.20..AND.ORICRU.GE.500. .AND.
     5OILSAT(I).GE.0.50)  IV1=9
      IF(IV1.NE.9) GOTO 530
C
C     SCREENING GUIDELINE VALUES FOR IN-SITU COMBUSTION PROCESS
C
  400 IF(API(I).LE.25. .AND.
     1VISC(I).GE.20. .AND.
     2THICK(I).GT.8. .AND.
     3ORICRU.GE.500. .AND.
     4OILSAT(I).GE.0.50) IV2=10
      IF(IV2.NE.10) GO TO 530
      IF(IV1.EQ.9) WRITE(6,420)
      CALL STEAM(I)
      IF(IV2.EQ.10) WRITE(6,520)
      CALL INSITU(I)
  530 IF(IV1.LT.9 .OR. IV2.GT.10) GO TO 600
      GO TO 700
  600 WRITE(6,620)
      WRITE(6,630)
      WRITE(6,640)
  700 CONTINUE
  800 CONTINUE
   99 FORMAT(I2)
  100 FORMAT(24A1/35A1/40A1)
  150 FORMAT(6F10.3)
  200 FORMAT(6F10.3)
  201 FORMAT(4F10.3)
  350 FORMAT(1H1,/////)
  370 FORMAT(1H1,/////)
  420 FORMAT(1H0,20X,'COMMENT:   STEAM DRIVE IS RECOMMENDED')
  520 FORMAT(1H0,20X,'COMMENT:IN-SITU COMBUSTION IS RECOMMENDED')
  620 FORMAT(1H0,20X,'COMMENT: THESE DATA CANNOT BE PROCESSED FOR ANY
     *')
  630 FORMAT(30X,'THERMAL PROCESS AT THIS TIME FOR LACK OF')
  640 FORMAT(30X,'INSUFFICIENT DATA OR CANNOT PASS SCREENING')
      STOP
      END
C

      SUBROUTINE PRINT(I)
      DIMENSION PRES(45),TEMP(45),ACRE(45),DEPTH(45),
     1THICK(45),API(45),PERM(45),VISC(45),POR(45),
     2WATSAT(45),RS(45),OILSAT(45),GASAT(45),PIS(45),TRS(45)
C
      COMMON / FNAME / STATE(24),CNTY(35),FIELD(40)
      COMMON /RESPAR / PRES, TEMP, ACRE, DEPTH, THICK, API,
     1      PERM,VISC,POR,WATSAT,OILSAT,GASAT,RS,PIS,TRS
      COMMON / FPARM / ORICRU, AGSCM, CUCRU
      WRITE(6,1692)
```

```
      WRITE(6,1693)
      WRITE(6,1694)
      WRITE(6,2870) ( STATE(J),J=1,24)
      WRITE(6,2880) CNTY
      WRITE(6,2890) FIELD
      WRITE(6,3120) ORICRU
      WRITE(6,3200) CUCRU
      WRITE(6,3400) AGSCH
      WRITE(6,3800) PRES(I)
      WRITE(6,3810) TEMP(I)
      WRITE(6,3820) ACRE(I)
      WRITE(6,3830) DEPTH(I)
      WRITE(6,3840) THICK(I)
      WRITE(6,3850) PERM(I)
      WRITE(6,3860) API(I)
      WRITE(6,3870) VISC(I)
      WRITE(6,3920) RS(I)
      WRITE(6,3880) POR(I)
      WRITE(6,3890) OILSAT(I)
      WRITE(6,3900) WATSAT(I)
      WRITE(6,3910) GASAT(I)
 1692 FORMAT(32X,'  PDS SUPPLIED DATA OF A RESERVOIR')
 1693 FORMAT(32X,'  **********************************')
 1694 FORMAT(1H0,40X,'( ORIGINAL DATA )')
 2870 FORMAT(1H0,20X,'1',10X,'STATE NAME :     ',24A1)
 2880 FORMAT(1H0,20X,'2',10X,'COUNTY NAME:       ',35A1)
 2890 FORMAT(1H0,20X,'3',10X,'FIELD NAME :      ',40A1)
 3120 FORMAT(1H0,20X,'4',10X,'ORIGINAL OIL (BBLS/AF): ',
     *F14.2)
 3200 FORMAT(1H0,20X,'5',10X,'CUM. CRU. PROD.(BBLS):',2X,F14.2)
 3400 FORMAT(1H0,20X,'6',10X,'ASSO. GAS PROD.(MSCF):',2X,F14.2)
 3800 FORMAT(1H0,19X,' 7',10X,'PRESSURE(PSIA) : ', 7X,F14.2)
 3810 FORMAT(1H0,19X,' 8',10X,'TEMPERATURE(DEG):', 7X,F14.2)
 3820 FORMAT(1H0,19X,' 9',10X,'PROVED ACREGE(ACRE): ',3X,F14.2)
 3830 FORMAT(1H0,19X,'10',10X,'DEPTH(FT) :      ', 8X,F15.2)
 3840 FORMAT(1H0,19X,'11',10X,'ZONE THICKNESS(FT) :',4X,F14.2)
 3870 FORMAT(1H0,19X,'14',10X,'VISCOSITY SURFACE(CP) :',1X,F14.2)
 3860 FORMAT(1H0,19X,'13',10X,'API GRAVITY(DEG) :    ',3X,F14.2)
 3850 FORMAT(1H0,19X,'12',10X,'PERMEABILITY(MD) :',6X,F14.2)
 3880 FORMAT(1H0,19X,'16',10X,'POROSITY : ',13X,F14.3)
 3890 FORMAT(1H0,19X,'17',10X,'OIL SATURATION :       ',3X,
     *F14.3)
 3900 FORMAT(1H0,19X,'18',10X,'WATER SATURATION :    ',3X,
     *F14.3)
 3910 FORMAT(1H0,19X,'19',10X,'GAS SATURATION :       ',3X,
     *F14.3)
 3920 FORMAT(1H0,19X,'15',10X,'GAS-OIL RATIO(SCF/STB):',1X,
     *F14.2)
      RETURN
      END
C

      SUBROUTINE LIQVIC (I, TR, API, PR, VISC, RS)
C
C     CALCULATE DEAD OIL VISCOSITY AND LIVE OIL VISCOSITY
C     BELOW THE BUBBLE POINT PRESSURE USING THE BEGGS AND
C     ROBINSON CORRELATIONS. JPT, (SEPT. 1975),P1140.
C
C     CALCULATE DEAD OIL VISCOSITY,CP
      DIMENSION TR(45),API(45),PR(45),VISC(45),RS(45),
```

```
     *VISD(45)
      Z = 3.0324 -(.02023*API(I))
      Y = 10**Z
      X = Y/(TR(I)**1.163)
      VISD(I) = (10.**X) -1.
C
C     CALCULATE LIVE OIL VISCOSITY,CP
C     GAS-OIL RATIO FOR HEAVY OIL IS USING CHEW & CONNALLY
C     CORRELATION CHART
      IF(RS(I).LT.0.001) RS(I) = 40.
      A = 10.715/(RS(I) + 100.)**.515
      B = 5.44/(RS(I) +150.)**.338
      VISC(I) = A*(VISD(I)**B)
      RETURN
      END
C *********************************************************
C     THIS MODEL IS BUILT BASING ON MARX-LANGENHEIM         *
C     SOLUTION:"RESERVOIR HEATING BY HOT FLUID INJECTION    *
C     TRANS.AIME(1959) P216-312                             *
C *********************************************************
C
C     STEAM PERFORMANCE MODEL
C     ***********************
C


      SUBROUTINE STEAM (I)
C
      REAL*4 MO,MSA,MS1,MS2,MS3,N,NP,K,INJ,MVT
      DIMENSION H(45),K(45), PR(45), TR(45), VISO(45),
     1SW(45), SG(45), API(45), A(45), POR(45), SO(45),
     2EH1(45), ROS(45), MS1(45), QO(45,30), PINJ(45), NP(45),
     3RECUT(45), VS(45), Z(45), MU(45), RS(45), CNP(45,30),
     4CROS(45), TS(45), PIS(45), TRS(45), TNP(45), TCAOR(45),
     5TCAI(45)
C
      COMMON /RESPAR / PR  , TR  , A   , Z    , H   , API,
     1           K, MU , POR, SW, SO ,SG ,RS, PIS, TRS
      COMMON / STEAMP/EH1,ROS,MS1,QO,PINJ,NP,RECUT,VS,CNP,CROS,TS
C
      DATA RO,XSU,Q,B,DIA,RW,PKH,EB/38.,0.9,410.,1.01,467.,
     *0.3,34.,0.8/
      DATA BOI,T,SOR,AE/1.0,2.5,.2,0.7/
C
C
C     STEAM INJECTION PRESSURE & RATE OPTIMIZATION PROCEDURE
C
      IF(PR(I).GT.1000. .AND. PR(I).LT.2000.) PINJ1=PR(I)
      CALL OPTINJ(I,PR, TS, PINJ1, K, API, H, XSU, PINJ, A
     *,MSA, VTSW, MS3, Z, Q)
C
C     CALCULATION OF THE STEAM DRIVE PROCESS PER PATTERN
C     THERMAL EFFICIENCY
      HWR = 91.*(PINJ(I)**.2574)
      HWU = 1318.*(PINJ(I)**(-.08774))
      HWS = 1119.*(PINJ(I)**.01267)
      RF  = (18.08*SO(I) + 48.8*SW(I) -32.2)*POR(I) + 32.2
      CW  = 1.0504 -(6.05E-4)*TS(I) +(1.79E-6)*(TS(I)**2)
      MS2 = MSA*350.
      XAU = XSU - ((24.*Q*Z(I))/(MS3*350.*HWU))
      TH = XAU*HWU + HWS - HWR
```

```
      IF(H(I).LE.100.) HN = H(I)
      IF(VTSW.LE.0.6)  VTSW = 0.6
      HN = H(I)*VTSW
      A1 = 0.6*43560.
      AP = 5.
      WRITE(6,1)
    1 FORMAT(1H1,4X,'RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR
     *(STEAM DRIVE PROCESS)')
      WRITE(6,2)
    2 FORMAT(1H0,4X,'***************************************************
     **********************')
      WRITE(6,3)
    3 FORMAT(8X,'EH1= THERMAL EFFECIENCY; ROS= OIL-STEAM RATIO(B/B); ')
      WRITE(6,4)
    4 FORMAT(8X,'QNP= OIL PROD RATE (B/D) QINJ= STEAM INJ RATE (B/D);')
      WRITE(6,5)
    5 FORMAT(8X,'PINJ= STEAM INJ PRESS(PSI) NP= CUM PRDO A PATT.(B);')
      WRITE(6,6)
    6 FORMAT(7X,' VISO= OIL VISCOSITY # RES TEMP(CP); REC= OIL RECOVERY
     *(FRACTION);')
      WRITE(6,7)
    7 FORMAT(8X,'PIS= POROSITY*OIL SAT.;  TRS= TRANSMISSIBILITY;')
      WRITE(6,8)
    8 FORMAT(7X,' VS= VOL STEAM INJ.(BBLS); TS= STEAM TEMP(DEG F);')
      II = 1
   11 II = II + 1
      TI = (II -1)*1.
      TAU = ( 4.*PKH*RO*(TI))/((H(I)**2)*(RP**2))
      IT = 1
      CNP(I,IT) = 0.0
      CO(I,IT) = 0.0
      SKIP = 0.0
   10 IT = IT + 1
      TP = (IT -1)*1. + TI
      TAU = (4.*PKH*RO*TP)/((H(I)**2)*(RP**2))
      SKIP = SKIP + 1.
      IF (SKIP.GE.30.) SKIP = 0.
C
C     USE MANDL-VOLEK REFINEMENT FOR HOT WATER BANK CORRECTION
C     "HEAT AND MASS TRANSPORT IN STEAM DRIVE PROCESSES",SPE J
C     (MAR. 1969),P59
C
      FHD = (HWU*XAU)/( TS(I)- TR(I))*CW
      BETA = 1/(1+ FHD)
      ELSI = ABS(TAU - (.48*(FHD**1.71)))
      TAU1 = 1.- (ERF(SQRT(TAU)))
      IF(TAU.GE.174.0) TAU = 174.0
      ELPSI = EXP(TAU)*TAU1 + (2*(SQRT(TAU))/SQRT(3.14)) -1.
      MVT=(SQRT(ELSI/3.14))*(BETA+(((ELSI-3.)/3.)*EXP(TAU)*TAU1)
     *- (ELSI/(3*SQRT(3.14*TAU))))
C
C     STEAM FLOODING AREA AS
      AT  = (H(I)*RF*ELPSI)/(4.*PKH*RO*(TS(I)-TR(I))*43560.)
      TH1 = 14.6*MSA*XAU*HWU
      AS  = TH1*AT
C
C     HOT-WATER AREA AW
      TH2 = 14.6*MSA*(HWR+XAU*HWU -CW*(TR(I)-32.))
      AW  = TH2*AT
      IF (AW.GT.AS) GO TO 14
```

```
      EH1(I) = ELPSI/TAU
      IF(EH1(I).GT.1.) GO TO 14
   14 EH1(I) = (ELPSI-HVT)/TAU
      TH = TI
      IF(EH1(I).GT.1.0) GO TO 11
      NP(I) = 7758.*AE*VTSW*AP*H(I)*POR(I)*(SO(I)-SOR)/(BOI)
C
C     OIL-STEAM RATIO, PRODUCTION RATE, OIL RECOVERY PER PATTERN
      RO1=((62.4*POR(I)*H(I)*EH1(I))/(H(I)*(TS(I)-TR(I))*RF))*(XAU
     1*HWU*(SO(I)-SOR))
      ROS(I) = (1000./(CW*(TS(I) -75.) +XSU*HWU))*RO1
      CALL LIQVIS(I,TR,API,PR,VISD,VISC,MU)
      INJ = A(I)/5.
      VS(I) = MSA*TP
      CNP(I,IT) = ROS(I)*MSA*30.
      QO(I,IT) = CNP(I,IT)/30.
      CNP(I,IT) = CNP(I,IT) + CNP(I,(IT-1))
      RECUT(I) = CNP(I,IT)/(NP(I))
      REC = SO(I) - SOR
      CROS(I ) = NP(I)/VS(I)
      TRS(I) = K(I)*H(I)/VISO(I)
      FIS(I) = POR(I)*SO(I)*10000.
      MS1(I) = MSA
      IF(SKIP.LE.0.0) GO TO 15
      IC = IT - 1
      CALL ANS(I,IC,EH1,ROS,QO,MS1,PINJ,NP,VISO,CNP,VS,CROS,RECUT,TS,
     1FIS,TRS,POR,SO)
      IF(IC.GE.8 ) GO TO 12
      SOC = SO(I) - 0.15
      IF(RECUT(I).GE.SOC) GO TO 12
   15 IF(0.17 - ROS(I)) 10, 12,12
C
C     PRINT THE PERFORMANCE EVALUATION FOR THE ENTIRE RESERVOIR
C
C     PROJECTION TO THE WHOLE RESERVOIR
   12 INJ = A(I)/5.
      CNP(I,IC)=7758.*AE*VTSW*A(I)*H(I)*POR(I)*(SO(I)-SOR)/(BOI*1000.)
      VS(I) = MSA*INJ/1000.
      CROS(I) = CNP(I,IC)/VS(I)
      IF(RECUT(I).GE.SO(I)) RECUT(I) = SO(I)
      WRITE(6,100)
      WRITE(6, 105)
      WRITE(6, 106)
      WRITE(6, 107)
      WRITE(6,110) I
      WRITE(6,121) H(I)
      WRITE(6,122) K(I)
      WRITE(6,124) Z(I)
      WRITE(6,125) A(I)
      WRITE(6,126) PR(I)
      WRITE(6,127) TR(I)
      WRITE(6,128) POR(I)
      WRITE(6,129) SO(I)
      WRITE(6,130) SG(I)
      WRITE(6,131) API(I)
      WRITE(6,132) SW(I)
      WRITE(6,140)
      WRITE(6,150) VISO(I)
      WRITE(6,203) QO(I,IC)
      WRITE(6,202) MS1(I)
```

```
      WRITE(6,204) PINJ(I)
      WRITE(6,205) RECOT(I)
      WRITE(6,206) CNP(I,IC)
      WRITE(6,208) VS(I)
C
  100 FORMAT(1H1,/////)
  105 FORMAT(1H0,25X,'STEAM DRIVE PROJECT PERFORMANCE MODEL')
  106 FORMAT(26X,'**************************************** ')
  107 FORMAT(27X,' (PROJECTION TO THE WHOLE RESERVOIR)')
  110 FORMAT(1H0,20X,'RECORD #',I3,10X,'INPUT DATA')
  121 FORMAT(1H0,20X,'NET THICKNESS (FT):     ',7X,F20.2)
  122 FORMAT(1H0,20X,'PERMEABILITY (MD):          ', 5X,F20.2)
  124 FORMAT(1H0,20X,'DEPTH (FT):                 ', 5X,F20.2)
  125 FORMAT(1H0,20X,'AREA (ACRE):                ', 5X,F20.2)
  126 FORMAT(1H0,20X,'RESERVOIR PRESS. (PSIA): ', 5X,F20.2)
  127 FORMAT(1H0,20X,'RESERVOIR TEMP. (DEG F): ', 5X,F20.2)
  128 FORMAT(1H0,20X,'POROSITY:                   ', 5X,F20.3)
  129 FORMAT(1H0,20X,'OIL SATURATION BEFORE STEAMDR:',F20.3)
  130 FORMAT(1H0,20X,'GAS SATURATION BEFORE STEAMDR:',F20.3)
  131 FORMAT(1H0,20X,'API GRAVITY (DEG):          ',5X,F20.2)
  132 FORMAT(1H0,20X,'WATER SAT. BEFORE STEAMDR:',4X,F20.3 )
  140 FORMAT(1H0,40X,'OUTPUT RESULT')
  150 FORMAT(1H0,20X,'VISCOSITY ,RES. TEMP.(CP):',7X,F17.2)
  202 FORMAT(1H0,20X,'OPTIM. MAX. STEAM INJ RATE (B/D):',F17.2)
  203 FORMAT(1H0,20X,'OIL PROD RATE (B/D/PATTERN):',3X,F19.2)
  204 FORMAT(1H0,20X,'OPTIM. MAX. INJ PRESSURE (PSIA):',1X,F17.2)
  205 FORMAT(1H0,20X,'ULTIMATE OIL RECOVERY:     ',5X,F20.3)
  206 FORMAT(1H0,20X,'CUMULATIVE PROD (MBBLS): ',5X,F20.2)
  208 FORMAT(1H0,20X,'STEAM REQUIREMENT (MBBL):',5X,F20.2)
      RETURN
      END
C
C     THIS SUBROUTINE BASED ON VAN LOOKEREN:'CALCULATION METHODS
C     FOR LINEAR AND RADIAL STEAM FLOW IN OIL RESERVOIRS,"
C     SPE 6788
C

      SUBROUTINE OPTINJ(I,PR,TS,PINJ1,K,API,H,XSU,PINJ,A
     *,MSA, VTSW, MS3, Z, Q)
      REAL*4 MS1,KS,MUS,MS3,K,INJ,MS2,MSC,MSA
      DIMENSION PR(45), K(45), API(45), H(45), PINJ(45), Z(45),
     *A(45),TS(45)
      IF(PR(I).LE.1000) PINJ1=PR(I)
      IF(PR(I).GE.2000) PINJ1=2000.
      MS1 = 350.
      MSC = 1000.
      PINJ2 = PINJ1 +50.
      MS2 = MS1
    5 MS2 = MS2+ 10.
      SLOPE = ((ALOG(PINJ1/PINJ2))/(MSC-MS1))
      PINJ(I) = PINJ1*(EXP(SLOPE*(MS2-MS1)))
      IF(PINJ(I).GT.2000.) PINJ(I)=2000.
      TS(I) = 115.1*(PINJ(I)**0.225)
      DO = (141.5/(API(I)+131.5))*62.4
      DS = (5.06*(EXP(.000359*PINJ(I)))) - 5.
      MUS = (0.0000517*TS(I) + .00049)
      KS = K(I)/1000.
      MS3 = MS2
      BWU = 1318.*(PINJ(I)**(-.08774))
      XAU = XSU -((24.*Q*Z(I))/(MS3*350.*BWU))
```

```
      AR = SQRT((5900.*MUS*MS2*XAU)/(3.14*(DO-DS)*(H(I)**2)*
     *KS*DS))
      VTSW = 0.626*AR
      MSA = MS2
      IF(VTSW.LE.(0.6) .AND. MS3.LE.1000.) GO TO 5
      RETURN
      END
C
      SUBROUTINE ANS(I,IC,EH1,ROS,QO,MS1,PINJ,NP,VISO,CNP,VS,
     1CROS,RECUT,TS,PIS,TRS,POR,SO)
      REAL*4 NP, MU, MSB,NP2,MS1
      DIMENSION EH1(45), ROS(45), QO(45,30), PINJ(45), NP(45),
     1VISO(45), CNP(45,30), VS(45), CROS(45),RECUT(45), TS(45),
     2PIS(45), TRS(45), MS1(45),POR(45), SO(45)
      DIMENSION EH2(45,13), ROS2(45,13),QO2(45,13),PINJ2(45,13),
     *NP2(45,13),VISO2(45,13),CNP2(45,13),VS2(45,13),CROS2(45,13),
     *RECUT2(45,13),TS2(45,13),PIS2(45,13),TRS2(45,13),MSB(45,13),
     *POR2(45,13)
      EH2(I,IC) = EH1(I)
      ROS2(I,IC) = ROS(I)
      QO2(I,IC) = QO(I,IC)
      PINJ2(I,IC) = PINJ(I)
      NP2(I,IC) = NP(I)
      VISO2(I,IC) = VISO(I)
      CNP2(I,IC) = CNP(I,IC)
      VS2(I,IC) = VS(I)
      CROS2(I,IC) = CROS(I)
      RECUT2(I,IC) = RECUT(I)
      TS2(I,IC) = TS(I)
      PIS2(I,IC) = PIS(I)
      TRS2(I,IC) = TRS(I)
      MSB(I,IC) = MS1(I)
      IF(RECUT2(I,IC).GE.SO(I)) RECUT2(I,IC) =SO(I)
      WRITE(6,10)
   10 FORMAT(1H0,2X,'MONTH',3X,'EH1',6X,'VISO',7X,'TS',9X,'REC',5X,
     *'PIS',7X,'QNP')
      WRITE(6,15) IC,EH2(I,IC),VISO2(I,IC),TS2(I,IC),RECUT2(I,IC),
     *PIS2(I,IC),QO2(I,IC)
   15 FORMAT(2X,I3,F10.3, 5F10.2)
      WRITE(6,20)
   20 FORMAT(1H0,5X,'NP',8X,'VS',9X,'TRS',9X,'ROS',4X,'QINJ',7X,'PINJ'
      WRITE(6,25) CNP2(I,IC),VS2(I,IC),TRS2(I,IC),ROS2(I,IC),MSB(I,IC)
     *PINJ2(I,IC)
   25 FORMAT(2X,6F10.2)
      RETURN
      END
C
      SUBROUTINE INSITU(I)
C
C     IN-SITU COMBUSTION PERFORMANCE MODEL
C
C***************************************************************
C MODIFIED OIL-RECOVERED/VOLUME-BURNED METHOD                  *
C THIS MODIFIED METHOD IS BASED ON GATES & RAMEY:"A METHOD FOR *
C ENGINEERING IN-SITU COMBUSTION OIL RECOVERY PROJECTS",JPT,   *
C (FEB 1980),P285-294. THE AUTHOR MODIFIED FOR FIELD DATA FROM *
C AN ALGORITHM PUBLISHED BOTH IN SUPRI & DOE REPORT(OCT 1981)  *
C***************************************************************
```

```
      REAL*8 MU, MP, MPA,MD,MUA,MPR,M2,K,KA
      DIMENSION H(45),K(45),MU(45),Z(45),A(45),PR(45),TR(45),
     *SG(45),API(45),SW(45),VISO(45),ASR(45),CAI(45),VB(45),
     *AOR(45),FB(45),NP(45),CAOR(45),QMAX(45),QNP(45),FMAX(45),
     *SO(45),QMA(45),POR(45),REC(45),CF(45),RS(45),CNP(45),CROS(45)
     *,TS(45),PIS(45),TRS(45),TMP(45),TCAOR(45),TCAI(45),NPR(45)
C
      COMMON /RESPAR / PR  , TR  , A   , Z    , H    , API,
     1         K , MU , POR, SW , SO , SG , RS, PIS, TRS
      COMMON / INSITE/ VISO, ASR, CAI, VB, AOR, FB, NP, CAOR,
     1          QMAX,QNP,FMAX,QMA,REC,CF,TMP, TCAOR,TCAI,NPR
C
      DATA CO,CO2,O2,N2,VM,TINJ,MUA,KA,RW,BOI,AP/1.1,15.2,.2,83.2,
     C.5,100.,.0186,25.,.276,1.,5./
      DATA B,CN,AO,DO,HA/8860.,.46,3080.,970.,2940./
C
C     SINCE NO COMBUSTION TUBE RUN & WE USE THE FIELD TEST DATA,
C     FUEL CONC IS CALTED BY USING CHU'S CORRELATION. "A STUDY
C     OF FIREFLOOD FIELD PROJECTS",JPT(1977) P111-120.
C     WE CALCULATE FUEL CONC BY USING CHU'S CORRELATION
C
      CALL LIQVIS(I,TR,API,PR,VISD,VISC,MU)
      CF(I) =-.12+(.00262*H(I))+(.000114*K(I))+(2.23*SC(I))
     C-(.000189*Z(I))-(.0000652*VISO(I)) +(.000242*((K(I)
     C*H(I))/VISO(I)))
C
C     HYDROCARBON RATIO
      HCR = (4*(.2658*N2 -CO2-O2-.5*CO))/(CO2+CO)
C
C     AIR-FUEL RATIO & AIR-SAND RATIO
      AFR=(479.7*N2)/((CO2+CO)*(12.+HCR)*1000.)
      ASR(I) = (AFR*CF(I)*43.56)
      WRITE(6,4)
    4 FORMAT(1H1,4X,'RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR
     *(IN-SITU COMB. PROCESS)')
      WRITE(6,6)
    6 FORMAT(1H0,4X,'*************************************************
     ************************')
      WRITE(6,1)
    1 FORMAT(8X,' REC= OIL RECOVERY(%);  AOR= AIR-OIL RATIO(MCF/B); ')
      WRITE(6,2)
    2 FORMAT(8X,' QINJ= MAX AIR INJ RATE(MMCF/D); PINJ= INJ PRESSURE (
     *IA);')
      WRITE(6,3)
    3 FORMAT(8X,' PIS= POROSITY*OIL-SAT. ;  TRS= TRANSMISSIBILITY ;')
      WRITE(6,7)
    7 FORMAT(8X,' ASR= AIR-SAND RATIO (MCF/AF); FB= FUEL BURNED(B/AF)
     *')
      WRITE(6,8)
    8 FORMAT(8X,' CAI= CUM. AIR REQUIRED(MMCF/AF); QNP= OIL PROD RATE(
     *L/D);')
      WRITE(6,9)
    9 FORMAT(8X,' NP= CUM. OIL PROD.(BBLS); VB= VOL BURNED(%)  ;')
C
C
C     THE FOLLOWING STEPS ARE CURVE-FITTING PROCEDURES
C     VOL BURNED AT INITIAL GAS SATURATION
      SG1 = SG(I)*100.
      VBO = 0.0
      TIMER=0.0
```

```
      VBO = .147143*SG1 + .010714*(SG1**2)
      VB(I) = VBO
      SKIP = 0.0
      DO 5 N=1,12
      TIMER = TIMER + 1.
   10 VB(I) = VB(I) + 1.0
C
C     FRACTION OF THE VOL BURNED
      X=ABS((VB(I)-VBO)/(100.-VBO))
C
C     MAXIMUM DEVIATION
      MD=26.82295 -(.46787*SG1)
      DYDX=6.775267-(31.895588*X)+(48.561561*(X**2))-(28.058336*
     1(X**3))
      SLOPE=(100./(100.-VBO))+((MD/(100.-VBO))*DYDX)
C
C     CURRENT AIR-OIL RATIO
      NPA =(7758.*SO(I)*POR(I))/BOI
      REO = NPA -(CP(I)*(43560./350.))
      AOR(I) = ASR(I)*1000./(SLOPE*REO)
C
C     CUMULATIVE PRODUCTION, FUEL BURNED ESTIMATION PER PATTERN
      Y=6.775267*X-(15.947794*(X**2))+(16.187187*(X**3))-(7.01
     C4569*(X**4.))
      NPR(I)= (100.*X) + (Y*MD)
      NP(I) = (NPR(I)*REO*AP*H(I))/100.
      FB(I) = CP(I)*(43560./350.)
      SOR = FB(I)/(7758.*POR(I))
C
C     ESTIMATION OF INJECTION RATE AND PRESSURE AT
C     55% AREAL SWEEP PER PATTERN
      V1 =0.125
      D1 =SQRT(AP*43560./2.)
      RA = SQRT(2*(D1/2)**2)
C     ESTIMATION OF AIR REQUIREMENT PER PATTERN
      NPP = (NPR(I)*REO)/100.
      CAOR(I) = (VB(I)*ASR(I))/(NPP*100.)
      CAI(I) = (CAOR(I)*NPP*AP*H(I))/1000.
      AIR = (4.72+.0365*H(I)+9.996*SO(I)+.00069*K(I))*1000./43560.
      QMAX(I) = 4.77*V1*AIR*RA*H(I)/1000.
      T = (CAI(I)*1000.)/(QMAX(I)*30)
      QNP(I) = (QMAX(I)*1000.)/(AOR(I)*4.)
C
C     ESTIMATION OF INJECTION PRESSURE PER PATTERN
      TMAX=QMAX(I)/(2.*3.1416*H(I)*AIR*VM*VM)
      QMA(I) = QMAX(I)*1000.
      PMAX(I)=SQRT((PR(I)**2.)+((QMA(I)*MUA*(TR(I)+460.))
     C/(.703*KA*H(I)))*(ALOG((RA**2)/(RW*VM*TMAX))-1.238))
      TRS(I) =(K(I)*H(I))/VISO(I)
      PIS(I) = POR(I)*SO(I)*10000.
C     PROJECTION TO THE WHOLE RESERVOIR
      INJ = A(I)/5.
      TNP(I) = (NPR(I)*REO*AP*H(I)*INJ)/100000.
      TCAOR(I) = (VB(I)*ASR(I)*INJ)/(TNP(I)*100.)
      TCAI(I) = TCAOR(I)*NPP*AP*H(I)*INJ/1000.
      IF(T.GE.360.) GO TO 20
   16 IF(T - TIMER) 10,10,15
   15 II = T
      IC = N
      CALL RESULT(I,IC,NPR,AOR,QMAX,FB,CAI,NP,QNP,PMAX,VISO,VB,PIS,TRS
```

```
     *ASR,TNP,TCAOR,TCAI,POR)
      SOC = (SO(I) - 0.20)*100.
      IF(SOC.LE.NPR(I)) GO TO 20
    5 CONTINUE
C
C     PRINT THE PERFORMANCE EVALUATION OF THE ENTIRE RESERVOIR
C
C     PROJECTION TO THE ENTIRE RESERVOIR
   20 TNP(I) = (NPR(I)*RZO*A(I)*H(I))/100000.
      TCAOR(I)=(VB(I)*ASR(I))/NP(I)
      TCAI(I) = TCAOR(I)*NP(I)*A(I)*H(I)/1000000.
      WRITE(6,100)
      WRITE(6,102)
      WRITE(6,103)
      WRITE(6,104)
      WRITE(6,110) I
      WRITE(6,121) H(I)
      WRITE(6,122) K(I)
      WRITE(6,124) Z(I)
      WRITE(6,125) A(I)
      WRITE(6,126) PR(I)
      WRITE(6,127) TR(I)
      WRITE(6,128) POR(I)
      WRITE(6,129) SO(I)
      WRITE(6,130) SG(I)
      WRITE(6,131) API(I)
      WRITE(6,132) SW(I)
      WRITE(6,140)
      WRITE(6,209) VISO(I)
      WRITE(6,250) TCAI(I)
      WRITE(6,290) TNP(I)
      WRITE(6,450) NPR(I)
      WRITE(6,440) QNP(I)
      WRITE(6,420) QMAX(I)
      WRITE(6,430) PMAX(I)
C
  100 FORMAT(1H1)
  102 FORMAT(/////1H0,21X,'IN-SITU COMBUSTION PROCESS PERFORMANCE
     *')
  103 FORMAT(22X,'************************************************')
  104 FORMAT(27X,'(PROJECTION TO THE WHOLE RESERVOIR)')
  110 FORMAT(1H0,18X,'RECORD #',I3,10X,'INPUT DATA')
  121 FORMAT(1H0,18X,'NET THICKNESS (FT):                 ',1X,F20.2)
  122 FORMAT(1H0,18X,'PERMEABILITY (MD):                  ',1X,F20.2)
  124 FORMAT(1H0,18X,'DEPTH (FT):                         ',1X,F20.2)
  125 FORMAT(1H0,18X,'AREA (ACRE):                        ',1X,F20.2)
  126 FORMAT(1H0,18X,'RESERVOIR PRESS (PSIA):             ',1X,F20.2)
  127 FORMAT(1H0,18X,'RESERVOIR TEMP (DEG F):             ',1X,F20.2)
  128 FORMAT(1H0,18X,'POROSITY:                           ',1X,F20.3)
  129 FORMAT(1H0,18X,'OIL SATURATION BEFORE PROCESS:',1X,F20.3)
  130 FORMAT(1H0,18X,'GAS SATURATION BEFORE PROCESS:',1X,F20.3)
  131 FORMAT(1H0,18X,'API GRAVITY (DEG):                  ',1X,F20.2)
  132 FORMAT(1H0,18X,'WATER SAT. BEFORE PROCESS:     ',1X,F20.3)
  140 FORMAT(1H0,38X,'OUTPUT RESULT')
  209 FORMAT(1H0,18X,'VISCOSITY,RESERVOIR TEMP.(CP):',1X,F20.2)
  250 FORMAT(1H0,18X,'AIR REQUIREMENT (MMSCF/AF):    ',1X,F20.2)
  290 FORMAT(1H0,18X,'CUMULATIVE PROD (MBBLS):       ',1X,F20.2)
  420 FORMAT(1H0,18X,'OPTIM MAX INJ RATE (MSCF/D/W):',1X,F20.2)
  430 FORMAT(1H0,18X,'OPTIM MAX INJ PRESS (PSIA):    ',1X,F20.2)
  440 FORMAT(1H0,18X,'OIL PROD RATE (BBLS/D/PATTERN):',F20.2)
```

```
  450 FORMAT(1H0,18X,'ULTIMATE OIL RECOVERY (%):     ',1X,F20.2)
      RETURN
      END
C
      SUBROUTINE LIQVIS (I,TR,API,PR,VISD,VISO,MU)
      REAL*4 MU
      DIMENSION TR(45),API(45),PR(45),VISO(45),MU(45)
C
C     CALCULATE DEAD OIL VISCOSITY AND LIVE OIL VISCOSITY BELOW
C     THE BUBBLE POINT PRESSURE USING THE BEGGS AND ROBINSON
C     CORRELATIONS.(JOURNAL OF PETROLEUM TECHNOLOGY, SEPTEMBER,
C     1975, P.1140)
C
C     CALCULATE DEAD OIL VISCOSITY,CP
      Z = 3.0324 -(.02023*API(I))
      Y = 10**Z
      X = Y/(TR(I)**1.163)
      VISD = (10.**X) - 1.
C
C     CALCULATE LIVE OIL VISCOSITY, CP
C     GAS-OIL RATIO FOR HEAVY OIL IS USING CHEW & CONNALLY
C     CORRELATION CHART
      R = MU(I)/VISD
      IF(R.LE.0.7) GOR = 200.
      IF(R.LE.0.8 .AND. R.GT.0.7) GOR = 100.
      IF(R.LE.0.9 .AND. R.GT.0.8) GOR = 50.
      IF(R.GT.0.9) GOR = 20.
      A = 10.715/(GOR +100.)**.515
      B = 5.44/(GOR +150.)**.338
      VISO(I) = A*(VISD**B)
      RETURN
      END
C
      SUBROUTINE RESULT(I,IC,NPR,AOR,QMAX,FB,CAI,NP,QNP,PMAX,VISO,VB,
     *PIS,TRS,ASR,TNP,TCAOR,TCAI,POR)
      REAL*4 NP,NPR,NPR2,NP2
      DIMENSION NPR(45),AOR(45),QMAX(45),FB(45),CAI(45),NP(45),QNP(45)
     *PMAX(45),VISO(45),VB(45),PIS(45),TRS(45),ASR(45),TNP(45),POR(45)
     *,TCAOR(45),TCAI(45)
      DIMENSION NPR2(45,13),AOR2(45,13),QMAX2(45,13),CAI2(45,13),
     *NP2(45,13),QNP2(45,13),PMAX2(45,13),VISO2(45,13),VB2(45,13),
     *PIS2(45,13),TRS2(45,13),ASR2(45,13),TNP2(45,13),TCAOR2(45,13)
     *,TCAI2(45,13),POR2(45,13),FB2(45,13)
      NPR2(I,IC) = NPR(I)
      AOR2(I,IC) = AOR(I)
      QMAX2(I,IC) = QMAX(I)
      FB2(I,IC)  = FB(I)
      CAI2(I,IC) = CAI(I)
      NP2(I,IC)  = NP(I)
      QNP2(I,IC) = QNP(I)
      PMAX2(I,IC) = PMAX(I)
      VISO2(I,IC) = VISO(I)
      VB2(I,IC)  = VB(I)
      PIS2(I,IC) = PIS(I)
      TRS2(I,IC) = TRS(I)
      ASR2(I,IC) = ASR(I)
      TNP2(I,IC) = TNP(I)
      TCAOR2(I,IC) = TCAOR(I)
```

```
      TCAI2(I,IC) = TCAI(I)
      FCR2(I,IC) = FCR(I)
      WRITE(6,14)
   14 FORMAT(1H0,2X,'MONTH',4X,'REC',5X,'PIS',7X,'FB',9X,'CAI',5X,
     *'PINJ',9X,'NP')
      WRITE(6,15) IC,NPR2(I,IC),PIS2(I,IC),FB2(I,IC),CAI2(I,IC),
     *PMAX2(I,IC),NP2(I,IC)
   15 FORMAT(2X,I3,6F10.2)
      WRITE(6,20)
   20 FORMAT(1H0,4X,'ASR',7X,'TRS',9X,'AOR',7X,'VB',7X,'QNP',7X,
     *'VISO',5X,'QINJ')
      WRITE(6,25) ASR2(I,IC),TRS2(I,IC),AOR2(I,IC),VB2(I,IC),
     *QNP2(I,IC),VISO2(I,IC),QMAX2(I,IC)
   25 FORMAT(7F10.2)
      RETURN
      END

$EXEC
```

STEAM DRIVE PROJECT PERFORMANCE MODEL

****

(PROJECTION TO THE WHOLE RESERVOIR)

STATE NAME :	CALIF	CALIF	ARK	CALIF	HOLLAND	CALIF
COUNTY NAME:	KERN	SANTA BARBARA	OUACHITA	MONTERREY	-	MONTERREY
FIELD NAME :	N.SUNSET-1F.	CAT CANYON	SMACKOVER	SAN ARDO(LOMBARDI)	SCHOONEBECK	SAN ARDO(AURIGNAC)
NET THICKNESS (FT):	150.00	45.00	25.00	115.00	80.00	100.00
PERMEABILITY (MD):	1000.00	500.00	2000.00	6000.00	5500.00	2200.00
DEPTH (FT):	1900.00	3800.00	1920.00	2100.00	2800.00	2200.00
AREA (ACRE):	43.00	22.50	90.00	49.00	43.00	702.00
RESERVOIR PRESS. (PSIA):	950.00	1900.00	1050.00	1050.00	1000.00	1100.00
RESERVOIR TEMP. (DEG F):	115.00	130.00	130.00	125.00	100.00	145.00
POROSITY:	0.350	0.280	0.350	0.325	0.300	0.390
OIL SATURATION BEFORE STEAMDR:	0.650	0.990	0.500	0.700	0.850	0.730
GAS SATURATION BEFORE STEAMDR:	0.000	0.000	0.000	0.000	0.000	0.000
API GRAVITY (DEG):	16.00	10.00	20.00	11.00	14.00	13.00
WATER SAT. BEFORE STEAMDR:	0.350	0.010	0.500	0.300	0.150	0.270

OUTPUT RESULT

OIL PROD RATE (B/D/PATTERN):	376.86	350.20	229.21	377.79	439.36	499.06
OPTIM. MAX. STEAM INJ RATE (B/D):	1010.00	1010.00	1010.00	1010.00	1010.00	1010.00
OPTIM. MAX. INJ PRESSURE (PSIA):	901.79	1850.54	1001.56	1001.56	951.67	1051.45
ULTIMATE OIL RECOVERY:	0.235	0.528	0.482	0.298	0.417	0.357
CUMULATIVE PROD (MBBLS):	3310.08	729.76	769.79	2983.64	2185.71	47279.86
STEAM REQUIREMENT(MMBBL):	8.69	4.54	18.18	9.90	8.69	141.80

Appendix B

Curve-fitting Procedure of Oil Recovery/Volume Burned

From the Gates and Ramey work, the oil recovery/volume burned experimental results were correlated in the following figure:

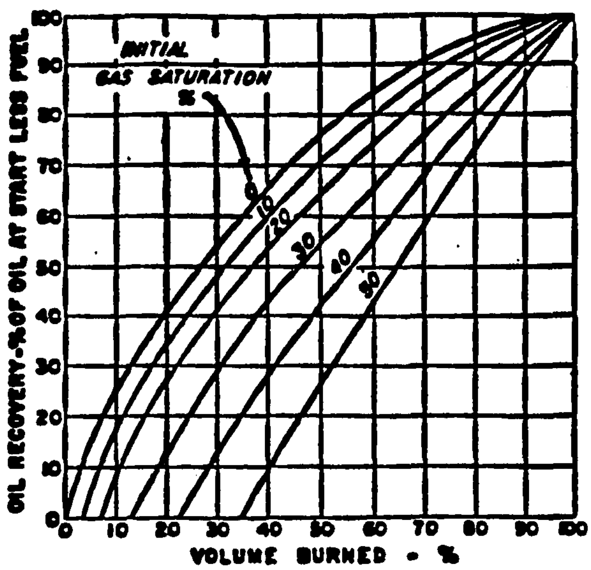


Figure B.1 Oil recovery vs. volume burned

In the above correlation chart, knowing the volume burned of the in-situ combustion process allows us to predict oil recovery of the process, or vice versa. This correlation chart can be curve-fitted into an equation for computation purposes.

In order to curve-fit the correlation chart (Figure B.1), we have to redefine both the vertical and horizontal axises so that we can put all the curves into a single curve. The procedures can be done as follows:

1) We assumed the recovery curves could be approximated by straight lines with intercepts $V_B(0)$ at initial oil breakthrough as shown in Figure B.2.

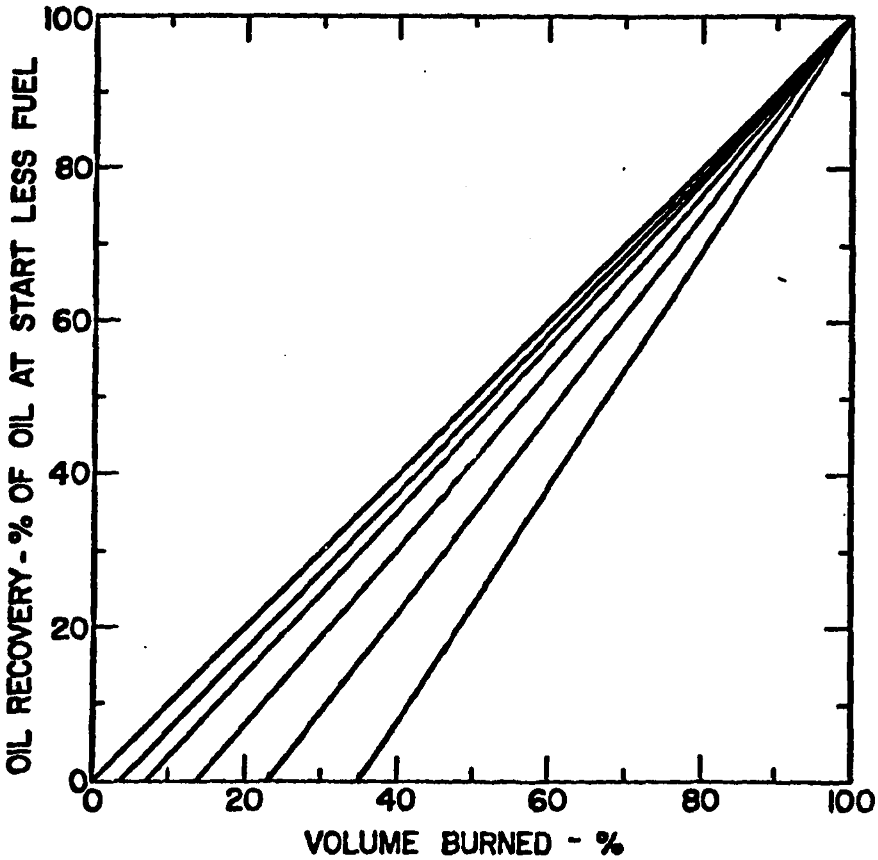


Figure B.2 Oil recovery vs. volume burned

2) Redefine the horizontal axis as:

$$X = \frac{V_B - V_B(0)}{100 - V_B(0)} \qquad \text{(B-1)}$$

in order to put all the straight lines into a single line then, we have to define the relationship between $V_B(0)$ and gas saturation. This step can be done by replotting percent volume burned at oil breakthrough, $V_B(0)$ versus gas saturation, %PV shown in Figure B.3.

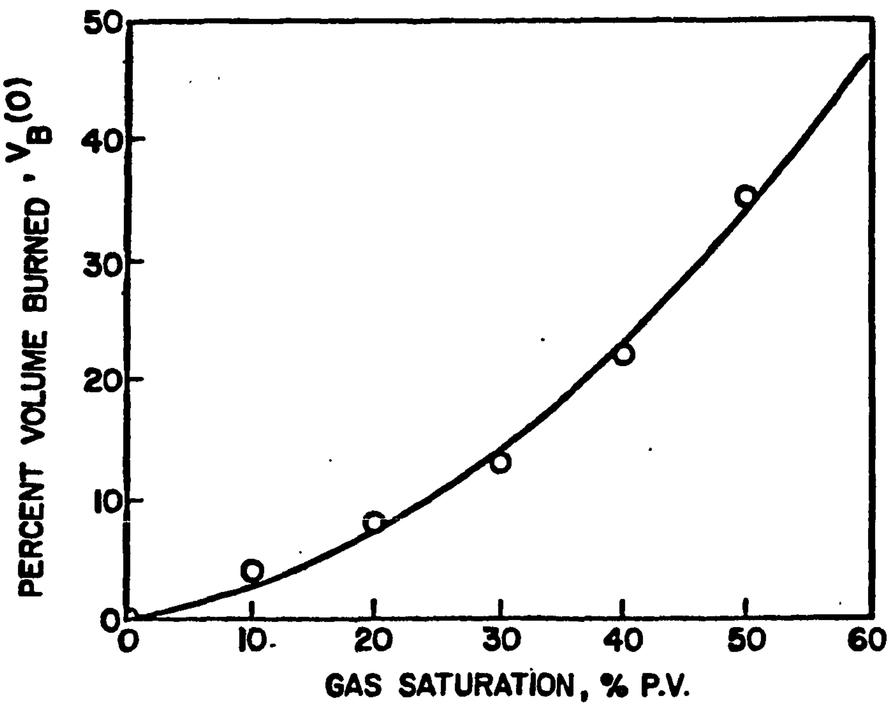


Fig. B.3 Volume burned at oil BT vs. Gas Saturation

And the above curve can be fitted into equation as follows:

$$V_B(0) = 0.14714g + 0.01071S_g^2 \qquad \text{(B-2)}$$

3) It was found that for each level of gas saturation, there is a maximum deviation from the straight line. The maximum deviation of each gas saturation can be found from Figure B.1. The maximum deviation is plotted versus gas saturation, %PV in Figure B.4 and then curve fitted into equation as:

$$\text{Maximum Deviation} = 26.8229 - 0.4678S_g \qquad \text{(B-3)}$$

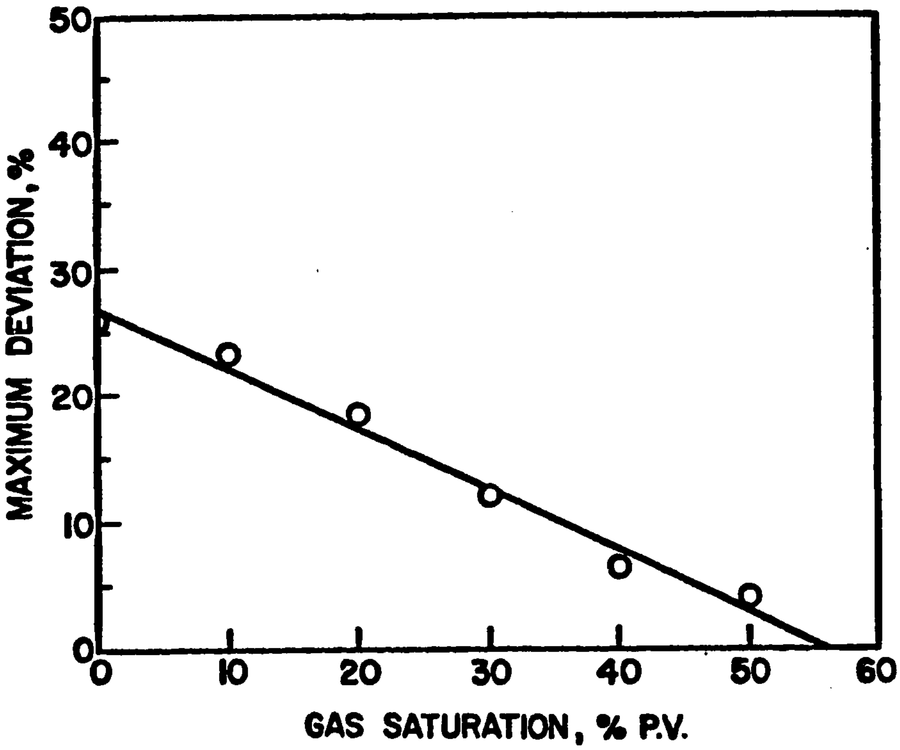


Figure B.4 Max deviation vs. gas saturation

4) The curve-fitting of oil recovery/volume burned method has been shown in Fassihi's DOE report (1981)[74]. In the report, the author used a combustion tube results for the data points in the curve plotting and fitting.

$V_B = 25\%$ $S_g = 10\%$

$V_B(o) = 2.54\%$ $MD = 22.145$ Deviation = 18

$$X = \frac{25 - 2.54}{100 - 2.54} = 0.23$$

$$\frac{\text{Deviation}}{MD} = \frac{18}{22.145} = 0.812$$

The deviations were normalized on the basis of maximum deviations and were graphed with respect to x in Figure B.5.

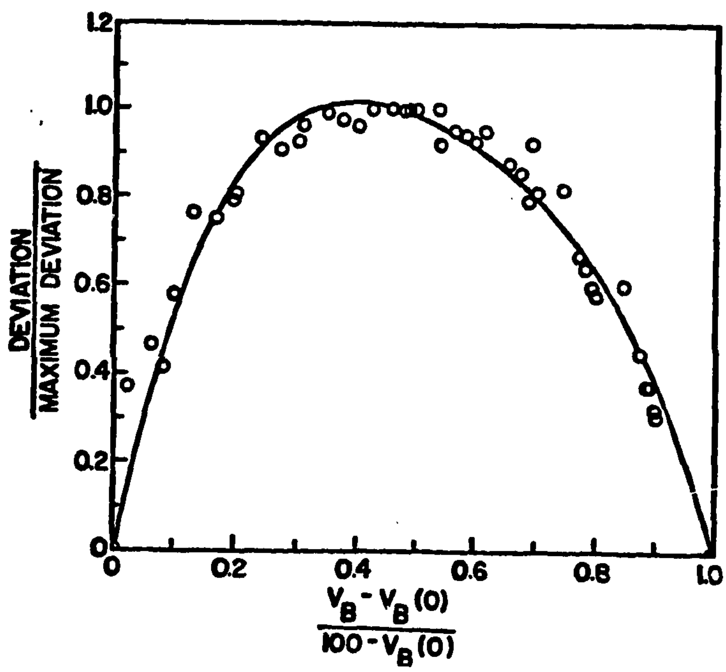


Figure B.5 Curve fitting graph

The data points of the above curve is fitted into a fourth order polynomial equation as:

$$\frac{\text{Deviation}}{\text{Maximum Deviation}} = 6.7752x - 15.9478x^2 + 16.1872x^3 - 7.0146x^4$$

As shown in figure B.6, that the actual oil recovery is a combination of oil recovery at zero gas saturation and oil recovery due to deviation of gas saturation.

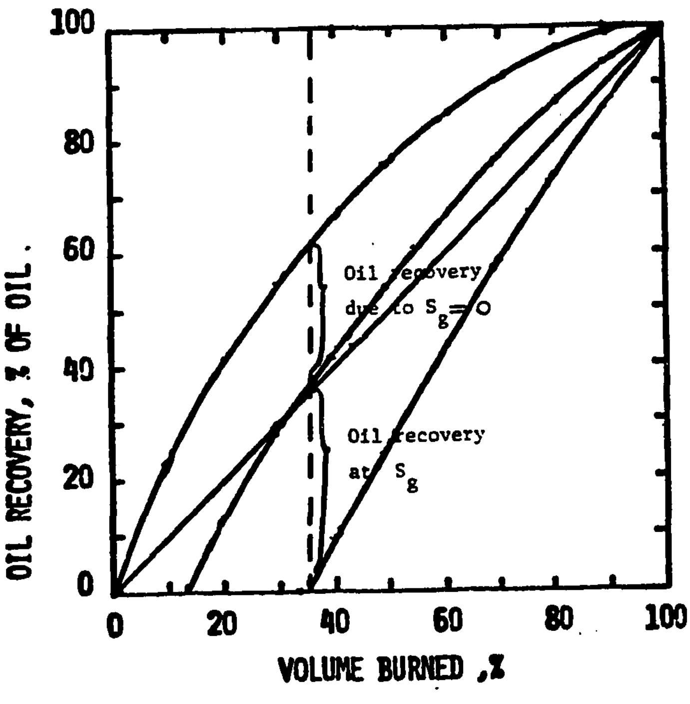


Figure B.6 Oil recovery vs. volume burned

The actual oil recovery can be formulated as follows:

Rec(%) = Oil recovery at zero gas saturation
+ Oil recovery due to deviation of gas saturation

$$= \frac{100(V_B - V_B(0))}{(100 - V_B(0))} + \frac{\text{deviation}}{\text{M.D.}} \quad (\text{MD})$$

$$= 100x + (y)\ (\text{M.D.}) \qquad (\text{B-5})$$

The slope can be obtained:

$$\text{slope} = \frac{d\text{Rec}}{dV_B}$$

From the oil recovery equation:

$$\text{slope} = 100\ \frac{dx}{dV_B} + \text{M.D.}\ \frac{dy}{dV_B}$$

$$= 100\ \frac{dx}{dV_B} + \text{M.D.}\ \frac{dy}{dx} \cdot \frac{dx}{dV_B}$$

$$= 100\left(\frac{1}{V_B - V_{BO}}\right) + \frac{\text{M.D.}}{V_B - V_{BO}} \cdot \frac{dy}{dx} \qquad (\text{B-6})$$

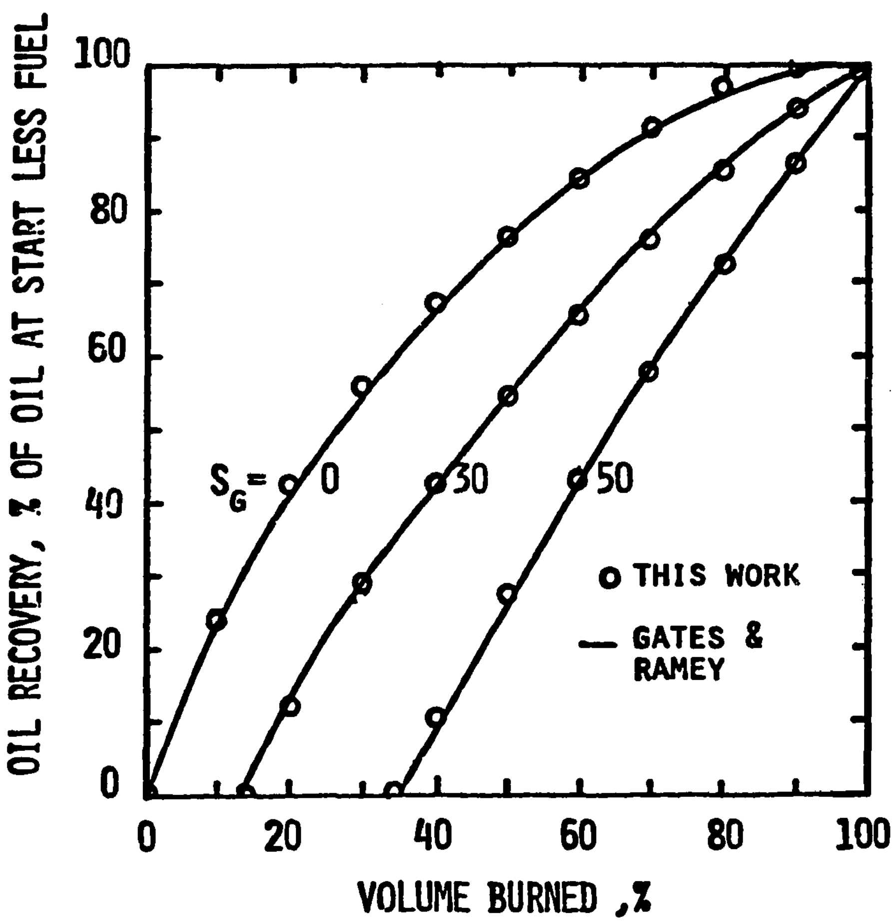


Figure B.7 Oil recovery vs. volume burned

The above figure shows the computed results (circles) as well as those of Gates and Ramey (straight line) for three different gas saturations. In general, the answers are within 1% of the actual ones.

Appendix B

Optimum Pressure of Air Injection for In-situ Combustion

The injection pressure vs production rate relationship during combustion is derived below for a developed five-spot pattern. Similar relationships can be obtained for other well patterns by application of the same method to interference flow-capacity equations for the type of well development selected (assuming the mobility ratio is unity). In addition to the usual limitations on these relationships, we assume:

1. Burning front is radial
2. Resistance to gas flow ahead of the zone
3. Gas mobility ahead of the burning zone is constant
4. Gas shrinkage as a result of combustion is negligible

The derivation is based on the fact that as long as the flow is radial at the burning zone, the flow distribution ahead of the zone is the same as the one that would prevail in the absence of the burnt-out region. Therefore, the pressure (Pr) at the radial location of the burning zone (r_f), resulting from injection at a given rate, can be calculated as the pressure which would occur at r_f, in the absence of the burned-out region and with injection from the well radius (r_w) at the same rate.

Since flow is assumed radial from r_w to r_f,

$$P_{iwf}^2 - P_r^2 = \left[\frac{i_a \mu_a T_f}{0.703kgh}\right](\ln r_f/r_w) \qquad \text{(B-7)}$$

Also, for the five-spot development with 1:1 mobility ratio (e.g. from M. Muskat[75] Physical Principles of Oil Production, p 688-715)

$$P_{iwf}^2 - P_w^2 = \left[\frac{i_a \mu_a T_f}{0.703kgh}\right]\left[(2\ln(a/r_w) - 1.238\right] \qquad \text{(B-8)}$$

Subtracting Eq. B-7 from Eq. B-8,

$$P_r^2 - P_w^2 = \left[\frac{i_a \mu a T_f}{0.703kgh}\right]\left[2\ln(a/r_w) -1.238 -\ln(r_f/r_w)\right] \qquad \text{(B-8)}$$

Combining the logarithmetic terms and noting the assumptions that $P_r = P_{iw}$

$$P_{iw}^2 - P_w^2 = \left[\frac{i_a \mu_a T_f}{0.703kgh}\right]\left[\ln(a^2/r_w r_f) - 1.238\right] \qquad \text{(B-9)}$$

or in terms of the time (t) required for the burning front to move outward to r_g at a velocity of V_1,

$$P_{iw}^2 - P_w^2 = \left[\frac{i_a \mu_a T_f}{0.703kgh}\right]\left[\ln(a^2/r_w V_1 t) - 1.238\right] \qquad \text{(B-10)}$$

Despite the assumptions of a radial burning zone, this relationship has been found to agree with potentiometric model data well beyond the period of radial burning, e.g., when the aerial sweep is 40% of the pattern area the burned zone is far from radial. However, values of P_{iw} calculated from the above equation are less than 2% higher than predicted for this aerial sweep by model data for infinite mobility ratio.

IN-SITU COMBUSTION PROCESS PERFORMANCE MODEL

****

(PROJECTION TO THE WHOLE RESERVOIR)

STATE NAME :	WYO	TX	CALIF	LA	N.M	CALIF
COUNTY NAME:	NATRONA	WILSON	L.A.	CADDO	MCKINLEY	ORANGE
FIELD NAME :	SHANNON	GLEN HUMMEL	B. OLINDA	PINE ISLAND	HOSPAH	DANNING
NET THICKNESS (FT):	33.00	8.11	150.00	24.00	13.00	100.00
PERMEABILITY (MD):	250.00	1000.00	300.00	650.00	750.00	3000.00
DEPTH (FT):	950.00	2432.00	3550.00	1000.00	4800.00	2300.00
AREA (ACRE):	5.00	544.00	31.00	15.00	1200.00	182.00
RESERVOIR PRESS (PSIA):	475.00	800.00	1775.00	500.00	2000.00	1100.00
RESERVOIR TEMP (DEG F):	78.00	113.00	135.00	90.00	185.00	130.00
POROSITY:	0.233	0.360	0.290	0.330	0.280	0.340
OIL SATURATION BEFORE PROCESS:	0.600	0.650	0.500	0.650	0.550	0.550
GAS SATURATION BEFORE PROCESS:	0.000	0.050	0.000	0.000	0.000	0.000
API GRAVITY (DEG):	25.00	21.90	22.00	21.00	10.00	12.00
WATER SAT. BEFORE PROCESS:	0.400	0.300	0.500	0.350	0.450	0.450

OUTPUT RESULT

AIR REQUIREMENT (MMSCF/AF):	0.03	0.93	0.71	0.09	1.04	4.54
CUMULATIVE PROD (MBBLS):	62.63	3456.00	1324.58	261.39	7849.16	7845.66
ULTIMATE OIL RECOVERY (%):	40.82	46.56	30.30	48.35	43.95	35.78
OIL PROD RATE (BBLS/D/PATTERN):	48.67	21.75	282.64	49.38	64.05	172.10
OPTIM MAX INJ RATE (MMCF/D/W):	1.27	0.32	7.38	0.96	0.47	5.09
OPTIM MAX INJ PRESS (PSIA):	475.33	800.21	1775.12	500.33	2000.09	1100.20

PDS SUPPLIED DATA OF A RESERVOIR
****

(ORIGINAL DATA)

1	STATE NAME :	OKLAHOMA
2	COUNTY NAME:	CARTER,GARVIN
3	FIELD NAME :	SHO-VEL-TUM(DEESE)
4	ORIGINAL OIL (BBLS/AF):	953.54
5	CUM. CRU. PROD.(BBLS):	297650900.00
6	ASSO. GAS PROD.(MSCF):	0.00
7	PRESSURE(PSIA) :	580.00
8	TEMPERATURE(DEG):	115.00
9	PROVED ACREGE(ACRE):	325.00
10	DEPTH(FT) :	2750.00
11	ZONE THICKNESS(FT) :	71.00
12	PERMEABILITY(MD) :	132.00
13	API GRAVITY(DEG) :	30.00
14	VISCOSITY SURFACE(CP) :	0.00
15	GAS-OIL RATIO(SCF/STB):	0.00
16	POROSITY :	0.170
17	OIL SATURATION :	0.723
18	WATER SATURATION :	0.277
19	GAS SATURATION :	0.000

COMMENT: THESE DATA CANNOT BE PROCESSED FOR ANY THERMAL PROCESS AT THIS TIME FOR LACKING SUFFICIENT DATA OR FAILURE IN SCREENING

PDS SUPPLIED DATA OF A RESERVOIR
****

(ORIGINAL DATA)

1	STATE NAME :	OKLAHOMA
2	COUNTY NAME:	GARVIN
3	FIELD NAME :	SE PAULS VALLEY
4	ORIGINAL OIL (BBLS/AF):	1370.84
5	CUM. CRU. PROD.(BBLS):	939000.00
6	ASSO. GAS PROD.(MSCF):	0.00
7	PRESSURE(PSIA) :	1850.00
8	TEMPERATURE(DEG):	110.00
9	PROVED ACREGE(ACRE):	325.00
10	DEPTH(FT) :	4300.00
11	ZONE THICKNESS(FT) :	100.00
12	PERMEABILITY(MD) :	2500.00
13	API GRAVITY(DEG) :	10.00
14	VISCOSITY SURFACE(CP) :	7500.00
15	GAS-OIL RATIO(SCF/STB):	0.00
16	POROSITY :	0.310
17	OIL SATURATION :	0.570
18	WATER SATURATION :	0.150
19	GAS SATURATION :	0.280

COMMENT: STEAM DRIVE IS RECOMMENDED

IN-SITU COMBUSTION IS RECOMMENDED

Pauls Valley Field:

```
RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR    (STEAM DRIVE PROCESS)

******************************************************************************
   ER1= THERMAL EFFICIENCY; ROS= OIL-STEAM RATIO(B/B);
   QNP= OIL PROD RATE (B/D) QINJ= STEAM INJ RATE (B/D);
   PINJ= STEAM INJ PRESS(PSI) NP= CUM PROD A PATT.(B);
   VISO= OIL VISCOSITY @ RES TEMP(CP); REC= OIL RECOVERY (FRACTION);
   PIS= POROSITY*OIL SAT.; TRS= TRANSMISSIBILITY;
   VS= VOL STEAM INJ.(BBLS); TS= STEAM TEMP(DEG F);

MONTH   ER1     VISC       TS          REC    PIS       QNP
 1     0.998   499.01    621.65        0.03  1767.00    0.00

   NP        VS         TRS         ROS    QINJ       PINJ
   0.00 449450.00     500.99       0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.262343  0.255918  1.681339 -0.990852 -0.866643 -1.534418
-1.534437  0.314586 -0.885493 -1.092066  0.172502  2.782578

MONTH   ER1     VISC       TS          REC    PIS       QNP
 2     0.996   499.01    621.65        0.06  1767.00  185.20

   NP        VS         TRS         ROS    QINJ       PINJ
 5555.88 450460.00    500.99       0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.481472  0.262289  1.715116 -1.048717 -0.913617 -1.115865
-1.302070  0.298979 -0.495094 -1.115820  0.178466  2.850224

MONTH   ER1     VISO       TS          REC    PIS       QNP
 3     0.995   499.01    621.65        0.09  1767.00  184.86

   NP        VS         TRS         ROS    QINJ       PINJ
 11101.69 451470.00    500.99      0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.630773  0.372917  1.781079 -1.185168 -1.011347 -0.992040
-1.142405  0.218845 -0.513089 -0.995610  0.168400  2.811962

MONTH   ER1     VISC       TS          REC    PIS       QNP
 4     0.993   499.01    621.65        0.12  1767.00  184.53

   NP        VS         TRS         ROS    QINJ       PINJ
 16637.53 452480.00    500.99      0.19  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.605752  0.365786  1.707604 -1.129570 -1.118199 -1.023896
-1.136956  0.148813 -0.552744 -1.030561  0.171499  2.679717

MONTH   ER1     VISC       TS          REC    PIS       QNP
 5     0.991   499.01    621.65        0.15  1767.00  184.20

   NP        VS         TRS         ROS    QINJ       PINJ
 22163.44 453490.00    500.99      0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.541277  0.362864  1.597354 -1.028371 -1.464137 -0.986577
-1.074199  0.136515 -0.589047 -1.005610  0.188983  2.517806

MONTH   ER1     VISC       TS          REC    PIS       QNP
 6     0.989   499.01    621.65        0.18  1767.00  183.87

   NP        VS         TRS         ROS    QINJ       PINJ
 27679.47 454500.00    500.99      0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.570293  0.342159  1.596559 -1.115396 -1.492920 -1.238172
-1.357237  0.080904 -0.665375 -1.167641  0.200300  2.474230

MONTH   ER1     VISC       TS          REC    PIS       QNP
 7     0.988   499.01    621.65        0.21  1767.00  183.54

   NP        VS         TRS         ROS    QINJ       PINJ
 33185.68 455510.00    500.99      0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.558623  0.287209  1.678978 -1.151384 -1.612942 -1.600728
-1.860715  0.956155 -0.613368 -1.201065  0.028787  1.211133

MONTH   ER1     VISC       TS          REC    PIS       QNP
 8     0.986   499.01    621.65        0.24  1767.00  183.22

   NP        VS         TRS         ROS    QINJ       PINJ
 38682.14 456520.00    500.99      0.18  1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.552859  0.292769  1.586099 -1.198894 -1.555529 -1.507459
-1.669944  0.135140 -0.653154 -1.167267  0.218218  2.377355
```

Pauls Valley Field:

RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR (IN-SITU COMB. PROCESS)

REC= OIL RECOVERY(%); AOR= AIR-OIL RATIO(MCF/B);
QINJ= MAX AIR INJ RATE(MMCF/D); PINJ= INJ PRESSURE (PSIA);
PIS= POROSITY*OIL-SAT. ; TRS= TRANSMISSIBILITY ;
ASR= AIR-SAND RATIO (MCF/AF); FB= FUEL BURNED(B/AF) ;
CAI= CUM. AIR REQUIRED(MMCF/AF); QOP= OIL PROD RATE(BBL/D);
NP= CUM. OIL PROD.(BBLS); VB= VOL BURNED(%) ;

MONTH	REC	PIS	FB	CAI	PINJ	NP
1	2.18	1767.00	121.23	0.52	1850.12	13606.00

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	2.86	13.52	440.59	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-1.328256 -0.477111 -1.156398 4.227872 2.246393 -0.433514
-1.156349 -0.377575 -0.542605 4.169042 1.684925 1.418438 0.963299

MONTH	REC	PIS	FB	CAI	PINJ	NP
2	4.30	1767.00	121.23	0.56	1850.12	26866.95

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	2.94	14.52	429.47	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-1.480722 -0.477111 -1.156399 2.188047 2.246353 -0.417067
-1.156349 -0.377575 -0.659031 3.308746 1.796351 1.418436 0.963299

MONTH	REC	PIS	FB	CAI	PINJ	NP
3	6.37	1767.00	121.23	0.60	1850.12	39794.92

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	3.01	15.52	418.74	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-1.626529 -0.477111 -1.156398 1.419297 2.246393 -0.409339
-1.156365 -0.377575 -0.789805 2.293591 1.902049 1.418438 0.963295

MONTH	REC	PIS	FB	CAI	PINJ	NP
4	8.39	1767.00	121.23	0.64	1850.12	52801.67

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	3.09	16.52	409.43	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-2.362897 -0.504602 -1.356203 0.912956 2.573538 -0.416194
-1.356247 -0.390916 -0.989494 2.927374 1.981127 1.271456 0.531659

MONTH	REC	PIS	FB	CAI	PINJ	NP
5	15.98	1767.00	121.23	0.79	1850.12	99845.06

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	3.40	20.52	370.70	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-1.681866 -0.504602 -1.356203 0.932587 2.573538 -0.018904
-1.356247 -0.390916 -0.926371 3.490942 1.876175 1.271432 0.931676

MONTH	REC	PIS	FB	CAI	PINJ	NP
6	22.09	1767.00	121.23	0.94	1850.12	143031.70

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	3.73	24.52	338.49	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-1.107811 -0.609491 -1.572584 0.980959 2.868375 0.222272
-1.573118 -0.399255 -0.879807 4.672957 1.757651 1.277727 0.975054

MONTH	REC	PIS	FB	CAI	PINJ	NP
7	29.23	1767.00	121.23	1.10	1850.12	182599.60

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	4.05	28.52	311.27	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-0.619063 -0.707110 -1.674830 1.020902 2.747821 0.383403
-1.674756 -0.366941 -0.804240 5.923847 1.631350 1.201780 0.999789

MONTH	REC	PIS	FB	CAI	PINJ	NP
8	33.65	1767.00	121.23	1.21	1850.12	210247.50

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	4.29	31.52	293.80	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-0.458256 -0.753901 -1.788882 0.895836 2.696585 0.403237
-1.789444 -0.330718 -0.810773 6.457581 1.604664 1.161876 0.962103

MONTH	REC	PIS	FB	CAI	PINJ	NP
9	35.19	1767.00	121.23	1.37	1850.12	244831.50

ASR	TRS	AOR	VB	QOP	VISC	QINJ
7.69	500.99	4.63	35.52	274.03	499.01	5.04

Z-VALUES OF ALL THE ABOVE VARIABLES
-0.109442 -0.852858 -1.794152 0.915240 2.716751 0.479162
-1.794644 -0.273428 -0.695876 6.888944 1.507823 1.079844 0.963251

PDS SUPPLIED DATA OF A RESERVOIR
****

(ORIGINAL DATA)

1	STATE NAME :	OKLAHOMA
2	COUNTY NAME:	GARVIN
3	FIELD NAME :	SE PAULS VALLEY
4	ORIGINAL OIL (BBLS/AF):	1370.84
5	CUM. CRU. PROD.(BBLS):	939000.00
6	ASSO. GAS PROD.(MSCF):	0.00
7	PRESSURE(PSIA) :	1850.00
8	TEMPERATURE(DEG):	110.00
9	PROVED ACREGE(ACRE):	325.00
10	DEPTH(FT) :	4300.00
11	ZONE THICKNESS(FT) :	100.00
12	PERMEABILITY(MD) :	878.00
13	API GRAVITY(DEG) :	10.00
14	VISCOSITY SURFACE(CP) :	7500.00
15	GAS-OIL RATIO(SCF/STB):	0.00
16	POROSITY :	0.310
17	OIL SATURATION :	0.570
18	WATER SATURATION :	0.150
19	GAS SATURATION :	0.280

COMMENT: STEAM DRIVE IS RECOMMENDED

IN-SITU COMBUSTION IS RECOMMENDED

Pauls Valley Field:

```
RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR   (STEAM DRIVE PROCESS)

*************************************************************************
   EH1= THERMAL EFFECIENCY; ROS= OIL-STEAM RATIO(B/B);
   QOP= OIL PROD RATE (B/D) QINJ= STEAM INJ RATE (B/D);
   PINJ= STEAM INJ PRESS(PSI) NP= CUM PROD A PATT.(B);
   VISO= OIL VISCOSITY @ RES TEMP(CP); REC= OIL RECOVERY (FRACTION);
   PIS= POROSITY*OIL SAT.;  TRS= TRANSMISSIBILITY;
   VS= VOL STEAM INJ.(BBLS); TS= STEAM TEMP(DEG F);

MONTH   EH1      VISO      TS        REC     PIS       QOP
 1      0.998    499.01    621.65    0.03    1767.00     0.00

   NP       VS          TRS        ROS    QINJ      PINJ
   0.00  449450.00    175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.262348  0.255918  1.681339 -0.990852 -0.866683 -1.534418
-1.530417  0.318586 -0.580840 -1.092066  0.172502  2.782578

MONTH   EH1      VISO      TS        REC     PIS       QOP
 2      0.996    499.01    621.65    0.06    1767.00   185.20

   NP       VS          TRS        ROS    QINJ      PINJ
 5555.88 450460.00    175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.481472  0.262289  1.715116 -1.048717 -0.913617 -1.115865
-1.342070  0.298879 -0.589729 -1.115820  0.174866  2.850224

MONTH   EH1      VISO      TS        REC     PIS       QOP
 3      0.995    499.01    621.65    0.09    1767.00   184.86

   NP       VS          TRS        ROS    QINJ      PINJ
 11101.69 451470.00   175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.630773  0.372817  1.781379 -1.185168 -1.011347 -0.992040
-1.182805  0.216845 -0.612326 -0.995610  0.164400  2.811962

MONTH   EH1      VISO      TS        REC     PIS       QOP
 4      0.993    499.01    621.65    0.12    1767.00   184.53

   NP       VS          TRS        ROS    QINJ      PINJ
 16637.53 452480.00   175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.605752  0.369786  1.707604 -1.129570 -1.118198 -1.023996
-1.136956  0.148813 -0.649473 -1.030561  0.171459  2.679717

MONTH   EH1      VISO      TS        REC     PIS       QOP
 5      0.991    499.01    621.65    0.15    1767.00   184.20

   NP       VS          TRS        ROS    QINJ      PINJ
 22163.44 453490.00   175.95      0.19   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.581277  0.362860  1.597358 -1.028371 -1.464137 -0.986577
-1.074199  0.196515 -0.678838 -1.005610  0.188983  2.517866

MONTH   EH1      VISO      TS        REC     PIS       QOP
 6      0.999    499.01    621.65    0.18    1767.00   183.87

   NP       VS          TRS        ROS    QINJ      PINJ
 27679.87 454500.00   175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.570293  0.342159  1.596559 -1.115396 -1.492928 -1.238172
-1.357237  0.083904 -0.789807 -1.167641  0.200000  2.474236

MONTH   EH1      VISO      TS        REC     PIS       QOP
 7      0.988    499.01    621.65    0.21    1767.00   183.54

   NP       VS          TRS        ROS    QINJ      PINJ
 33185.68 455510.00   175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.558623  0.287208  1.678978 -1.151384 -1.612982 -1.600728
-0.860715  0.956155 -0.733849 -1.281065  0.028787  1.211133

MONTH   EH1      VISO      TS        REC     PIS       QOP
 8      0.986    499.01    621.65    0.24    1767.00   183.22

   NP       VS          TRS        ROS    QINJ      PINJ
 38682.18 456520.00   175.95      0.18   1010.00   1800.58

Z-VALUES OF ALL THE ABOVE VARIABLES
 0.552859  0.292769  1.586099 -1.188894 -1.555529 -1.507459
-1.669944  0.135340 -0.770271 -1.167267  0.218218  2.377359
```

Pauls Valley Field:

```
RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR    (IN-SITU COMB. PROCESS)

**************************************************************************
     REC= OIL RECOVERY(%);  AOR= AIR-OIL RATIO(MCF/B);
     QINJ= MAX AIR INJ RATE(MMCF/D); PINJ= INJ PRESSURE (PSIA);
     PIS= POROSITY*OIL-SAT. ;  TRS= TRANSMISSIBILITY ;
     ASR= AIR-SAND RATIO (MCF/AF); FB= FUEL BURNED(B/AF) ;
     CAI= CUM. AIR REQUIRED(MMCF/AF); QOP= OIL PROD RATE(BBL/D);
     NP= CUM. OIL PROD.(BBLS); VB= VOL BURNED(%) ;

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   1       2.18   1767.00     88.43      0.38   1850.11   13963.16

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.03     13.52    575.95    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.328256 -0.477111 -1.785657  2.761108  2.246379 -0.419789
-1.745604 -0.753288 -1.252465  4.169042  2.576626  1.418438  0.816564

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   2       4.80   1767.00     88.43      0.41   1850.11   27572.22

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.09     14.52    561.42    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.480722 -0.477111 -1.785859  1.290504  2.246379 -0.400868
-1.745604 -0.753288 -1.368690  3.308746  2.721317  1.418438  0.816564

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   3       6.37   1767.00     88.43      0.44   1850.11   40839.57

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.14     15.52    547.39    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.626529 -0.477111 -1.785657  0.729049  2.248379 -0.391642
-1.745620 -0.753288 -1.502690  2.293591  2.857086  1.418438  0.816564

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   4      15.98   1767.00     88.43      0.58   1850.11  102466.00

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.42     20.52    484.59    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.990500 -0.504602 -2.003308  0.719454  2.573522  0.249450
-2.003386 -0.762404 -1.528016  4.770429  2.577956  1.271456  0.785259

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   5      24.53   1767.00     88.43      0.72   1850.11  157262.00

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.71     25.52    433.01    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.288832 -0.504602 -2.003308  0.739835  2.573522  0.614951
-2.003386 -0.762404 -1.460825  5.655744  2.396192  1.271432  0.785275

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   6      32.20   1767.00     88.43      0.86   1850.11  206490.80

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       2.99     30.52    391.33    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
 0.471035 -0.609491 -2.260624  0.780757  2.468358  0.829768
-2.261340 -0.808425 -1.418301  7.443166  2.225602  1.277727  0.821962

  MONTH    REC     PIS        FB         CAI     PINJ        NP
   7      39.19   1767.00     88.43      1.00   1850.11  251258.50

    ASR       TRS         AOR       VB       QOP       VISO      QINJ
     5.61    175.95       3.27     35.52    358.22    499.01      4.69

 Z-VALUES OF ALL THE ABOVE VARIABLES
 1.065042 -0.707110 -2.380509  0.918408  2.747805  0.956781
-2.380964 -0.804836 -1.372853  9.364497  2.062604  1.201780  0.845332
```

PDS SUPPLIED DATA OF A RESERVOIR

****

(ORIGINAL DATA)

1	STATE NAME :	OKLAHOMA,S
2	COUNTY NAME:	JEFFERSON
3	FIELD NAME :	LOCO (IDA BILLY)
4	ORIGINAL OIL (BBLS/AF):	1153.89
5	CUM. CRU. PROD.(BBLS):	0.00
6	ASSO. GAS PROD.(MSCF):	0.00
7	PRESSURE(PSIA) :	330.00
8	TEMPERATURE(DEG):	60.00
9	PROVED ACREGE(ACRE):	213.00
10	DEPTH(FT) :	526.00
11	ZONE THICKNESS(FT) :	12.90
12	PERMEABILITY(MD) :	2553.00
13	API GRAVITY(DEG) :	20.80
14	VISCOSITY SURFACE(CP) :	588.00
15	GAS-OIL RATIO(SCF/STB):	0.00
16	POROSITY :	0.256
17	OIL SATURATION :	0.581
18	WATER SATURATION :	0.316
19	GAS SATURATION :	0.103

COMMENT: STEAM DRIVE IS RECOMMENDED

IN-SITU COMBUSTION IS RECOMMENDED

Loco Field:

```
RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR   (STEAM DRIVE PROCESS)

**********************************************************************
   EH1= THERMAL EFFECIENCY; ROS= OIL-STEAM RATIO(B/B);
   QWP= OIL PROD RATE (B/D) QINJ= STEAM INJ RATE (B/D);
   PINJ= STEAM INJ PRESS(PSI) NP= CUM PRDC A PATT.(B);
   VISO= OIL VISCOSITY @ RES TEMP(CP); REC= OIL RECOVERY (FRACTION);
   PIS= POROSITY*OIL SAT.;  TRS= TRANSMISSIBILITY;
   VS= VOL STEAM INJ.(BBLS); TS= STEAM TEMP(DEG F);

 MONTH  EH1      VISO      TS         REC    PIS       CNP
  1     0.969   240.09    422.71      0.21   1487.36     0.00

    NP        VS        TRS        ROS    QINJ      PINJ
     0.00   6880.00   137.17     0.33   430.00    324.32

Z-VALUES OF ALL THE ABOVE VARIABLES
-2.590625 -0.339676 -0.240854  0.891327 -1.334925 -1.534418
-1.534417 -0.865275 -0.592215 -0.762390 -5.751556 -0.574473

 MONTH  EH1      VISO      TS         REC    PIS       CNP
  2     0.920   240.09    422.71      0.40   1487.36   141.06

    NP        VS        TRS        ROS    QINJ      PINJ
  4231.93   7310.00   137.17     0.31   430.00    324.32

Z-VALUES OF ALL THE ABOVE VARIABLES
-3.546228 -0.327556 -0.215460  0.993094 -1.388823 -1.221601
-1.394904 -0.873825 -0.601020 -0.921760 -5.683913 -0.549026

 MONTH  EH1      VISO      TS         REC    PIS       CNP
  3     0.877   240.09    422.71      0.53   1487.36   133.39

    NP        VS        TRS        ROS    QINJ      PINJ
  8248.54   7740.00   137.17     0.30   430.00    324.32

Z-VALUES OF ALL THE ABOVE VARIABLES
-5.303879 -0.282358 -0.529705  2.141108 -1.471699 -1.110992
-1.216304 -0.893846 -0.624170 -0.741116 -5.263293 -0.742193
```

Loco Field:

```
RESULTS OF FIVE-SPOT PILOT TEST IN THE RESERVOIR   (IN-SITU COMB. PROCESS)

*********************************************************************
    REC= OIL RECOVERY(%);  AOR= AIR-OIL RATIO(MCF/B);
    QINJ= MAX AIR INJ RATE(MMCF/D); PINJ= INJ PRESSURE (PSIA);
    PIS= POROSITY*OIL-SAT. ;  TRS= TRANSMISSIBILITY ;
    ASR= AIR-SAND RATIO (MCF/AF); FB= FUEL BURNED(B/AF) ;
    CAI= CUM. AIR REQUIRED(MMCF/AF); QNP= OIL PROD RATE(BBL/D);
    NP= CUM. OIL PROD.(BBLS); VB= VOL BURNED(%) ;

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  1       2.52   1487.36   176.55      0.03     330.48   1589.85

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       4.61      3.65      28.52     240.09     0.51

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.223494 -0.993815 -0.162652 -0.917785 -0.358125 -0.895290
-0.162611 -0.798112  0.955167  0.009367 -1.029610  0.257618 -0.891466

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  2       4.97   1487.36   176.55      0.01     330.48   3138.46

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       4.78      4.65      27.71     240.09     0.51

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.353884 -0.993815 -0.162652 -0.929482 -0.358125 -0.962150
-0.162613 -0.798112  0.851243 -0.497736 -1.020083  0.257618 -0.891466

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  3       9.67   1487.36   176.55      0.05     330.48   6093.62

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       5.02      6.65      26.16     240.09     0.51

 Z-VALUES OF ALL THE ABOVE VARIABLES
-1.143216 -0.993815 -0.162652 -0.926315 -0.358125 -0.980271
-0.162627 -0.798112  0.857018 -0.530315 -1.012277  0.257618 -0.891467

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  4      16.22   1487.36   176.55      0.07     330.48  10227.72

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       5.47      9.65      24.03     240.09     0.51

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.986380 -1.019485 -0.264903 -0.920856 -0.306735 -0.974929
-0.264893 -0.806724  0.925084 -0.236938 -1.027761  0.214253 -0.918803

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  5      20.30   1487.36   176.55      0.08     330.48  12796.10

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       5.78     11.65      22.73     240.09     0.51

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.937893 -1.019485 -0.264903 -0.922127 -0.306715 -0.974630
-0.264893 -0.806724  0.902752 -0.348152 -1.029065  0.214210 -0.918166

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  6      24.15   1487.36   176.55      0.10     330.48  15226.07

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       6.11     13.65      21.51     240.09     0.53

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.893591 -1.124057 -0.412250 -0.964849 -0.216226 -1.001215
-0.812480 -0.857241  0.836074 -0.344605 -1.050048  0.156005 -0.960067

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  7      27.80   1487.36   176.55      0.11     330.48  17527.21

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       6.45     15.65      20.38     240.09     0.53

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.859159 -1.213690 -0.483673 -0.961038 -0.237407 -0.995137
-0.483786 -0.857078  0.942274 -0.400825 -1.040200  0.099020 -0.952590

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  8      31.26   1487.36   176.55      0.13     330.48  19768.70

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       6.80     17.65      19.33     240.09     0.53

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.846810 -1.282781 -0.561411 -0.967288 -0.253175 -1.003886
-0.561637 -0.818669  0.900567 -0.409313 -1.061089  0.063620 -0.970148

 MONTH    REC     PIS       FB         CAI      PINJ        NP
  9      36.13   1487.36   176.55      0.15     330.48  22775.72

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       7.38     20.65      17.91     240.09     0.53

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.602381 -1.389152 -0.565107 -0.936612 -0.196476 -0.988382
-0.565289 -0.864696  1.068079 -0.080911 -1.047845  0.003516 -0.982898

 MONTH    REC     PIS       FB         CAI      PINJ        NP
 10      39.18   1487.36   176.55      0.16     330.48  24695.63

   ASR       TRS         AOR       VB        QNP       VISO      QINJ
  11.20     137.17       7.71     22.65      17.05     240.09     0.53

 Z-VALUES OF ALL THE ABOVE VARIABLES
-0.582213 -1.355926 -0.764038 -1.056215 -0.166743 -1.085125
-0.764192 -0.882102  0.922829 -0.022662 -1.166890  0.033848 -1.061682
```

Appendix D

OPTIMIZATION MODEL PROGRAM USER'S GUIDE

This user's guide provides some background with respect to the computer program used to solve the multi-criteria programming algorithm. The author used the S.E.Paul's Valley in-situ combustion formulation as an illustration. This computer program is general in nature and may be used to solve any multi-criteria programming formulation. The computer has been modified to adopt the IBM 360 mainframe computer and the VAX 11/780, and PDP 11/70 minicomputers.

(i) Double precision statements were added to the program to handle the round-off errors during the pivoting in the modified simplex algorithm.

(ii) Computer codes were modified for the character string in FORTRAN variables coding.

(iii) This program is capable of solving problems with a maximum

NUMBER OF VARIABLES	= 125 (NVAR)
NUMBER OF ROWS	= 60 (NROWS)
NUMBER OF PIRORITY LEVELS	= 20 (NPRT)

However, the capability can be expanded with a modification in the defined subscribers and it is only limited by the memory storage of the computer.

In-situ Combustion Formulation (First Timestep)

Main objective function:

$$\text{Min } Z = P_1\,(d_1^- + d_1^+) + P_2 d_2^+ + P_3 d_3^- + P_4 d_4^+ + P_5 d_5^-$$

Real constraints:

$$X_1 \leq REC$$
$$X_2 \leq PIS$$
$$X_3 \leq FB$$
$$X_4 \leq CAI$$
$$X_5 \leq PINJ$$
$$X_6 \leq NP$$
$$X_7 \leq ASR$$
$$X_8 \leq TRS$$
$$X_9 \leq AOR$$
$$X_{10} \leq VB$$
$$X_{11} \leq QNP$$
$$X_{12} \leq VISO$$

Goal constraints:

Recovery G_1: $REC = -1.099288X_9 - 0.832598X_2 + 0.572264X_3 + 0.14612X_4 + d_1^- - d_1^+$

Prod. rate G_2: $QNP = -.091530X_{10} - .081230X_5 + .117596X_{12} + 0.600794X_6 + d_2^- - d_2^+$

Inj. rate G_3: $QINJ = -0.02794X_5 + 0.099275X_{12} + 0.521800X_4 + .27496X_6 + 0.443930X_7 + 0.235473X_8 - 0.338854X_2 - 0.362949X_9 + d_3^- - d_3^+$

Inj. Press. G_4 $PINJ = -1.577117X_4 + 0.170476X_{12} + 0.891372X_{10} + 0.048741X_9 + 0.506780X_6 + 0.67741X_{11} + 0.834522X_8 + d_4^- - d_4^+$

Profit G_5: $PROF = (32.25X_6 - 675X_4)/100{,}000 + d_5^- - d_5^+$

Input

Introduction

The computer program is designed to automatically provide the proper deviational variables for execution. The user must specify the following data:

1. Number of constraints or goals (rows)

2. Number of choice variables (columns)

3. Number of priorities

4. Coefficients of choice variables for each constraint or goal

5. Direction of each constraint or goal (equality or sense of inequality)

6. Value of the right-hand side has to be positive. If the given value is negative, then it is necessary to reverse the sign by multiplication by (-1)

7. Objective function to include the priority level, the location and sign of the deviational variable, and any differential weight to be applied to the deviational variable.

The input data deck requires five basic sections to provide the required information. Each of the five sections will be described in detail below using data examples.

The Problem Card Section

The problem card supplies the first three items of data specified above as required and initializes several key variables internal to the program. The format for the problem card is as follows:

Columns	1-4	PROB
Columns	5-7	Number of rows
Columns	8-10	Number of columns
Columns	11-13	Number of priorities
Columns	14-16	Output switch
Columns	17-19	Blank
Columns	20-79	User comments

```
         1         2         3
12345678901234567890123456789012345. .
PROB170012005001   MODEL TIMESTEP ONE
```

The number of rows specifies the total number of real and goal constraints. The number of columns specifies the number of choice variables in the problem. This is not to include any deviational or slack variables since the program will generate these as required. The number of priorities specifies the distinct level of priority. Artificial variables necessary for solution will be generated by the computer program as required.

The output switch is a request by the user have to program print out each iteration of the simplex table as opposed to printing only the final solution table. This option may be activated by specifying any positive value in this field. If no value is specified, the program will default to zero and only the final solution table will be printed. This option should be used with caution since the number of iterations can be large and an excessive volume of output may be produced.

Sixty columns are provided for the user to enter any comments desired to aid in identification of the program run, input data, date, etc. This information will be printed on page one of the output.

The Sign Card Section

The sign card is used to describe the direction of the constraints. There are four possibilities:

1. B will allow the minimization of either the negative or positive deviational variable or both deviational variables in the objective function, when the absolute achievement is expected in a goal constraint.

2. E will not allow deviations in the solution from either the negative or positive direction. E is always used for real constraint variables.

3. G will allow only a positive deviation when

underachievement is desirable for the goal constraints.

4. L will allow only a negative deviation when overachievement is desirable for the goal constraints.

If either B or G is specified, the program will generate a positive deviational variable. If either E or G is specified, the program will generate an artificial variable. At least one deviational variable from each constraint (row) must appear in the objective function. If neither variable appears, it is possible for the program to generate a solution in which both deviational variables end up in the basis and the constraint $d_1^- \times d_1^+ = 0$ will be violated. If both deviational variables appear in the objective function, they may be assigned different priorities.

The format of the sign card is as follows:

Column 1 sign of 1st equation

Column 2 sign of 2nd equation

.

.

.

Column n sign of nth equation.

```
         1         2
12345678901234567890...

EEEEEEEEEEEEBGLGL
```

The Main Objective Function Section

The main objective function cards specify all information required in item seven above. These cards must be prefaced by a card with OBJ in the first three columns to signal the computer program that the objective function follows.

The format for these cards is as follows:

Columns 1-3 POS or NEG to indicate the sign of the deviational variable to be minimized. If POS is specified, it is mandatory that either B or G be specified on the sign card for the corresponding row.

Columns 8-9 The row in which the deviational variable appears

Columns 10-12 Blank

Columns 13-14 The priority assigned to the deviational variable. The priorities must be sequential with one indicating the highest priority.

Columns 15-25 The coefficient or differential weight to be assigned to the deviational variable within this priority.

```
SIGN   ROW   PRI   WEIGHT

         1         2
1234567890123456789012345...

POS     13    01      1.0
NEG     13    01      1.0
POS     14    02      1.0
NEG     15    03      1.0
POS     16    04      1.0
NEG     17    05      1.0
```

<u>The Data Section</u>

The input cards in this section specify the technological coefficients for the choice variables. These cards <u>must</u> be prefaced by a card with DATA in the first four columns to signal the computer program that the technological coefficients are to follow.

The format for these cards is as follows:

Columns 1-7 Blank

Columns 8-9 The row in which the coefficient is located

Columns 10-12 Blank

Columns 13-14 The column in which the coefficient is located

Columns 15-25 The value of the coefficient.

```
      ROW   COL    VALUE

         1         2
1234567890123456789012345...

        01    01        -1
        01    02        -1
        01    03        -1
etc.
```

The Right-Hand Side Section

The last section of the input data deck is the right-hand side section. These cards specify the value of the right-hand side of the constraints or goal equations. These cards must be prefaced by a card with RGHT in the first four columns to signal to the computer the end of the data section and the start of the right-hand side values.

The format for these cards is as follows;

Columns 1-10 Value for the 1st row

Columns 11-20 Value for the 2nd row

.

.

.

Columns 61-70 Value for the 7th row,

If there are more than seven rows, continue rows eight through fourteen on the second card, and so on.

```
          1         2         3
12345678901234567890123456789012..

RGHT
1.223490. 0.9938150  0.162652 0......
0.798112  0.9551670  0.009367 0......
   etc.         "         "
   etc.
```

A complete data deck set up is illustrated in the following figure:

```
PROB170012005001
EEEEEEEEEEEEBGLGL
POS     13   01      1.0
NEG     13   01      1.0
POS     14   02      1.0
NEG     15   03      1.0
POS     16   04      1.0
NEG     17   05      1.0
DATA    01   01   -1
        02   02   -1
        03   03   -1
        04   04   -1
        05   05   -1
        06   06   -1
        07   07   -1
        08   08   -1
        09   09    1
        10   10    1
        11   11   -1
        12   12    1
        13   09   +1.099288
        13   02   -0.835296
        13   03   -0.572264
        13   04   -0.146120
        14   10   -0.09153
        14   05   -0.081230
        14   04   -0.356053
        14   12   -0.117596
        14   06   -0.600794
        15   05   +0.017494
        15   12   -0.099275
        15   04   -0.521800
        15   06   -0.27496
        15   07   -0.443930
        15   08   -0.235473
        15   02   -0.338854
        15   09   -0.362949
        16   04   +1.577117
        16   12   -0.170476
        16   10   -0.891372
        16   09   -0.048741
        16   06   -0.506780
        16   11   -0.677410
        16   08   -0.834522
        17   06   +0.003225
        17   04   -0.067500

RIGHT
1.23494  0.993815 0.162652 0.917785 0.358125 0.895290 0.162613
0.798112 0.955167 0.009367 1.029610 0.257618 1.223494 1.029610
0.891466 0.358125 4.098842
```

<u>Output</u>

The computer program provides the following output:

a) A complete printout of the input data to include the righthand side values, the substitution rates, and the objective function, b) the final simplex solution table to inlcude the Z_j-C_j matrix and evaluation of the objective functions; c) the slack analysis presents the values of the right-hand side, and also values of the negative, positive variables for each equations. d) an analysis of the variables, and e) a summary of the objective achievements. The output listings are self-explanatory. The results of the program are basically obtained from (d) and (e).

VARIABLE ANALYSIS

VARIABLE	AMOUNT
3	0.336562
5	2.246393
7	0.336596
4	1.227771
11	0.389944
9	1.434628
8	2.681349
10	4.169042

ANALYSIS OF THE OBJECTIVE

PRIORITY	ACHIEVEMENT
5	4.098442
4	2.349988
3	0.000000
2	0.000000
1	0.227122

Since the above example has been run in Z-value and the conversion can be done with a f77 program, the program is listed as following and the converted results have been listed in the S.E. Pauls Valley case study of Chapter V.

F-77 Z-values Conversion Program:

```
      REAL*4 NP
      data a11,a12,a13,a14,a15,a16,a17,a18,a19,a110,a111,a112,a113,s11
     *,s12,s13,s14,s15,s16,s17,s18,s19,s110,s111,s112,s113/6.544063,
     *3.495,184.815,185.6087,0.114375,24886.75,2.6975,539.4297,
     *182.6344,3.63,2025.213,827.6484,11.77125,3.287327,1.166213,
     *151.8019,55.6682,0.095881,26021.62,2.436151,583.4621,
     *223.0439,2.372191,541.2009,865.1397,3.530535/
      write(6,5)
 5    format(2x,'DECISION VARIABLES')
      do 600 n= 1,12
      read (5,*) ix,zval
      if (ix.eq.999) go to 110
      if (ix.eq.1) then
      rec = zval*s11 + a11
      write(6,10) rec
 10   format(22x,'rec =',f10.3)
      else if (ix.eq.2) then
      write(6,11) aor
 11   format(2x,'aor =',f10.3)
      else if (ix.eq.3) then
      qnp=zval*s13 + a13
      write(6,12) qnp
 12   format(2x,'qnp =',f10.3)
      else if (ix.eq.4) then
      fb=zval*s14 + a14
      write(6,13) fb
 13   format(2x,'fb =',f10.3)
      else if (ix.eq.5) then
      cai=zval*s15 +a15
      write(6,14) cai
 14   format(2x,'cai =',f10.3)
      else if (ix.eq.6) then
      np=zval*s16 + a16
      write(6,15) np
 15   format(2x,'np =',f10.3)
      else if (ix.eq.7) then
      qinj=zval*s17 + a17
      write(6,16) qinj
 16   format(2x,'qinj =',f10.3)
      else if (ix.eq.8) then
      pinj=zval*s18 + a18
      write(6,17) pinj
 17   format(2x,'pinj =',f10.3)
      else if (ix.eq.9) then
      viso=zval*s19 + a19
      write(6,18) viso
 18   format(2x,'viso =',f10.3)
      else if (ix.eq.10) then
      vb=zval*s110 + a110
      write(6,19) vb
 19   format(2x,'vb =', f10.3)
      else if (ix.eq.11) then
      pis=zval*s111 + a111
      write(6,20) pis
 20   format(2x,'pis =', f10.3)
      else if (ix.eq.12) then
      trs=zval*s112 + a112
      write(6,21) trs
 21   format(2x,'trs =',f10.3)
      else if (ix.eq.13) then
      asr=zval*s113 + a113
      write(6,22) asr
 22   format(2x,'asr =', f10.3)
      end if
 600  continue
 110  do 80 m = 1,5
      read(5,*) ip, zval
      if (ip.eq.5) then
      prof=zval*100000.
      else if (ip.eq.4) then
      pinj=zval*s18 + a18
      else if (ip.eq.3) then
      qinj=zval*s17 + a17
      else if (ip.eq.2) then
      qnp=zval*s13 + a13
      else if (ip.eq.1) then
      rec=zval*s11 + a11
      write(6,23)
 23   format(15x,' PROCESS ACHIEVEMENT ')
      write(6,24)
 24   format(4x,'prof',7x,'pinj',7x,'qinj',3x,'qnp',10x,'rec')
      write(6,25) prof,pinj,qinj,qnp,rec
 25   format(5f10.3)
      end if
 80   continue
      stop
      end
```

```
$JOB
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER*1 SIGN
      COMMON/BLOK1/ KEPT(60), RHS(60), RHST(60), Y(60)
      COMMON/BLOK2/ VALT(60,20), ZVAL(20), ENAME(10)
      COMMON/BLOK3/ C(60,150), PVLI(20,150), VALI(20,150)
      COMMON/BLOK4/ NROWS, NVAR, NPRT, KPCK, TEST, ITAB
      COMMON/BLOK5/ AMT(60), D(60,150), SIGN(80), X(150)
C**********************************************************************
C
C
C     MULTI-CRITERIA OPTIMIZATION PROGRAM FOR DECISION ANALYSIS
C
C        THIS PROGRAM IS CAPABLE OF SOLVING PROBLEMS WITH A MAXIMUM
C         NUMBER OF VARIABLES      = 125   (NVAR)
C         NUMBER OF ROWS           = 60    (NROWS)
C         NUMBER OF PRIORITY LEVELS = 20   (NPRT)
C
C     THE ORIGINAL PROGRAM WAS WRITTEN BY FIGEL BASING ON SANG LEE'S
C     MULTI-CRITERIA GOAL PROGRAM FOR DECISION ANALYSIS.
C     JOHN YU MODIFIED THE PROGRAM FOR FITTING INTO MOST OF THE FORTRAN
C     COMPILERS; NAMELY:
C                       1) WATFIV IN IBM 360
C                       2) FORTRAN 77 IN PDP 11/70 AND VAX 11/780
C
C            THE PROGRAM REQUIRES 35K OF CORE TO EXECUTE
C
C
C**********************************************************************
C
C        CALL START TO INITIALIZE MATRICES AND READ INPUTS
C
C
      CALL START
      ITPP =0
      TOLR =0.000001
      LISP = NPRT + 1
      DO 10 J=1,NVAR
      X(J) = J
   10 CONTINUE
      DO 20 I=1,NROWS
      Y(I) = I
   20 CONTINUE
      DO 30 K=1,NPRT
      DO 30 I=1,NROWS
      VALT(I,K) = VALI(K,I)
   30 CONTINUE
C
C     BRING IN NEW VARIABLES
C     CALCULATE NET CONTRIBUTION OF EACH VARIABLE  (NVLI(K,J))
C
      L1 = 0
   40 K3 = NPRT - L1
      IF(K3-1) 360,50,50
   50 DO 70 K=1,K3
      DO 70 J=1,NVAR
      SUMP = 0.
      DO 60 I=1,NROWS
      P = VALT(I,K) * C(I,J)
      SUMP = SUMP + P
   60 CONTINUE
      IF(DABS(SUMP) .LT. TOLR) SUMP = 0.0
      PVLI(K,J) = SUMP - VALI(K,J)
      IF(DABS(PVLI(K,J)) .LT. TOLR) PVLI(K,J) = 0.0
   70 CONTINUE
C
C     BRING INTO THE BASIS A VARIABLE FROM COLUMN (K2)
C
      ZMAX = 0.
      DO 120 J=1,NVAR
      IF(K3-NPRT) 80,100,100
   80 K4 = K3 + 1
      DO 90 K=K4,NPRT
      IF(PVLI(K,J)) 120,90,90
   90 CONTINUE
  100 IF(PVLI(K3,J)-ZMAX) 120,120,110
  110 ZMAX = PVLI(K3,J)
      K2 = J
  120 CONTINUE
      IF(ZMAX) 350,350,130
C
C     TO CALCULATE WHICH VARIABLE IS TO BE REMOVED FROM THE BASIS
C     FIRST CALCULATE THE LIMITING AMOUNT FOR EACH BASIS VARIABLE
C     BY DIVIDING THE RHS CONSTANTS BY THE COEFFICIENTS OF COLUMN (K2)
C
  130 DO 180 I=1,NROWS
      IF(RHS(I)) 903,150,150
  150 IF(C(I,K2)) 160,160,170
  160 AMT(I) = -1.
      GO TO 180
  170 AMT(I) = RHS(I) / C(I,K2)
  180 CONTINUE
C
C     SELECT SMALLEST POSITIVE LIMITING AMT (INCLUDING ZERO)
C
  190 K1 = 0
      DO 250 I=1,NROWS
      IF (AMT(I)) 250,220,220
  220 IF (K1 .EQ. 0) GO TO 240
      IF (ZMIN-AMT(I)) 250,250,240
  240 ZMIN = AMT(I)
      K1 = I
  250 CONTINUE
      IF (K1 .EQ. 0) GO TO 901
C
C     REMOVE Y(K1)
C
  260 Y(K1) = X(K2)
      DO 270 K=1,NPRT
      VALT(K1,K) = VALI(K,K2)
  270 CONTINUE
C     CALCULATE NEW RIGHT-HAND SIDE VALUES
C
      DO 280 I=1,NROWS
      RHS(I) = RHS(I) - ZMIN * C(I,K2)
  280 CONTINUE
      RHS(K1) = ZMIN
C
C     CALCULATE NEW SUBSTITUTION RATES
C
```

```
      DO 290 J=1,NVAR
      DO 290 I=1,NROWS
      IF(I .EQ. K1) GO TO 290
      D(I,J) = C(I,J) - C(K1,J) / C(K1,K2) * C(I,K2)
  290 CONTINUE
      DO 300 J=1,NVAR
      D(K1,J) = C(K1,J) / C(K1,K2)
  300 CONTINUE
      DO 305 I=1,NROWS
  305 D(I,K2) = 0.0
      D(K1,K2) = 1.0
      DO 310 J=1,NVAR
      DO 310 I=1,NROWS
      C(I,J) = D(I,J)
      IF(DABS(C(I,J)) .LT. TOLR) C(I,J) = 0.0
  310 CONTINUE
      ITER = ITER + 1
C
C     WRITE ALL SUBSTITUTION TABLES IF ITAB IS POSITIVE
C
      IF(ITAB) 50,50,320
  320 WRITE (6,5000)
 5000 FORMAT (1H1)
      WRITE (6,5001)
 5001 FORMAT (15X,'THE RIGHT HAND SIDE AND SUBSTITUTION RATES INTERIM'
     1' TABLE 01',//)
      DO 330 I=1,NROWS
      WRITE (6,5002) Y(I),RHS(I)
 5002 FORMAT(1H0,15X,'ROW',F6.0,F17.6)
  330 CONTINUE
      DO 340 I=1,NROWS
      WRITE (6,5003) I
 5003 FORMAT(1H0,15X,'ROW',I3)
      WRITE(6,5004) (C(I,J),J=1,NVAR)
 5004 FORMAT(15X,5F12.6)
  340 CONTINUE
      GO TO 50
C
C     MOVE TO NEXT LOWER PRIORITY LEVEL
C
  350 L1 = L1 + 1
      GO TO 40
C
C     WRITE FINAL RESULTS
C
  360 WRITE(6,5005) ITER
 5005 FORMAT(1H0,14X,'ITERATIONS....',I8)
      WRITE(6,5000)
      WRITE(6,5006)
 5006 FORMAT(15X,'THE RIGHT HAND SIDE',26X,'OUTPUT TABLE 01',//)
      DO 370 I=1,NROWS
      WRITE(6,5002) Y(I), RHS(I)
  370 CONTINUE
      WRITE(6,5000)
      WRITE(6,5007)
 5007 FORMAT (15X,'THE SUBSTITUTION RATES',23X,'OUTPUT TABLE 02',//)
      DO 380 I=1,NROWS
      WRITE(6,5003) I
      WRITE(6,5004) (C(I,J),J=1,NVAR)
  380 CONTINUE
      WRITE(6,5000)
      WRITE(6,5008)
 5008 FORMAT(15X,'THE ZJ-CJ MATRIX',29X,'OUTPUT TABLE 03',//)
      DO 390 K=1,NPRT
      I = LISP - K
      WRITE(6,5009) I
 5009 FORMAT(1H0,15X,'PRIORITY',I3)
      WRITE(6,5004) (DVLI(K,J),J=1,NVAR)
  390 CONTINUE
C
C     EVALUATE OBJECTIVE FUNCTION
C
      DO 400 K=1,NPRT
      ZVAL(K) = 0
      DO 400 I=1,NROWS
      ZVAL(K) = ZVAL(K) + RHS(I) * VALT(I,K)
  400 CONTINUE
      WRITE(6,5000)
      WRITE(6,5010)
 5010 FORMAT(15X,'AN EVALUATION OF THE OBJECTIVE FUNCTION',36X,
     1'OUTPUT TABLE 04',//)
      DO 420 K=1,NPRT
      KK = NPRT - K
      IF(TEST .EQ. 1.0) GO TO 410
      KK = KK + 1
  410 WRITE(6,5011) KK,ZVAL(K)
 5011 FORMAT (1H0,15X,'PRIORITY',I3,F20.6)
  420 CONTINUE
C
C     CALL FINISH TO TERMINATE PROGRAM
C
      CALL FINISH
      GO TO 999
C
C     OUTPUT APPROPRIATE ERROR MESSAGE AND ABORT THE RUN
C
  900 WRITE(6,9000) I,RHS(I)
 9000 FORMAT(' THE RIGHT HAND SIDE VALUE FOR ROW',I3,'HAS GONE',
     1' NEGATIVE AND EQUALS',F15.3)
      GO TO 999
  901 WRITE(6,9001)
 9001 FORMAT(' THERE WAS NO VARIABLE ELIGIBLE TO BE REMOVED FROM',
     1' THE BASIS')
  999 STOP
      END

      SUBROUTINE START
C
C     THE START SUBROUTINE IS DESIGNED TO TAKE INFORMATION IN A SPEC-
C     IFIED FORMAT AND TRANSFORM IT INTO A SERIES OF USABLE MATRICES.
C
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER*1 B,G,E,L, SIGN
      CHARACTER*4 POS, NEG, ANAME, OBJ, DATA, RGHT, PROB
      COMMON/BLOK1/ KEPT(60), RHS(60), ARHS(60), Y(60)
      COMMON/BLOK2/ VALT(60,20), ZVAL(20), ZNAME(10)
      COMMON/BLOK3/ C(60,150), DVLI(20,150), VALI(20,150)
      COMMON/BLOK4/ NROWS, NVAR, NPRT, KPCK, TEST, ITAB
      COMMON/BLOK5/ ANT(60), D(60,150), SIGN(80), X(150)
      DATA PROB,OBJ,DATA,RGHT/'PROB','OBJ ','DATA','RGHT'/
```

```
      DATA B,E,G,L/'B','E','G','L'/
      DATA POS,NEG/'POS ','NEG '/
C
C     INITIALIZE CONSTANTS
C
      NPCK = 0
      NART = 0
      NFLDS = 0
      NP = 20
      NR = 60
      NV = 150
      TEST = 0.0
C
C     CLEAN ALL MATRICES
C
   10 DO 20 I=1,NR
      ANT(I) = 0.0
      REPT(I) = 0
      RHS(I) = 0.0
      RHS1(I) = 0.0
      Y(I) = 0.0
      DO 20 J=1,NV
      C(I,J) = 0.0
      D(I,J) = 0.0
   20 CONTINUE
      DO 30 I=1,NP
      ZVAL(I) = 0.0
      DO 30 J=1,NV
      NVLX(I,J) = 0.0
      VALX(I,J) = 0.0
      X(J) = 0.0
   30 CONTINUE
      DO 40 I=1,NR
      DO 40 J=1,NP
      VALY(I,J) = 0.0
   40 CONTINUE
C
C     READ THE PROBLEM CARD FOR THE NUMBER OF ROWS, VARIABLES, AND
C     PRIORITIES FOR THIS CASE
C
   50 READ(5,5001) ANAME,NROWS,NVAR,NPRT,ITAB,(ZNAME(I),I=1,10)
 5001 FORMAT(A4,4I3,3X,10A6)
      IF(ANAME .NE. PROB) GO TO 901
      IF(NROWS .LE. 0) GO TO 903
      IF(NVAR .LE. 0) GO TO 900
      IF(NPRT .LE.0) GO TO 900
C
C     INITIALIZE THE C(I,J) MATRIX DIAGONAL TO ONES
C
      DO 70 I=1,NROWS
      J = I
      C(I,J) = 1.0
   70 CONTINUE
      LISP = NPRT + 1
C     READ THE SIGN CARD
C     IT WILL CONTAIN ONE OF THE FOLLOWING LETTERS FOR EACH ROW
C     FOR BOTH DEVIATIONS          B
C     FOR EQUALS                   E
C     FOR GREATER THAN OR EQUAL TO  G
C     FOR LESS THAN OR EQUAL TO     L
```

```
C
   80 READ(5,5002) (SIGN(I),I=1,NROWS)
 5002 FORMAT(80A1)
C
C     COUNT THE NUMBER OF POSITIVE SLACK VARIABLES
C
   90 DO 100 I=1,NROWS
      IF(SIGN(I) .EQ. B)  NFLDS = NFLDS + 1
      IF(SIGN(I) .EQ. G)   NFLDS = NFLDS + 1
  100 CONTINUE
C
C     TEST FOR SIZE LIMITATIONS
C
  110 NSIZE = NFLDS + NROWS + NVAR
      IF(NROWS .GT. NR) GO TO 902
      IF(NSIZE .GT. NV) GO TO 902
C
C     ADJUST THE SLACK VARIABLES AND OBJECTIVE FUNCTION TO MEET THE
C     REQUIREMENTS OF THE SIGN.
C
      K = LISP
      DO 180 I=1,NROWS
      IF(SIGN(I) .EQ. B) GO TO 150
      IF(SIGN(I) .EQ. E) GO TO 160
      IF(SIGN(I) .EQ. G) GO TO 170
      IF(SIGN(I) .EQ. L) GO TO 160
      GO TO 903
  150 NPCK = NPCK + 1
      J = NPCK + NROWS
      C(I,J) = -1.0
      REPT(I) = J
      GO TO 180
  160 J = I
      VALX(K,J) = 1.0
      NART = NART + 1
      TEST = 1.0
      GO TO 180
  170 NPCK = NPCK + 1
      J = NROWS + NPCK
      C(I,J) = -1.0
      REPT(I) = J
      J = I
      VALX(K,J) = 1.
      NART = NART + 1
      TEST = 1.0
  180 CONTINUE
C
C     READ THE OBJECTIVE FUNCTION
C
      READ(5,5004) ANAME
  190 N = 0
      IF(ANAME .NE. OBJ) GO TO 904
  200 READ(5,5004) ANAME,N,M,TEMP
 5004 FORMAT(A4,2I5,F16.8)
      IF(ANAME .EQ. DATA) GO TO 240
      IF(M .LE. 0) GO TO 905
      K = LISP - N
      IF(N .LE. 0) GO TO 905
      IF(K .GT. NPRT) GO TO 908
      IF(ANAME .EQ. POS) GO TO 210
```

```
      IF(ANAME .EQ. NEG) GO TO 220
      GO TO 230
  210 J = NEPT(N)
      IF(NEPT(N) .EQ. 0) GO TO 907
      VALE(K,J) = TEMP
      GO TO 200
  220 J = N
      IF(SIGN(N) .EQ. G) GO TO 907
      IF(SIGN(N) .EQ. E) GO TO 907
      VALE(K,J) = TEMP
      GO TO 200
  230 IF(TEMP) 908,200,908
C
C     READ THE DATA MATRIX IN
C
  240 READ(5,5004) ANAME,I,J,TEMP
      IF(ANAME .EQ. RGHT) GO TO 250
      IF(I .LE. 0) GO TO 909
      IF(J .LE. 0) GO TO 909
      J = NPCK + NROWS + J
      C(I,J) = TEMP
      GO TO 240
C
C     READ THE RIGHT HAND SIDE
C
  250 READ(5,5005) (RHS(N),N=1,NROWS)
 5005 FORMAT(7F10.5)
C
C     WRITE THE ABOVE INPUT PARAMETERS
C
      WRITE(6,5016) (ZNAME(I),I=1,10)
 5016 FORMAT(15X,10A6,//)
      WRITE(6,5006)
 5006 FORMAT(1H1)
      WRITE(6,5007)
 5007 FORMAT(15X,'THE RIGHT HAND SIDE',27X,'INPUT TABLE 01',//)
      DO 280 I=1,NROWS
      IF(RHS(I)) 910,260,270
  260 RHS(I) = .00001
  270 RHS1(I) = RHS(I)
      WRITE(6,5008) I,RHS(I)
 5008 FORMAT(1H0,'ROW',I3,2X,F15.6)
  280 CONTINUE
      WRITE(6,5006)
      WRITE(6,5009)
 5009 FORMAT(15X,'THE SUBSTITUTION RATES',28X,'INPUT TABLE 02',//)
      DO 290 I=1,NROWS
      WRITE(6,5010) I
 5010 FORMAT(1H0,15X,'ROW',I3)
      WRITE(6,5011) (C(I,J),J=1,NSIZE)
 5011 FORMAT(15X,5F12.6)
  290 CONTINUE
      WRITE(6,5006)
      WRITE(6,5012)
 5012 FORMAT(15X,'THE OBJECTIVE FUNCTION',28X,'INPUT TABLE 03',//)
      DO 300 N=1,NPRT
      K=LISP - N
      WRITE(6,5013) K
 5013 FORMAT(1H0,15X,'PRIORITY',I3)
      WRITE(6,5011) (VALE(K,J),J=1,NSIZE)
  300 CONTINUE
      WRITE(6,5006)
      WRITE(6,5014)
 5014 FORMAT(15X,'SUMMARY OF INPUT INFORMATION',10X,'INPUT TABLE 04',/
      NVAR = NSIZE
      WRITE(6,5015) NROWS,NVAR,NORT,NART
 5015 FORMAT(1H0,14X,'NUMBER OF ROWS..........',I4,//
     1            ,15X,'NUMBERS OF VARIABLES...',I4,//
     2            ,15X,'NUMBER OF PRIORITIES...',I4,//
     3            ,15X,'ADDED PRIORITIES.......',I4)
      IF(NART .GT.0) NPRT=NPRT+1
      RETURN
C
C     OUTPUT APPROPIATE ERROR MESSAGE AND ABORT THE RUN
C
  900 WRITE(6,9000)
 9000 FORMAT(' THE NUMBER OF ROWS, VARIABLES, OR PRIORITIES CANNOT BE'
     1' EQUAL TO ZERO',/,'       UNDER ANY CIRCUMSTANCES.')
      GO TO 999
  901 WRITE(6,9001)
 9001 FORMAT(' THE PROBLEM CARD IS MISSING OR IT IS MISPUNCHED.')
      GO TO 999
  902 WRITE(6,9002)
 9002 FORMAT('THE NUMBER OF VARIABLES NEEDED TO COMPLETE THIS PROBLEM'
     1',IS TOO GREAT',/,'    UNDER PRESENT DIMENSIONS. SEE YOUR PROG',
     2'RAMMER FOR ALTERING THIS',/,'       RESTRICTION TO MEET YOUR',
     3' NEEDS.')
      GO TO 999
  903 WRITE(6,9003)
 9003 FORMAT('THE PROBLEM CONTAINS AN ERROR IN EITHER THE NUMBER OF',
     1' ROWS PUNCHED OR',/,'       IN THE SIGN CARD. THE VALUE IS SOME'
     2'THING OTHER THAN E, G, OR L.')
      GO TO 999
  904 WRITE(6,9004) TEMP
 9004 FORMAT(' AN OBJECTIVE CARD WITH THE VALUE',F16.3,' HAS BEEN',
     1' FOUND, BUT',/,'       INSTRUCTIONS AS TO WHICH DEVIATION TO',
     2' MINIMIZE HAVE BEEN NEGLECTD.')
      GO TO 999
  905 WRITE(6,9005)
 9005 FORMAT(' THE COLUMN VALUE OR THE PRIORITY VALUE IS EQUAL TO OR',
     1' LESS THAN ZERO.')
      GO TO 999
  906 WRITE(6,9006)
 9006 FORMAT(' THE OBJECTIVE FUNCTION PRIORITY EXCEEDS STATED NUMBER',
     1' OF PRIORITIES.')
      GO TO 999
  907 WRITE(6,9007)
 9007 FORMAT(' AN ATTEMPT IS MADE TO MINIMIZE A NON-EXISTANT POSITIVE'
     1' DEVIATIONAL',/,'       VARIABLE.   CHECK YOUR SIGN CARD AGAIN.'
      GO TO 999
  908 WRITE(6,9008)
 9008 FORMAT(' A CARD IN THE OBJECTIVE SECTION DEFINED SOME VALUE FOR'
     1' THE OBJECTIVE',/,'     FUNCTION, BUT FAILED TO DEFINE WHETHER'
     2' THIS HAS TO APPLY TO THE',/,'      POSITIVE OR NEGATIVE',
     3' DEVIATION.')
      GO TO 999
  909 WRITE(6,9009)
 9009 FORMAT(' IMPROPER DATA COLUMN OR ROW DEFINITION')
      GO TO 999
  910 WRITE(6,9010)
```

```
 9010 FORMAT(' NEGATIVE VALUES ARE NOT ALLOWED ON THE RIGHTHAND SIDE.
     1'   CORRECT THE',/,'      PROBLEM BY MULTIPLYING THE ENTIRE',
     3' CONSTRAINT BY MINUS ONE.')
  999 STOP
      END

      SUBROUTINE FINISH
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/BLOK1/ KEPT(60), RHS(60), RHS1(60), Y(60)
      COMMON/BLOK2/ VALY(60,20), ZVAL(20), ZNAME(10)
      COMMON/BLOK4/ NROWS, NVAR, NPRT, KPCK, TEST, ITAB
C
C      RHS1 IS THE RESERVED VECTOR OF RHS VALUES FROM THE BEGINNING.
C     THE ENDING RHS VALUES ARE SUBTRACTED FROM THE BEGINNING ONES
C     AND THE RESULT IS PLACED INTO THE APPROPIATE SLACK COLUMN.
C     THE REMAINDER OF THE VALUES ARE PRINTED ON PAGE TWO OF THE RE-
C    SULTS.
C
C     SLACK ANALYSIS
C
      WRITE(6,5001)
 5001 FORMAT(1H1)
      WRITE(6,5002)
 5002 FORMAT(15X,'SLACK ANALYSIS',31X,'OUTPUT TABLE 05',//)
      WRITE(6,5003)
 5003 FORMAT(1H0,15X,'ROW',10X,'AVAILABLE',11X,'POS-SLK',12X,'NEG-SLK
      DO 60 I=1,NROWS
      CEGSLK = 0.0
      POSSLK = 0.0
      DO 20 J=1,NROWS
      M = Y(J)
      IF(I-M) 10,30,10
   10 IF(J-KEPT(I)) 20,40,20
   20 CONTINUE
      GO TO 50
   30 CEGSLK = RHS(J)
      GO TO 50
   40 POSSLK = RHS(J)
   50 WRITE(6,5004) I,RHS1(I),POSSLK,CEGSLK
 5004 FORMAT(1H0,15X,I3,3F19.6)
   60 CONTINUE
C     VARIABLE ANALYSIS
C
      DO 80 I=1,NROWS
      NCHCK = Y(I) - KPCK - NROWS
      IF(NCHCK) 80,80,70
   70 WRITE(6,5007) NCHCK,RHS(I)
 5007 FORMAT(1H0,18X,I3,F18.6)
   80 CONTINUE
C
C     OBJECTIVE ANALYSIS
C
      WRITE(6,5009)
 5009 FORMAT (1H0,19X,'999',14X,'0')
      DO 110 K=1,NPRT
      ZVAL(K) = 0.0
      DO 90 I=1,NROWS
      ZVAL(K) = ZVAL(K) + VALY(I,K) * RHS(I)
   90 CONTINUE
      LISP = NPRT + 1
```