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Prediction of Steamflood Performance in Heavy Oil Reservoirs Using Correlations Developed by Factorial Design Method

C. Chu, Texaco Inc.

SPE Member

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ABSTRACT

By using the factorial design method, statistically significant correlations have been developed which enable one to predict steamflood performance in terms of project life, oil recovery and cumulative steam-oil ratio. The effects of various reservoir rock and fluid properties and steamflood design and operating variables on steamflood performance were discusssed.

INTRODUCTION

The ideal way of predicting reservoir performance under steamflood is through numerical simulation. However, this approach may not be always feasible due to either the lack of a reliable thermal simulator or the lack of qualified personnel to run the simulator. In some instances, such as estimation of oil reserves, screening thermal prospects or making preliminary engineering design, detailed simulation may not be warranted. Besides, early in the development of a detailed simulation, a simple method of predicting reservoir performance will provide a means of comparison. Under all these circumstances, some correlations which allow the prediction of steamflood performance without resorting to numerical simulation will be useful. The purpose of this work is to develop such correlations. The end result of this study is a simple computer program, written in BASIC, which can be used to predict steamflood performance in heavy oil reservoirs (Appendix A).

A large amount of simulation by use of a three-dimensional numerical model has been made in this work so that the users of the correlations can predict steamflood performance without the expense of doing simulation. The independent variables used in the correlations include reservoir rock and fluid properties such as reservoir thickness, porosity, permeability, initial oil saturation, and oil viscosity, along with steamflood design and operating variables such as pattern size, steam injection rate, and steam quality. With these quantities known, one can use the correlations hereby developed to predict steamflood performance in regard to project life, oil recovery and cumulative steam-oil ratio (SOR).

In 1980 Gomaa[1] developed a set of correlation charts for predicting oil recovery and cumulative oil-steam ratio, emphasizing the effects of steam quality, mobile oil saturation, reservoir thickness and net-gross ratio. One conspicuous absence in the independent variables included in his work is the oil viscosity which could greatly affect the steamflood performance. Gomaa's method uses graphical solutions which usually lack precision because the reading of values from a chart is subject to the user's judgment. The errors will be compounded if several charts needed to be read to obtain the answer. In his method, finding the oil recovery requires the use of no less than four charts.

BASIC ASSUMPTIONS

1. The reservoir is horizontal, with no dipping.
2. The reservoir is homogeneous throughout the entire thickness, with no intervening shale breaks.
3. There is neither gas cap at the top nor free gas inside the oil sand.
4. There is no water sand underneath the oil sand.
5. The oil is sufficiently heavy to be adequately represented by a single hydrocarbon component which is non-volatile.

6. Single sand operation is assumed, with no intervention from sands above or below.

7. Repeated 5-spot patterns are assumed.

8. Constant steam injection rate and constant steam quality are assumed throughout the project, with no tapering in either injection rate or steam quality.

9. Two or more steam stimulation cycles are assumed in the initial part of the steamflood. The slug size is 10,000 bbls [1589.9m^3] of steam for each cycle. The cycle length is 182.5 days. The number of cycles needed is determined by the movement of the heat front, whether or not heat bridge-over is forthcoming in the following half-year period.

10. The steamflood is terminated when the instantaneous ratio between heat injection and oil production is equivalent to an SOR of 10 B/B, [M^3/M^3] the steam being 60 % quality at a saturation temperature of 366°F [185.B°C].

11. The steamflood performance is measured at that cutoff point. Any additional recovery by using hot waterflood, infill drilling, etc., is not considered.

Whereas the data are obtained from Kern River Field, California, the results should apply to other horizontal homogeneous heavy oil reservoirs with properties not too far outside the ranges covered by this work.

FACTORIAL DESIGN METHOD

The factorial design method chooses the values of independent variables in a pre-determined fashion. In the terminology of the factorial design, the independent variables, normally after some transformation, are called factors. Two or more levels of each factor are chosen and the combinations of the levels are used for experimentation. A factorial design refers to a particular combination of factor levels (Davies[2]). The advantage of using the factorial design method is that the number of experiments (or simulation runs) can be minimized by using a systematic choice of variable combinations. While this method has been applied mainly to experiments in biological, agricultural, medical and chemical research, it did find application in the study of firefloods (Sawyer et al.[3]).

The use of factorial design methods for development of steamflood design correlations involves the following steps:

1. Choose primary variables that have influence on steamflood performance
2. Transform the variables
3. Choose the factorial design
4. Make simulation runs and obtain the steamflood performance variables for each run.
5. Analyze the results

Choice of Independent Variables

The following are used as independent variables for the correlation:

Reservoir rock and fluid properties

Thickness, h, ft - gross thickness is used
Porosity, ϕ, % bulk volume - measured based on gross thickness Permeability, k, md
Oil viscosity, μ, cp - oil viscosity at 90°F {3.2.2°C}is used
Oil saturation, S_o, % PV - initial oil saturation at the start of the steamflood

Steamflood design and operating variables

Pattern size, A, acre - This refers to 5-spot patterns
Steam injection rate, i_s, B/D - steam at 366° F [185.6°C] is used Steam quality, f_g, %

Transformation of Variables

Since there are 8 factors, a total of $2^8 = 256$ runs will be needed for a complete two-level factorial design. To minimize the number of runs without sacrifice of information obtainable from the design, a 1/4 replicate was used which calls for $2^6 = 64$ runs. According to Box and Hunter[4], a specific design will be needed to assure that all the main effects and two-factor interactions will be clear of one another. That particular design calls for equating x_7 with the product $x_1 x_2 x_3 x_4$ and equating x_8 with the product $x_1 x_2 x_5 x_6$. To assure that these four-factor interactions will be negligible, the variables were reordered before being subject to transformation.

The following equations define the transformed variables such as x_1, x_2, etc., used for the factorial design in terms of the original independent variables such as S_o, μ, etc., and vice versa:

$$x_1 = \frac{S_o - 50}{5} \qquad S_o = 50 + 5x_1$$

$$x_2 = \frac{\mu - 7000}{2500} \qquad \mu = 7000 + 2500x_2$$

$$x_3 = \frac{h - 80}{20} \qquad h = 80 + 20x_3$$

$$x_4 = \frac{i_s - 300}{50} \qquad i_s = 300 + 50x_4$$

$$x_5 = \frac{A - 2.6}{0.3} \qquad A = 2.6 + 0.3x_5$$

$$x_6 = \frac{f_g - 55}{15} \qquad f_g = 55 + 15\, x_6$$

$$x_7 = \frac{\o - 31}{2.5} \qquad \o = 31 + 2.5\, x_7$$

$$x_8 = \frac{k - 3500}{750} \qquad k = 3500 + 750\, x_8$$

It is obvious that the above equations are in the following form:

$$x = \frac{V - a_0}{a_1} \qquad V = a_0 + a_1\, x$$

The value of a_0 represents the average value of V. The value of a_1 is meant to represent 1/4 of the range of V so that the value of V will vary throughout the normally expected range when x changes from -2 to +2.

The values of a_0 and a_1 for S_o, μ, h, i_s, A, and ø were estimated from data on 60 steamflood projects in Kern River Field, California compiled by Restine[5]. Those for k and f_g were based on data from the history match paper by Johnson, et al[6].

There was only one exception, namely, the a_1 value for f_g, which was purposely increased so as to obtain a fair indication of the effect of steam quality on steamflood performance. Gomaa[1] indicated that the heat utilization factor increases with steam quality, reaches a maximum at approximately 40% quality, and decreases when steam quality increases further.

Based on the above equations, the factor levels are given in Table 1.

Composite Factorial Design

The fractional factorial design in terms of the *transformed* variables, x_1, x_2, etc., is shown in the upper part of Table 2, namely, Runs 1-64. Some reflection will show that the following substitutions, called for by Box and Hunter[4], have indeed been made:

$$x_7 = x_1\, x_2\, x_3\, x_4 \qquad x_8 = x_1\, x_2\, x_5\, x_6$$

To obtain quadratic (second-order) effects of the variables, 17 more runs were added. Whereas each variable in Runs 1-64 assumes either -1 (the low level) or +1 (the high level), all the variables assume the 0 level, at the center of all the variations, in Run 65. In Runs 66-81, each variable in turn steps out along the coordinate axes to -2 and +2, with all other variables remaining at the 0 level. These runs combined with the first 64 runs form a non-orthogonal composite factorial design as shown in Table 2.

Simulation

A three-dimensional numerical model was used for simulation. The input data for the primary variable corresponding to the composite factorial design in Table 2 are obtained from Table 1. The rest of the input data are given in Appendix B.

Each run was terminated at the time when the instantaneous steam/oil ratio is 10.0 B/B [M3 f/M3] for a 60% quality steam. Since steam quality varies with the runs, the cutoff point is determined by the following equation:

$$\text{Oil production rate} = \frac{i_s\,(h_f + h_{fg}\, f_g)}{10.0\,(h_f + h_{fg} \times 0.60)}$$

where h_f and h_{fg} are enthalpy of saturated liquid water and latent heat of vaporization at 366.0°F [185.6°C], respectively.

This determines the project life, the oil recovery and the cumulative SORt the cutoff point.

Analysis of Results

The entire set of 81 runs is used to obtain the main effect, b_o, the linear effects, $b_1, \ldots b_8$, the second-order interactions, $b_{12}, \ldots b_{78}$, and the quadratic effects, $b_11, \ldots b_88$ in the following equation:

$$y = b_0 + b_1\, x_1 + \ldots\ldots + b_8\, x_8 + b_{12}\, x_1\, x_2 + \ldots + b_{78}\, x_7\, x_8 + b_{11}\, x_1^2 + \ldots + b_{88} x_8^2$$

The response variable y may refer to project life, oil recovery or cumulative SOR, as the case may be. The coeffinents b_0, b_1, etc., are obtained by the method given in Davies[2], and are given in Table 3.

Analysis of variance was applied to the above equation. The results are summarized in Table 4. This table includes F values, tail area, % variation explained by the model, and the residual standard deviation expressed as a percentage of the response mean. The tail area denotes the probability that there is no correlation between the independent and dependent variables. The term called % variation explained by the model is also known as r^2, or r-square. This is often considered as the most meaningful statistic since it gives us a measure of the usefulness of the prediction (Dowdy and Wearden[7]). All four quantities listed in Table 4 show that the equation is statistically significant.

DISCUSSION OF RESULTS

The correlations developed here enable us to predict the effects of various rock and fluid properties and steamflood design and operating variables on steamflood performance. In the following discussions, the variables are varied, either one at a time or two at a time, while all the other variables are held constant at the 0 factor levels. For example, if the initial oil saturation is to be varied, the viscosity is held at 7,000 cp [7.0 Pa.s] and thickness is held at 80 ft [24.4m], etc.

Effects of Single Variables

Figures 1-3 show the effects of the 8 independent variables on project life, oil recovery and cumulative SOR, respectively. Each figure consists of 8 subfigures. The first 5 subfigures refer to reservoir rock and fluid properties, namely, thickness, porosity, permeability, oil viscosity and initial oil saturation. The remaining 3 subfigures refer to steamflood design and operating variables, namely, pattern size, steam rate and steam quality.

1. Project Life (Figure 1)

The most influential variable among the various reservoir properties is reservoir thickness. Project life almost triples as thickness changes from 40 ft [12.2M] to 120 ft [36.6M]. The next influential is oil saturation, which is followed by porosity. Increases in oil saturation or porosity will lengthen the project life nearly proportionately.

Permeability and oil viscosity have only minor influence on project life. It should be noted that, since this work is based on statistical treatment, each curve carries with it a band of uncertainty. Because of this, the shallow maximum in the effect of permeability and the shallow minimum in the effect of oil viscosity, as seen in this figure, may not be entirely significant. No belabouring was, therefore, made on the shapes of these curves and other curves in the following figures wherever the responses appear to be rather minor.

All the three steamflood design and operating variables have profound influences on project life. Project life is nearly proportional to pattern size and almost inversely proportional to steam rate. Besides, project life is also shortened to some extent with higher steam quality.

2. Oil Recovery (Figure 2)

The most influential variable is the initial oil saturation. It should be noted that, whereas the oil recovery increases almost proportionately with the initial oil saturation, the remaining oil saturation after steamflood is almost unchanged. For example, with $S_o = 40\%$, the predicted oil recovery is 44.2% of the OIP. The remaining oil saturation is, then, 40 x (1-0.442) = 22.3%. If $S_o = 60\%$, the predicted oil recovery is 60.4%. The remaining oil saturation is 60 x (1-0.604) = 23.7%. The increase in the remaining oil saturation is a measly 23.7 - 22.3 = 1.4% PV when the initial oil saturation is increased by 60 - 40 = 20% PV.

Other influential variables include porosity and oil viscosity. Oil recovery increases with an increase in porosity or a decrease in oil viscosity. The effect of reservoir thickness on oil recovery is minimal within the range of variation investigated, and when all the other variables are kept at the 0 factor level, e.g. steam quality = 55%, etc.

Although the steamflood design and operating variables have profound influences on project life, their influences on oil recovery are rather insignificant, in the ranges used in this work and when one variable is taken at one time with all the other variables kept at their respective 0 factor levels. This points out the unfortunate fact that oil recovery is governed mainly by how much oil there is in the reservoir and how mobile the oil is. Judicious choice of pattern size, steam rate and steam quality will help to enhance the oil recovery but to a much less extent than is hoped to be.

3. Cumulative SOR (Figure 3)

The most influential variable is again the initial oil saturation. With the same amount of steam, more oil will be produced with a higher initial oil saturation, thus lowering the cumulative SOR.

The cumulative SOR is also greatly influenced by reservoir thickness and oil viscosity. As mentioned previously, the effect of thickness on oil recovery is minimal. However, to obtain the same level of oil recovery, it is necessary to use more steam in a thinner reservoir so as to compensate for the greater heat loss to the overburden and underburden. Cumulative SOR increases with oil viscosity because more heat is needed to improve the oil mobility needed for production.

The fact that the cumulative SOR decreases with an increase in steam quality prompts us to see if the heat input per unit volume of oil produced remains the same with a change in steam quality. This was found to be true especially when the steam quality is 55% or above, even though the cumulative SOR changes to a great extent as the steam quality varies.

Effects of Combinations of Variables

With 8 independent variables, there will be 8 x 7 = 56 combinations if two variables are varied at a time. It will serve no purpose if the effects of all the combinations of the variables on steamflood performance are included in this work. Rather, only two combinations have been selected to be discussed, namely, the porosity-oil saturation pair and the thickness-steam quality pair. The results are shown in Figure 4.

1. The porosity-oil saturation pair (Figure 4-A)

This pair exemplifies the results of most of the pairs where the effects of the individual variables are essentially additive and, therefore, show no surprises. With increases in both porosity and oil saturation, the project life is lengthened, oil recovery is enhanced and cumulative SOR is reduced, to a much greater extent than if the increase is in porosity alone or oil saturation alone.

2. The thickness-steam quality pair (Figure 4-B)

This is a much more interesting combination since the interaction between the two variables plays a great role in the predicted steamflood performance. When the thickness is 40 ft [12.2m], the project life stays about the same when the steam quality increases from 25 [36.6M]to 85%. The situation is completely different when the thickness is 120 ft, where the project life is doubled with the same increase in steam quality.

As to the oil recovery, it increases with increasing thickness when steam quality = 25% and decreases with increasing thickness when steam quality = 85%. This contrasts with the previous finding that the effect of thickness on oil recovery is minimal when steam quality = 55%. Because of the strong interaction between thickness and steam quality, higher steam quality (85%) is favored when the thickness is low (40 ft). The opposite is true for a thick reservoir (120 ft), favoring a lower steam quality (25%). Apparently, the sweep efficiency becomes intolerably low due to steam override if high quality steam is used in a thick reservoir.

Additional Remarks

It is interesting to know that, of the 81 runs made in this work, the main values and standard deviations of the three response variables, shown in Table 5, appear to be reasonable based on more than a decade of steamflood experience in Kern River Field, California.

CONCLUSIONS

1. Statistically significant correlations have been developed which enable one to predict steamflood performance in terms of project life, oil recovery and cumulative steam-oil ratio (SOR). From these three basic performance variables, some other important variables can be derived which include cumulative oil production, cumulative steam injection, net oil recovery and remaining oil saturation after the steamflood.

2. The effects of various reservoir rock and fluid properties and steamflood design and operating variables on steamflood performance were found as follows when each variable was varied one at a time:

   a. Project life is influenced by a number of variables. It is lengthened with increases in pattern size, reservoir thickness, porosity and initial oil saturation, and decreases in steam injection rate, nearly proportionately with respect to all five variables. Project life is shortened with increase in steam quality.

   b. Initial oil saturation is the most significant factor influencing the oil recovery. Whereas oil recovery increases almost proportionately with initial oil saturation, the remaining oil saturation after steamflood is almost unchanged. Oil recovery increases with an increase in porosity or decrease in viscosity. The effect of reservoir thickness on oil recovery is, however, minimal within the range of variation investigated. With a given reservoir, changes in pattern size, steam rate or steam quality have only minor effects on oil recovery.

   c. Initial oil saturation is the most influential factor in determining the cumulative SOR, which is reduced with an increase in intial oil saturation. Increase in reservoir thickness or decrease in oil viscosity also decreases cumulative SOR. Although increase in steam quality will reduce cumulative SOR, the heat input per unit volume of oil produced remains nearly the same with a change in steam quality, especially when steam quality is 55% or above.

3. When two variables are varied at the same time, their effects are usually cumulations of the effects of the individual variables. In some cases, however, the interactions between the two variables play such an important role that unorthodox results are obtained. For the thickness-steam quality pair, it was found that high quality steam is favored for a thin reservoir whereas low quality steam is more desirable for a thck reservoir.

NOMENCLATURE

A = Patter size, acre
a_o = Intercept
a_1 = Slope
b_o = Main effect
b_i = Linear effect
b_{ii} = Quadratic effect
b_{ij} = Interaction
F = Variance ratio
f_g = Steam quality, %
h = Thickness, ft
h_f = Enthalpy of saturated liquid water, Btu/lb_m
h_{fg} = Latent heat of vaporization of water, Btu/lb_m
i_s = Steam injection rate, B/D
k = Permeability, md
k_{rgro} = Gas relative permeability at residual oil saturation, dimensionless
k_{rolw} = Oil relative permeability at interstitial water saturation, dimensionless
k_{rwro} = Water relative permeability at residual oil saturation, dimensionless
n_g = Exponent for gas relative permeability calculation, dimensionless
n_{og} = Exponent for oil relative permeability calculation in a gas/oil system, dimensionless
n_{ow} = Exponent for oil relative permeability calculation in a water/oil system, dimensionless
n_w = Exponent for water relative permeability calculation, dimensionless
r = Correlation coefficient
S_{gc} = Critical gas saturation, % PV
S_{gr} = Residual gas saturation, % PV
S_{iw} = Interstitial water saturation, % PV
S_o = Initial oil saturation, %
S_{org} = Residual oil to gas flood, % PV
S_{orw} = Residual oil to waterflood, % PV
S_{wir} = Irreducible water saturation, % PV
V = Untransformed Variable
x = Transformed variable
x_i = Transformed variable, factor
y = Response variable
μ = Oil viscosity, cp
ϕ = Porosity, %

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SI METRIC CONVERSION FACTOR

acre	X 4. 046 873	E + 04 = m^2
bbl	X 1.589 873	E - 01 = m^3
Btu	X 1.055 056	E + 00 = kJ
cp	X 1.0*	E - 03 = Pa·s
ft	X 3.048*	E - 01 = m
°F	(°F-32)/1.8	=°C
md	X 9.869 233	E - 04 = μm^2
psi	X 6.894 757	E + 00 = kPa
psi^{-1}	X 1.450 377	E - 01 = kPa^{-1}

*Conversion factor is exact.

APPENDIX A - PROGRAM STMCORR

```
1 REM   PROGRAM STMCORR
2 REM
3 REM THIS PROGRAM PREDICTS STEAMFLOOD PERFORMANCE IN HEAVY OIL RESERVOIRS
4 REM
5 REM INPUT DATA:  OIL SATURATION  OIL VISCOSITY  THICKNESS  STEAM RATE
6 REM          PATTERN SIZE   STEAM QUALITY  POROSITY   PERMEABILITY
7 REM
8 REM OUTPUT:    PROJECT LIFE   OIL RECOVERY   CUMULATIVE SOR
9 REM
10  DIM  X(8),B0(3),BI(3,8),BIJ(3,28),BII(3,8),Y(3)
20 FOR K=1 TO 3
30 READ B0(K)
40 NEXT K
50  DATA    7.0493,53.3135,  5.9626
60 FOR I=1 TO 8
70 FOR K=1 TO 3
80 READ BI(K,I)
90 NEXT K
100 NEXT I
110  DATA    0.7992,  4.0418,-0.4100,-0.0883,-2.0279,  0.1614
120  DATA     1.5014,-0.1504,-0.2561,-1.0781,-0.2637,  0.0944
130  DATA    0.8917,-0.0162,  0.0592,-0.8580,-0.7295,-0.6264
140  DATA    0.4869,  1.1999,-0.2075,-0.1786,-0.7576,-0.0878
150 FOR N=1 TO 28
160 FOR K=1 TO 3
170 READ BIJ(K,N)
180 NEXT K
190 NEXT N
200  DATA   0.0112,-0.0995,-0.0013,  0.3069,  0.5289,  0.0766
210  DATA  -0.1050,  0.0948,  0.0053,  0.0647,-0.1183,-0.0181
220  DATA   0.0300,  0.4267,  0.0997  ,0.0316,-0.0642,  0.0259
270  DATA   0.0194,  0.1648,  0.0256,  0.0009,-0.0036,  0.0053
280   DATA   -0.0222,-0.0833,-0.0191,-0.0687,-0.1508,-0.0062
290   DATA   -0.1528,-0.6052,-0.0703,-0.0544,-0.0698,-0.0147
300  DATA  -0.0397,-0.2620,-0.0050,-0.1016,  0.4758,  0.0513
310  DATA    0.1375,-0.0992,-0.0216,-0.3916,-1.8636,  0.0612
320  DATA    0.0575,-0.1527,  0.0100,-0.0309,-0.0856,  0.0459
330  DATA  -0.1994,-0.4233,-0.0184,  0.0797,-0.3720,-0.0038
340   DATA  -0.0962,-0.3573,-0.0100,-0.0278,-0.3645,-0.0009
350  DATA  -0.1725,-0.2014,-0.0559,  0.0372,  0.1364,-0.0128
360  DATA  -0.1387,-0.1889,-0.0313,  0.0138,  0.1133,  0.0350
370  DATA  -0.1109,-0.4839,-0.0459,  0.0269,  0.1395,  0.0184
380 FOR I=1 TO 8
390 FOR K=1 TO 3
400 READ BII(K,I)
410 NEXT K
420 NEXT I
430  DATA  -0.0754,-0.2484,  0.0177,  0.1671,  0.1878,  0.1239
440  DATA  -0.1942,-0.2022,  0.0014,  0.1721,  0.1741,-0.0761
450  DATA    0.0258,  0.2853,-0.0436,-0.0192,  0.3453,-0.0123
460   DATA  -0.0404,  0.1316,-0.0323,-0.2367,-0.4809,-0.1123
461 PRINT
462 PRINT "  IMPORTANT: TO END CALCULATION, ENTER 999 FOR OIL SATURATION."
463 PRINT
470 INPUT"Oil saturation, % =          ";SOIL
471 IF SOIL > 100 THEN GOTO 700
480 INPUT"Oil viscosity, cp =          ";VISC
490 INPUT"Sand thickness, ft =         ";THIK
500 INPUT"Steam injection rate, BPD = ";RATE
510 INPUT"Pattern size, acre =         ";AREA
520 INPUT"Steam quality, % =           ";QUAL
530 INPUT"Porosity, % =               ";PORO
540 INPUT"Permeability, MD =           ";PERM
541  X(1)=(SOIL-50!)/5!
542  X(2)=(VISC-7000!)/2500!
543  X(3)=(THIK-80!)/20!
544  X(4)=(RATE-300!)/50!
545  X(5)=(AREA-2.6)/.3
546  X(6)=(QUAL-55!)/15!
547  X(7)=(PORO-31!)/2.5
548  X(8)=(PERM-3500!)/750!
549 PRINT
550 FOR K=1 TO 3
560  Y(K)=B0(K)
570 FOR I=1 TO 8
580  Y(K)=Y(K)+BI(K,I)*X(I)+BII(K,I)*X(I)^2
590 NEXT I
591  N=0
600 FOR I=1 TO 7
610 FOR J=I+1 TO 8
620 N=N+1
630  Y(K)=Y(K)+BIJ(K,N)*X(I)*X(J)
640 NEXT J
650 NEXT I
651 NEXT K
652 IF (SOIL<40)   OR (SOIL>60)    THEN PRINT "Warning: SOIL out of range."
653 IF (VISC<2000) OR (VISC>12000) THEN PRINT "Warning: VISC out of range."
654 IF (THIK<40)   OR (THIK>100)   THEN PRINT "Warning: THIK out of range."
655 IF (RATE<200)  OR (RATE>400)   THEN PRINT "Warning: RATE out of range."
656 IF (AREA<2!)   OR (AREA>3.2)   THEN PRINT "Warning: AREA out of range."
657 IF (QUAL<25)   OR (QUAL>85)    THEN PRINT "Warning: QUAL out of range."
658 IF (PORO<26)   OR (PORO>36)    THEN PRINT "Warning: PORO out of range."
659 IF (PERM<2000) OR (PERM>5000)  THEN PRINT "Warning: PERM out of range."
660 PRINT
661 PRINT USING "         Project life, years =              ##.##"; Y(1)
670 PRINT USING "        Oil recovery, % OIP =               ##.##"; Y(2)
680 PRINT USING "           Cumulative steam/oil ratio, B/B =  ##.##"; Y(3)
690 GOTO 461
700 END
```

APPENDIX B
RESERVOIR ROCK AND FLUID PROPERTIES

This Appendix lists some selected input data which were used in addition to the 8 primary variables. As can be seen, some data vary with the primary variables under presumed relationships.

1. Grid used

7 x 4 x 5 parallel grid simulating 1/8 of a 5-spot pattern

2. Reservoir Description

Vertical permeability	0.9 x horizontal permeability
Rock heat capacity	35.0 Btu/cu ft-°F
Rock thermal conductivity	25.6 Btu/ft-day-°F
Overburden heat capacity	39.0 Btu/cu ft-°F
Overburden thermal conductivity	27.6 Btu/ft-day-°F
Rock compressibility	0.000735 $(\mathrm{psi})^{-1}$
Initial temperature	90° F
Initial pressure	80 psi

Oil Viscosity-Temperature Relationship

Temp.,°F	Viscosity, cp				
90	2,000	4,500	7,000	9,500	12,000
300	6.5	8.0	9.0	10.2	10.8

Water-Oil and Gas-Oil Relative Permeability Data (400°F)

S_{iw}	$1.114-S_o$	S_{orw}	0.229	S_{org}	0.050	S_{gc}	0.00
S_{gr}	0.00	k_{rwro}	0.0630	k_{roiw}	0.400	k_{rgro}	0.460
n_w	1.94	n_{ow}	2.24	n_{og}	2.52	n_g	2.58

Temperature-Dependent End Point Data

Temp., °F	S_{iw}	S_{wir}	S_{orw}	S_{org}	k_{rwro}	k_{rocw}
90	$0.980-S_o$	$0.980-S_o$	0.369	0.369	0.0502	0.710
245	$1.047-S_o$	$1.047-S_o$	0.234	0.050	0.0566	0.555
400	$1.114-S_o$	$1.114-S_o$	0.229	0.050	0.0636	0.400

Note: Here, S_o is initial oil saturation, fraction

DZ for Layer 1 = thickness/15
DZ for Layer n = n x DZ for Layer 1

3. Steamflood Operating Data

Completion intervals	Injector Bottom 1/3 of interval Producer Entire interval
Steam temperature for displacement	366° F

Steam stimulation data

Steam temperature	417° F
Steam quality	70%
Slug Size	10,000 STB
Cycle Length	182.5 days

TABLE 1. Factor Levels

Factor	Factor Levels -2	-1	0	+1	+2
x_1, S_o, %	40	45	50	55	60
x_2, μ, cp	2000	4500	7000	9500	12000
x_3, h, ft	40	60	80	100	120
x_4, i_s, BPD	200	250	300	350	400
x_5, A, acre	2.0	2.3	2.6	2.9	3.2
x_6, f_q, %	25	40	55	70	85
x_7, ø, %	26.0	28.5	31.0	33.5	36.0
x_8, k, md	2000	2750	3500	4250	5000

TABLE 2. Composite Factorial Design

Run No.	Factor Levels x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
1	-1	-1	-1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1	-1	-1	-1
3	-1	1	-1	-1	-1	-1	-1	-1
4	1	1	-1	-1	-1	-1	1	1
5	-1	-1	1	-1	-1	-1	-1	1
6	1	-1	1	-1	-1	-1	1	-1
7	-1	1	1	-1	-1	-1	1	-1
8	1	1	1	-1	-1	-1	-1	1
9	-1	-1	-1	1	-1	-1	-1	1
10	1	-1	-1	1	-1	-1	1	-1
11	-1	1	-1	1	-1	-1	1	-1
12	1	1	-1	1	-1	-1	-1	1
13	-1	-1	1	1	-1	-1	1	1
14	1	-1	1	1	-1	-1	-1	-1
15	-1	1	1	1	-1	-1	-1	-1
16	1	1	1	1	-1	-1	1	1
17	-1	-1	-1	-1	1	-1	1	-1
18	1	-1	-1	-1	1	-1	-1	1
19	-1	1	-1	-1	1	-1	-1	1
20	1	1	-1	-1	1	-1	1	-1
21	-1	-1	1	-1	1	-1	-1	-1
22	1	-1	1	-1	1	-1	1	1
23	-1	1	1	-1	1	-1	1	1
24	1	1	1	-1	1	-1	-1	-1
25	-1	-1	-1	1	1	-1	-1	-1
26	1	-1	-1	1	1	-1	1	1
27	-1	1	-1	1	1	-1	1	1
28	1	1	-1	1	1	-1	-1	-1
29	-1	-1	1	1	1	-1	1	-1
30	1	-1	1	1	1	-1	-1	1
31	-1	1	1	1	1	-1	-1	1
32	1	1	1	1	1	-1	1	-1
33	-1	-1	-1	-1	-1	1	1	-1
34	1	-1	-1	-1	-1	1	-1	1
35	-1	1	-1	-1	-1	1	-1	1
36	1	1	-1	-1	-1	1	1	-1
37	-1	-1	1	-1	-1	1	-1	-1
38	1	-1	1	-1	-1	1	1	1
39	-1	1	1	-1	-1	1	1	1
40	1	1	1	-1	-1	1	-1	-1
41	-1	-1	-1	1	-1	1	-1	-1
42	1	-1	-1	1	-1	1	1	1
43	-1	1	-1	1	-1	1	1	1
44	1	1	-1	1	-1	1	-1	-1
45	-1	-1	1	1	-1	1	1	-1
46	1	-1	1	1	-1	1	-1	1
47	-1	1	1	1	-1	1	-1	1
48	1	1	1	1	-1	1	1	-1
49	-1	-1	-1	-1	1	1	1	1
50	1	-1	-1	-1	1	1	-1	-1
51	-1	1	-1	-1	1	1	-1	-1
52	1	1	-1	-1	1	1	1	1
53	-1	-1	1	-1	1	1	-1	1
54	1	-1	1	-1	1	1	1	-1
55	-1	1	1	-1	1	1	1	-1
56	1	1	1	-1	1	1	-1	1
57	-1	-1	-1	1	1	1	-1	1
58	1	-1	-1	1	1	1	1	-1
59	-1	1	-1	1	1	1	1	-1
60	1	1	-1	1	1	1	-1	1
61	-1	-1	1	1	1	1	1	1
62	1	-1	1	1	1	1	-1	-1
63	-1	1	1	1	1	1	-1	-1
64	1	1	1	1	1	1	1	1
65	0	0	0	0	0	0	0	0
66	-2	0	0	0	0	0	0	0
67	2	0	0	0	0	0	0	0
68	0	-2	0	0	0	0	0	0
69	0	2	0	0	0	0	0	0
70	0	0	-2	0	0	0	0	0
71	0	0	2	0	0	0	0	0
72	0	0	0	-2	0	0	0	0
73	0	0	0	2	0	0	0	0
74	0	0	0	0	-2	0	0	0
75	0	0	0	0	2	0	0	0
76	0	0	0	0	0	-2	0	0
77	0	0	0	0	0	2	0	0
78	0	0	0	0	0	0	-2	0
79	0	0	0	0	0	0	2	0
80	0	0	0	0	0	0	0	-2
81	0	0	0	0	0	0	0	2

TABLE 3. Coefficients Generated by the Factorial Design Method

Coef.	Project Life years	Oil Recovery % OIP	Cumulative SOR B/B
B 0	7.0493	53.3135	5.9626
B 1	0.7992	4.0418	-0.4100
B 2	-0.0883	-2.0279	0.1614
B 3	1.5014	-0.1504	-0.2561
B 4	-1.0761	-0.2637	0.0944
B 5	0.8917	-0.0162	0.0592
B 6	-0.8580	-0.7295	-0.6264
B 7	0.4869	1.1999	-0.2075
B 8	-0.1786	-0.7576	-0.0878
B12	0.0112	-0.0995	-0.0013
B13	0.3069	0.5289	0.0766
B14	-0.1050	0.0948	0.0053
B15	0.0647	-0.1183	-0.0181
B16	0.0300	0.4267	0.0997
B17	0.0316	-0.0642	0.0259
B18	0.0194	0.1648	0.0256
B23	0.0009	-0.0036	0.0053
B24	-0.0222	-0.0833	-0.0191
B25	-0.0687	-0.1508	-0.0062
B26	-0.1528	-0.6052	-0.0703
B27	-0.0544	-0.0698	-0.0147
B28	-0.0397	-0.2620	-0.0050
B34	-0.1016	0.4758	0.0513
B35	0.1375	-0.0992	-0.0216
B36	-0.3916	-1.8636	0.0612
B37	0.0575	-0.1527	0.0100
B38	-0.0309	-0.0898	0.0459
B45	-0.1994	-0.4233	-0.0184
B46	0.0797	-0.3720	-0.0038
B47	-0.0962	-0.3573	-0.0100
B48	-0.0278	-0.3645	-0.0009
B56	-0.1725	-0.2014	-0.0559
B57	0.0372	0.1364	-0.0128
B58	-0.1387	-0.1889	-0.0313
B67	0.0138	0.1133	0.0350
B68	-0.1109	-0.4839	-0.0459
B78	0.0269	0.1395	0.0184
B11	-0.0754	-0.2484	0.0177
B22	0.1671	0.1878	0.1239
B33	-0.1942	-0.2022	0.0014
B44	0.1721	0.1741	-0.0761
B55	0.0258	0.2853	-0.0436
B66	-0.0192	0.3453	-0.0123
B77	-0.0404	0.1316	-0.0323
B88	-0.2367	-0.4809	-0.1123

TABLE 4. Statistical Significance of the Equation

	Project Life	Oil Recovery	Cumulative SOR
F value*	15.49	6.98	9.18
Tail Area	0.000	0.000	0.000
Percent variation explained by the model	95.0	89.5	91.8
Residual standard deviation expressed as a percentage of response mean	11.50	4.84	6.14

*The degrees of freedom for the numerator and denominator are 44 and 36 respectively.

TABLE 5. Mean Values and Standard Deviations of Response Variables

	Mean Value	Standard Deviation
Project life, years	7.05	2.89
Oil recovery, % OIP	53.31	6.33
Cumulative SOR, B/B	5.96	1.02

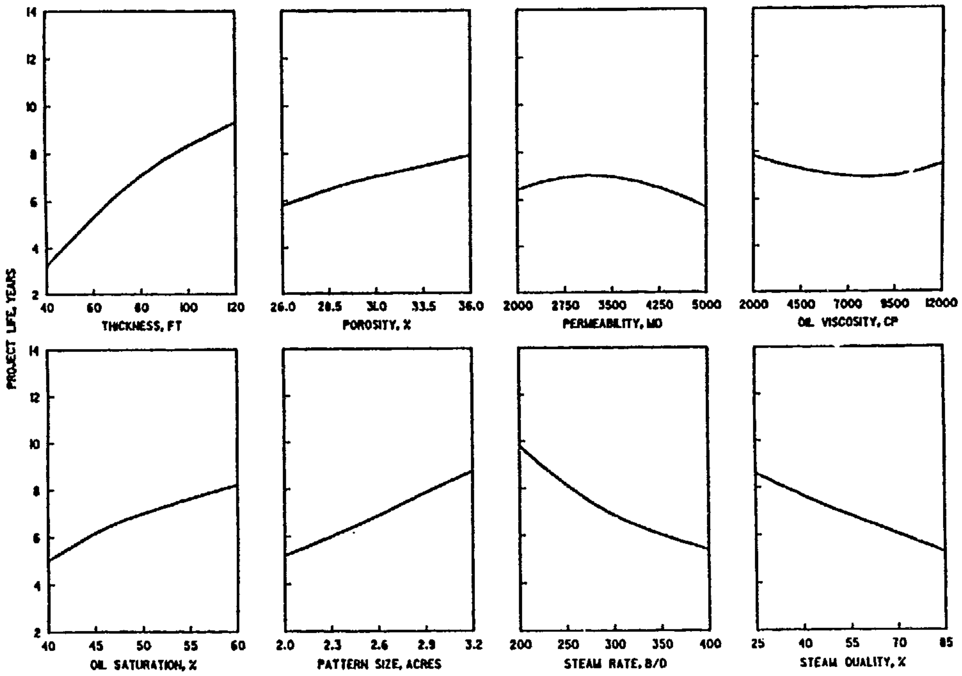

Figure 1. Effects of Single Variables on Project Life

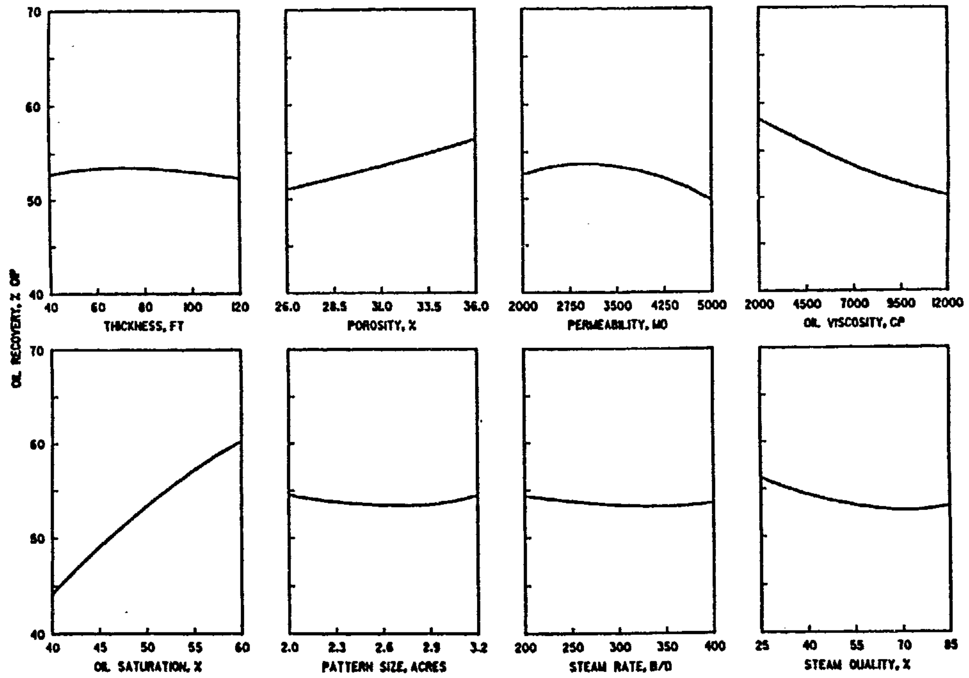

Figure 2. Effects of Single Variables on Oil Recovery

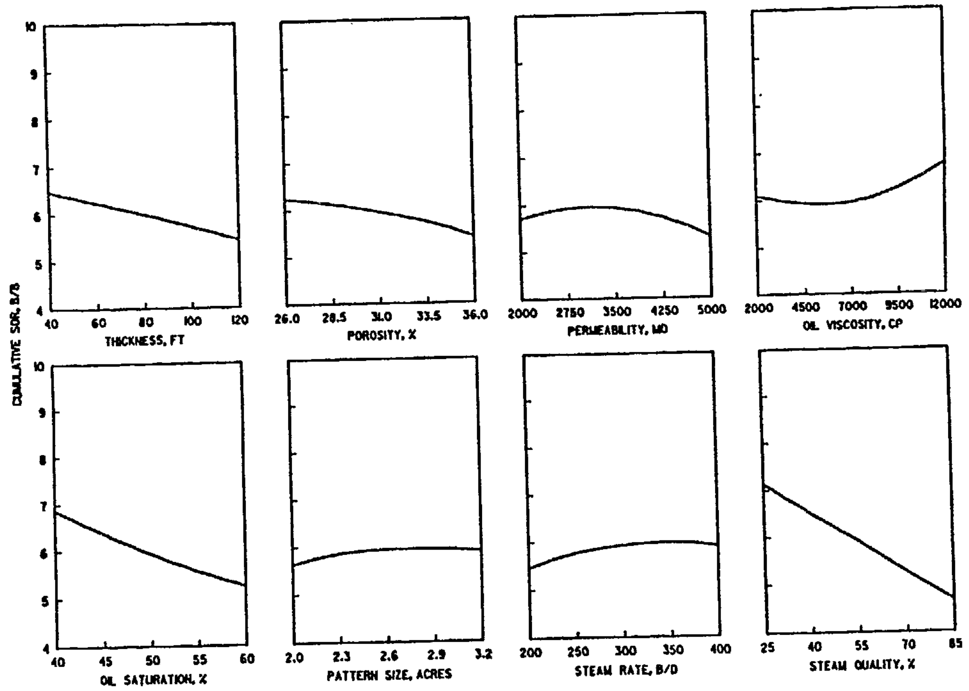

Figure 3. Effects of Single Variables on Cumulative SOR

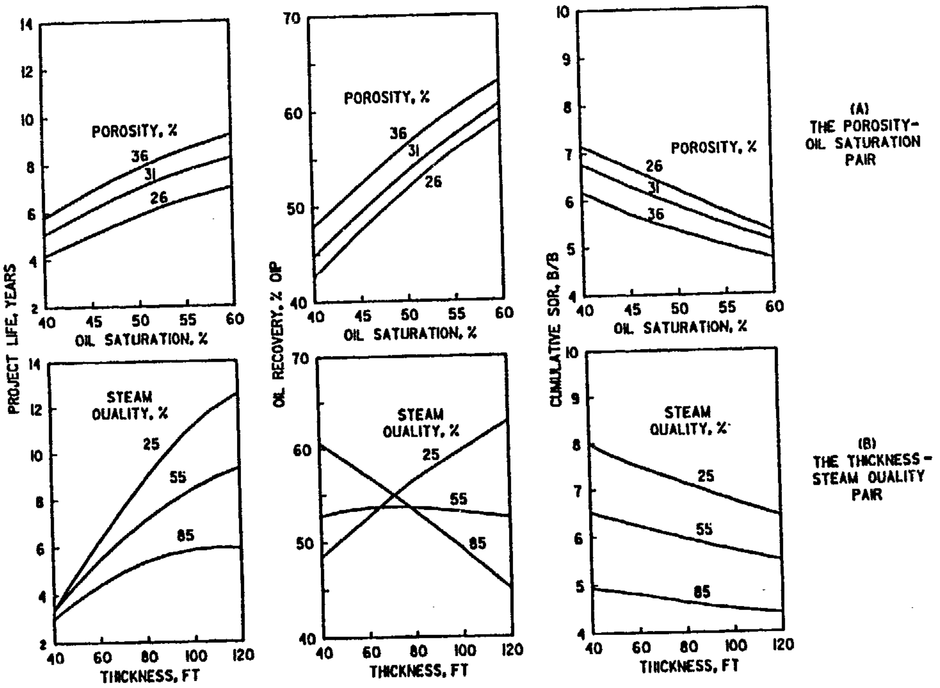

Figure 4. Effects of Combinations of Variables on Steamflood Performances