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REVIEW OF STATISTICAL METHODS USED IN ENHANCED OIL
RECOVERY RESEARCH AND PERFORMANCE PREDICTION

By
Judith E. Selvidge

MASTER

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**REVIEW OF STATISTICAL METHODS USED IN ENHANCED
OIL RECOVERY RESEARCH AND PERFORMANCE PREDICTION**

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ABSTRACT

Recent literature in the field of enhanced oil recovery (EOR) was surveyed to determine the extent to which researchers in EOR take advantage of statistical techniques in analyzing their data. In addition to determining the current level of reliance on statistical tools, another objective of this study is to promote by example the greater use of these tools. To serve this objective, the discussion of the techniques highlights the observed trend toward the use of increasingly more sophisticated methods and points out the strengths and pitfalls of different approaches. Several examples are also given of opportunities for extending EOR research findings by additional statistical manipulation (through the use of any relevant but neglected techniques).

The search of the EOR literature, conducted mainly through computerized data bases, yielded nearly 200 articles containing mathematical analysis of the research. Of these, 21 were found to include examples of statistical approaches to data analysis and are discussed in detail in this review. The use of statistical techniques, as might be expected from their general purpose nature, extends across nearly all types of EOR research covering thermal methods of recovery, miscible processes, and micellar polymer floods. Data come from field tests, the laboratory, and computer simulation. The statistical methods range from simple comparisons of mean values to multiple non-linear regression equations and to probabilistic decision functions. The methods are applied to both engineering and economic data. In some cases, the statistical analysis is a minor part of the research; in other cases it is central to the findings. Two of the articles were written specifically to demonstrate the use of new statistical methods.

The results of the survey are grouped by statistical technique and include brief descriptions of each of the 21 relevant papers. Complete abstracts of the papers are included in the bibliography. Brief bibliographic information (without abstracts) is also given for the articles identified in the initial search as containing mathematical analyses using other than statistical methods.

REVIEW OF STATISTICAL METHODS FOR ENHANCED OIL RECOVERY RESEARCH AND PERFORMANCE PREDICTION

CHAPTER I INTRODUCTION

The principal objective of this review is to assess the current level of use of statistical techniques in enhanced oil recovery (EOR) research and performance prediction. In carrying out this assessment we describe the types of techniques being used and the amount of use they receive, we suggest additional analyses to extend the findings, and we summarize trends and advances in the use of statistical techniques. A secondary purpose of the review is to encourage the broader use of formal statistical methods in the analysis of EOR data in order to exploit more fully the information contained in such data. The examples of current analyses using statistical techniques demonstrate the power and possibilities of these methods. To facilitate their increased use, we also incorporate into the discussion of the examples a brief review of some of the pertinent statistical principles governing the use of the techniques.

The presentation of this review is designed for readers with some familiarity in statistical methods either from college or short courses or from self study. In order to provide a reminder, however, a glossary of statistical terms is supplied and several recommended statistical texts are cited (Appendix A).

This review of statistical techniques is based on a survey of the quantitative techniques cited in publications in the EOR literature. Searches were made of the "Petroleum Abstracts" file¹ using the topic

1. Available through Orbit IV, System Development Corporation International Search Service.

"mathematical analysis of tertiary recovery operations", and of two U.S. Department of Energy files using the topic "enhanced recovery and statistics." These key word searches produced over 180 articles whose abstracts were reviewed. Of these, 18, or about 10 percent, were directly pertinent to the issue of interest: the use of statistical techniques to analyze EOR data. Three additional articles² were located through other channels. It is not possible to determine whether all recent examples of statistical analysis applied in the EOR area have been identified by this search. However, the wide range of EOR processes examined, the types of data analyzed, and the different statistical techniques used suggest that the articles studied are a representative, if not exhaustive, selection.

Copies of the 21 selected articles were obtained, and the articles studied in detail. These form the basis of the assessment of usage of statistics in EOR research. Bibliographic information on these articles, including their complete abstracts, is presented in Appendix B. Details of the literature search, including the titles of the articles reviewed but not selected, are given in Appendix C.

2. Private communication from John R. Fanchi, Keplinger and Associates, Inc.

CHAPTER II

SUMMARY OF FINDINGS

A. ARTICLES REVIEWED

The 21 articles studied include reports of basic research whose purpose is to investigate underlying relationships among variables, screening models for different EOR processes, project selection and scheduling studies, and production planning techniques. Each of the articles is listed in Table II-1 and is briefly described by characteristics such as EOR method, data source, statistical approach, and variables analyzed. The entries in the table are placed in chronological order to show the general progression over time of statistical techniques from the simple to the more complex; throughout this review however, the standard approach of referring to the articles by their reference number taken from an alphabetically arranged bibliography (Appendix B) is followed. The first column of Table II-1 lists the articles' reference numbers.

B. STATISTICAL TECHNIQUES OBSERVED

A summary of the statistical techniques used and their frequency of use in this sample of articles is shown in Table II-2. Some articles make use of more than one technique. The techniques range from simple, traditional statistical techniques, such as averages and correlations, to the more complicated multiple regressions and analyses of variance and to the more recently developed probabilistic techniques, such as decision diagrams, risk analysis, and probabilistic production and economic models.

The details of the application of these statistical techniques to EOR research are given in Chapter III. The discussions are grouped by technique. Within each technique the examples of applications are cited and described. Some background information is also presented on the definition of the technique and the way of using the technique in setting up and testing statistical hypotheses.

TABLE II-1. SUMMARY OF ARTICLES REVIEWED

REFERENCE NUMBER (SEE APPENDIX B)	TITLE, AUTHORS(S), SOURCE	YEAR	EOR METHOD	DATA TYPE			STATISTICAL TECHNIQUES	VARIABLES ANALYZED STATISTICALLY
				LAB	FIELD	SIMULATION MODEL		
12	"MECHANISMS OF OIL DISPLACEMENT BY CARBON DIOXIDE," HOLM, L. W. AND JOSENDAL, V. A., <u>SPE.</u>	1974	CO ₂ INJECTION	X			CORRELATION (SIMPLE SIDE-BY-SIDE COMPARISON) OF LAB TEST TO THEORETICAL.	CO ₂ MISCIBLE PRESSURE (DEPENDENT) VS. TEMP. (FOR KNOWN OIL COMPOSITION).
3	"A STUDY OF FIREFLOOD FIELD PROJECTS," CHU, C., <u>SPE.</u>	1976	FIREFLOOD FOR RECOVERY OF MEDIUM TO HIGH VISCOSITY CRUDES		X		DIFFERENCE BETWEEN TWO MEANS. MULTIVARIATE REGRESSION EQUATIONS INCLUDING INTERACTION TERM. (40 PROJECTS)	INDEPENDENT: - RESERVOIR - THICKNESS - PERMEABILITY - OIL SAT. FRACTION - DEPTH - VISCOSITY DEPENDENT: - FUEL CONTENT - AIR-OIL RATIO
10	"HOW TO ORGANIZE AND PLAN ENHANCED OIL RECOVERY EFFORTS," HASIBA, H. H., WILSON, JR., L. A. AND MARTINELLI, J. W., <u>WORLD OIL.</u>	1977	VARIOUS		X		PROBABILITY TREE. SUBJECTIVE PROBABILITY ASSESSMENTS (3 VALUES) BASED ON EXTENSIVE DATA. EXPECTED VALUE OF RESERVES.	OIL IN PLACE RECOVERY FRACTION COST PER BARREL
15	"STEAM DRIVE CORRELATION AND PREDICTION," MYHILL, N. A. AND STEGEMEIER, G. L., <u>J. PET. TECH.</u>	1978	STEAM DRIVE AND STEAM SOAK	X	X		CORRELATION COMPARES COMPUTED VALUES TO ACTUALS BY PLOT.	DEPENDENT: STEAM OIL RATIO FROM ENERGY BALANCE EQUATIONS (COMPLEX).
6	"ENGINEERING OF IN-SITU COMBINATION OIL RECOVERY PROJECTS," GATES, C. F., AND RAMEY, JR., H. J., <u>SPE.</u>	1978	IN-SITU COMBUSTION	X	SOME X		AVERAGES. DATA POINTS FIT BY EYE. INTERPOLATION.	OIL DISPLACED VOLUME BURNED FUEL CONCENTRATION AIR-OIL RATIO OIL RECOVERED
7	"EVALUATION OF SURFACTANT SYSTEMS FOR OIL RECOVERY USING STATISTICAL DESIGN PRINCIPLES & ANALYSIS," GERBACIA, W., <u>SPE.</u>	1978	MICELLAR AQUEOUS SURFACTANT SOLUTIONS	X			BOX & BEHNKEN VARIATION OF FACTORIAL DESIGN. MULTIPLE ANALYSIS OF VARIANCE. MULTIPLE QUADRATIC REGRESSION. (15 OBSERVATIONS)	INDEPENDENT: - ALCOH. CHAIN LENGTH - ALCOH-SULFONATE RATIO - SULFONATE CONCENTRATION DEPENDENT: - SODIUM CHLORIDE TOLERANCE - CRUDE OIL RECOV.
16	"A PARAMETRIC STUDY OF THE CO ₂ HUF-N-PUF PROCESS," PATTON, J. T., COATS, K. J., AND SPENCE, K., <u>SPE.</u>	1979	CYCLIC CO ₂ STIMULATION			X 200 OBS	MULTIPLE REGRESSION. ONE QUADRATIC TERM. 6 OUT OF 9 VARIABLES USED. (NO INTERACTIONS.)	INCREM. OIL RECOVERY (DEPENDENT) VS. 3 OPERATIONS PARAMETERS AND 6 RESERVOIR PARAMETERS.
18	"THE USE OF PSEUDOCOMPONENTS IN THE REPRESENTATION OF PHASE BEHAVIOR OF SURFACTANT SYSTEMS," VINATIERI, J. E. AND FLEMMING, P. D., <u>J. PET. TECH.</u>	1979	SURFACTANTS	X			MULTIPLE LINEAR REGRESSION TO CONSTRUCT ALTERNATIVE SETS OF PSEUDOCOMPONENTS.	PROPORTION OF OIL, SULFONATE, ALCOHOL, WATER & ELECTROLYTE.

TABLE II-1. SUMMARY OF ARTICLES REVIEWED (CONTINUED)

REFERENCE NUMBER (SEE APPENDIX B)	TITLE, AUTHORS(S), SOURCE	YEAR	EOR METHOD	DATA TYPE			STATISTICAL TECHNIQUES	VARIABLES ANALYZED STATISTICALLY
				LAB	FIELD	SIMULATION MODEL		
4	"STATUS OF MICELLAR-POLYMER FIELD TESTS," LAKE, L. W. AND POPE, G. A., <u>PEI</u> .	1979	MICELLAR- POLYMER FLOODING		44 TESTS CONSIDERED 21 ANALYSED		CORRELATION COEFFICIENTS. LINEAR REGRESSION.	RECOVERY EFFICIENCY VS. VPS = SLUG SIZE (PV), SURFACTANT CON- CENTRATION = CS. TOTAL SURFACTANT IN- JECTED = VPS x CS. MOBILITY BUFFER SIZE : PLUS SOME COMPUTED VARIABLES.
1	"APPLICATION OF RISK ANALYSIS TO ENHANCED RECOVERY PILOT TESTING DECISION," ANDERSON, M. L., <u>J. PET. TECH.</u>	1979	SURFACTANT WATER FLOOD (HYPOTHETICAL EXAMPLE).		X		MONTE CARLO SIMULATION OF UNCERTAINTY BEFORE AND AFTER PILOT TEST, TO ESTI- MATE ECONOMIC OUTCOME: DISCOUNTED CASH FLOW RETURN ON INVESTMENT.	PROBABILITY DISTRIBUTION: - RESERVES - CHEMICAL REQ. - CHEMICAL COST - OIL PRICE DETERMINISTIC SENSITIVITY: - OIL PRICE - RESERVES - CHEMICAL COST - FIXED CAPITAL
21	"DETERMINATION AND PREDICTION OF CO ₂ MINIMUM MISCIBILITY PRESSURES," YELLIG, W. F. AND METCALFE, R. S., <u>J. PET. TECH.</u>	1980	CO ₂ INJECTION	X			CORRELATION TO COMPARE 3 MODELS; ACTUAL TO PRE- DICTED VALUES ARE STUDIED.	CO ₂ MMP (DEPENDENT) VS.: - TEMPERATURE - OIL COMPOSITION
8	"CORRELATIONS FOR PREDICTING OIL RECOVERY BY STEAM FLOOD," GOMAA, E. E., <u>J. PET. TECH.</u>	1980	STEAM FLOODING			X	1 DEPENDENT, INDEPENDENT NON-LINEAR FITS FOR MANY PAIRS OF VARIABLES. OTHER VARIABLES HELD AT MEAN VALUES. NO INTERACTIONS CONSIDERED. VARIABLES THEN COMBINED TO PRODUCE PREDICTOR EQUATION.	DEPENDENT: - STEAMFLOOD OIL RECOVERY - OIL/STEAM RATIO INDEPENDENT: - RESERVOIR CHARACTERISTICS - OPERATING CONDITIONS
9	"REVIEW AND ANALYSIS OF PAST AND ONGOING CO ₂ INJECTION FIELD TESTS," GOODRICH, J. H., <u>SPE</u> .	1980	CO ₂ INJECTION		7 FULL SCALE 12 PILOT 19		CORRELATIONS QUOTED FROM EARLIER WORK. FIELD DATA ANALYSIS IS <u>QUALITATIVE</u> .	CO ₂ MMP (DEPENDENT) VS.: - TEMPERATURE - OIL COMPOSITION
11	"STATUS OF MICELLAR-POLYMER FIELD TESTS - ANOTHER VIEW," HOLM, L. W., <u>PEI</u> .	1980	MICELLAR POLYMER FLOODING		RE-ANALYSIS OF 21 TESTS WITH SOME DATA POINTS CHANGED.		CORRELATION COEFFICIENTS. LINEAR REGRESSION.	RECOVERY EFFICIENCY VS VPS = SLUG SIZE, SURFACTANT CONCEN- TRATE = CS. TOTAL SURFACTANT INJECTED = VPS x CS MOBILITY BUFFER SIZE : PLUS SOME COMPUTED VARIABLES.

TABLE II-1. SUMMARY OF ARTICLES REVIEWED (CONTINUED)

REFERENCE NUMBER (SEE APPENDIX B)	TITLE, AUTHORS(S), SOURCE	YEAR	EOR METHOD	DATA TYPE			STATISTICAL TECHNIQUES	VARIABLES ANALYZED STATISTICALLY
				LAB	FIELD	SIMULATION MODEL		
19b	"ECONOMIC APPRAISAL OF THERMAL DRIVE PROJECTS - A NEW APPROACH," WILLIAMS, R. L., BROWN, S. L., AND RAMEY, JR., H. J., SPE. (SHORT VERSION OF THIS REPORT. ALSO SEE REF. 19a)	1980	STEAM INJECTION AND IN-SITU COMBUSTION.	X	X		DISCOUNTED CASH FLOW MODEL LINKED TO 2 OIL RECOVERY MODELS. NET PRESENT VALUE UNDER DIFFERENT RESERVOIR CHARACTERISTICS AND OPERA- TIONS.	NET PRESENT VALUE COMPUTED FROM VARIOUS FINANCIAL AND OPERATING VARIABLES.
20	"CRUDE OIL STEAM DISTILLATION IN STEAM FLOODING," WU, C. H., AND ELDER, R. B., <u>U.S. DOE REPORT.</u>	1980	STEAM FLOODING	X			REGRESSION. MANY UNIVARI- ATE LINEAR AND QUADRATIC MODELS. TRANSFORMATION (1n).	INDEPENDENT: - API GRAVITY - OIL VISCOSITY CHARACTERIZATION FACTOR - SIMULATED DISTIL- LATION YIELDS DEPENDENT: - DISTILLATION YIELDS
2	"RECOVERY CORRELATIONS FOR IN- SITU COMBUSTION FIELD PROJECTS AND APPLICATION TO COMBUSTION PILOTS," BRIGHAM, W. E., SATMAN, A. AND SOLIMAN, M. Y., <u>J. PET. TECH.</u>	1980	IN-SITU COMBUSTION		X		CORRELATION EXPRESSED IN TERMS OF MULTIPLE REGRES- SION EQUATIONS. INTER- ACTIONS AMONG VARIABLES ARE SPECIFIED (NO SIMPLE EFFECTS). TWO HIGHER ORDER TERMS INCLUDED. (14 PROJECTS.)	7 VARIABLES (INDE- PENDENT): CUM. AIR INJECTION, OXYGEN UTILIZATION, THICK- NESS OF FORMATION, PERMEABILITY, OIL SATURATION, VISCOS- ITY, AND POROSITY. 1 DEPENDENT: OIL PRODUCTION (VARIOUS NORMALIZED FORMS).

TABLE II-1. SUMMARY OF ARTICLES REVIEWED (CONTINUED)

REFERENCE NUMBER (SEE APPENDIX B)	TITLE, AUTHORS(S), SOURCE	YEAR	EOR METHOD	DATA TYPE			STATISTICAL TECHNIQUES	VARIABLES ANALYZED STATISTICALLY
				LAB	FIELD	SIMULATION MODEL		
4	"STATE-OF-THE-ART REVIEW OF FIREFLOOD FIELD PROJECTS," CHU, C. I., <u>SPE</u> .	1981	FIREFLOOD		X		INCLUDES SOME REGRESSIONS FROM ELSEWHERE. COMPUTES ADDITIONAL LINEAR REGRES- SIONS (3 VARIABLES). COM- PUTES CORRELATION COEFFI- CIENT. FREQUENCY HISTO- GRAMS OF RESERVOIR CHAR- ACTERISTICS. (34 PROJECTS)	MANY, INCLUDING FUEL CONTENT, OIL-AIR RATIO, WATER-AIR RATIO, OIL RECOVERY AND AIR REQUIREMENT.
5	"EVALUATION OF SURFACTANT EOR POTENTIALS USING A SCALING LAW INTERPRETATION OF CORE FLOOD RESIDUAL OIL SATURATION PROFILES," DAVIS, L. A., TYLER, T. N., BROST, D. F. AND HASKIN, H. K., <u>SPE</u> .	1981	SURFACTANTS	X			STEPWISE MULTIPLE REGRES- SION TO SUPPORT THEORY ABOUT BEHAVIOR OF SURFAC- TANTS.	DEPENDENT VARIABLE: - RECOVERY EFFICIENCY INDEPENDENT VARIABLES: - SEVEN DIMENSIONLESS GROUPS DERIVED FROM 11 PHYSICAL VARIABLES.
13	"MEASUREMENT AND CORRELATION OF CO ₂ MISCIBILITY PRESSURES," JOHNSON, J. P. AND POLLIN, J. S., <u>SPE</u> .	1981	CO ₂ INJECTION	X			CURVILINEAR EQUATION IN FOUR VARIABLES. COMPARI- SON OF PREDICTED AND EXPERIMENTAL VALUES.	DEPENDENT VARIABLE: - CO ₂ MISCIBILITY PRESSURE INDEPENDENT VARIABLES - RESERVOIR TEMP. - OIL MOLECULAR WT. - OIL GRAVITY - GAS INJECTION - COMPOSITION
17	"CORRELATION OF GELATION TIMES FOR POLYMER SOLUTIONS USED AS SWEEP IMPROVEMENT AGENTS," TERRY, R. E., HUANG, C., GREEN, D. W., MICHNICK, J. M., AND WILLHITE, G. P., <u>J. PET. TECH.</u>	1981	GELLED POLYMERS	X			FITTING STRAIGHT LINES BY EYE.	GELATION TIME VERSUS INITIAL POLYMER CON- CENTRATION, AT DIF- FERENT METAL ION CONCENTRATIONS.

TABLE II-2. STATISTICAL TECHNIQUES USED

<u>TECHNIQUE</u>	<u>NO. OF OCCURRENCES</u>
AVERAGES	1
CURVE-FITTING BY EYE	3
DIFFERENCE BETWEEN TWO MEANS	1
CORRELATION (QUALITATIVE)	2
CORRELATION COEFFICIENTS	3
DATA TRANSFORMATIONS	3
UNIVARIATE REGRESSION	3
MULTIPLE REGRESSION	7
ANALYSIS OF VARIANCE	1
FREQUENCY PROFILES	1
DECISION AND PROBABILITY TREES	1
RISK ANALYSIS	1

CHAPTER III

DETAILS OF STATISTICAL USAGE

A. BASIC DESCRIPTIVE STATISTICS AND INFERENCE

1. Averages

The most basic descriptors of research data are simple statistics on a single variable such as the average (mean, median, mode³), the range, and the standard deviation. Gates and Ramey (6) use averages in a 1978 publication on in-situ combustion projects. This article supports the use of the "oil recovery to volume burned" method for engineering calculations (for in-situ projects) of air-oil ratios, oil rates, oil recovery, and economic limits. The results are superior to those obtained using frontal displacement calculations. In their analysis, simple averages (arithmetic means) are used to summarize three series of laboratory combustion tube data for graphical presentation. No indication is given of the variability among the three tests.

2. Statistical Hypotheses About Means

A common statistical procedure involving averages is to test for the difference between two means. In this test the researcher has two samples of data and wants to know whether the value of some particular variable differs significantly from one sample to the other. The procedure is used by Chu (3) in a study of data from a large number of fireflood field projects. The fireflood projects are classified as either successful or unsuccessful, and Chu carries out tests for a difference in mean value between the successful and unsuccessful floods of each of a number of different variables. Statistically speaking, the question being

3. These and other statistical terms are briefly defined in the glossary (Appendix A).

asked is whether the observed difference in mean value of some variable, say the crude gravity expressed in °API, from the sample or group of successful floods to the sample of unsuccessful floods arises only from sampling variability or whether the difference is due to a true difference in this value in the general populations of successful and unsuccessful floods. The latter case is of engineering interest because it would permit the use of this variable as a screening factor to identify, in advance, potentially successful and unsuccessful projects. In statistical terms two explanations exist for the difference observed in the sample means of a variable:

- (1) The underlying population means are the same, the observed difference being due to sampling (the null hypothesis), and
- (2) The underlying population means are different (the alternative hypothesis).

The null hypothesis is tested by computing "student's t" from a formula involving the sample means, variances, and number of observations. (See Appendix A for a listing of standard statistical tests. For large samples a Z statistic can be computed.) Having selected in advance a level of significance, say the 0.05 level, the researcher compares the computed t to that tabulated for this level of significance and the appropriate degrees of freedom (computed from the sample size). Suppose the computed t is greater (as was the case for °API in the Chu example). The interpretation is that the probability of obtaining a t this large or larger if the population means for the two groups (successful and unsuccessful floods) were the same is five percent or less. The hypothesis that the population means are the same is, therefore, rejected. In other words, these data favor the rejection of the null hypothesis, and the probability of the decision to reject being wrong is only 5 percent. Consequently, the alternative hypothesis, that the two population means are different, is accepted. By this method Chu finds significant differences for four out of nine variables or combinations of variables tested, namely porosity, oil saturation, the product of porosity and saturation, and crude gravity.

The standard test for the difference between two means assumes that the variable studied is normally distributed and that the population variances for the variable from group to group are the same. The test, however, is not particularly sensitive to departures from the normality assumption. If the sample variances are quite different from one group to the other, a procedure to test this difference in variances should be employed. If the difference is found to be significant, either the test for a difference in means is abandoned or an adjustment is made in calculating the t value to account for the unequal variances.⁴

3. Comparing Means of More Than Two Groups

If the data fall into more than two groups, an alternative method for comparing means is available. Suppose, for example, the fire-flood projects were classified into five groups:

- (1) Highly successful,
- (2) Moderately successful,
- (3) Marginally successful,
- (4) Failure, and
- (5) Indeterminate.

To investigate whether or not a variable such as porosity was different depending on the group, it would be possible to apply the difference between two means test as shown above for all possible combinations of pairs of groups (e.g., highly successful and moderately successful, moderately successful and marginally successful, highly successful and marginally successful, and so on). There are ten such different pairs of groups. If nine variables were studied this would require ninety tests. The problem with this approach, apart from time considerations, is that a number of apparently "significant" results would be expected just

4. Unfortunately, the problem of how to adjust for differences in the variances does not have a universally accepted solution.

on a chance basis. (For example, applying t tests at the 0.05 level to 100 different pairs of sample means drawn from two populations with the same population means would be expected to yield "significant" results about five times. If ten significant values were obtained in 100 comparisons of pairs of variables from possibly different populations, we would not know which might be due to true differences in population means and which to random variation in the sample means.) The more efficient statistical approach is to carry out a one-way analysis of variance for each variable of interest. The analysis of variance procedure gives as output an F statistic. A significant F indicates that the population means for the different groups are probably unequal, however it does not pinpoint where the differences lie. In the event of overall significance, a variety of multiple comparisons can then be used to determine which of the pair-wise differences are statistically significant.

An underlying assumption of the analysis of variance method is that the population variances for each group are equal (the "homogeneity of variances" requirement). Moderate departures from this assumption do not, however, seriously affect the validity of the F statistic in the ranges of interest.

B. CORRELATION

1. Background

The term "correlation" is used popularly to describe the relationship between two variables. When an increase in one variable is associated with an increase in the other variable, such as the pressure required for miscible displacement in CO₂ flooding increasing with the increase in temperature, the variables are said to be positively correlated. When the increase in one variable is associated with a decrease in the other, such as viscosity of CO₂-crude oil mixtures and saturation pressure, they are said to be negatively correlated. Correlation is also commonly used to describe the comparison of different

ways of measuring or computing the same quantity, as in a typical statement "oil recovery predicted by the volume burned calculation correlates well with recovery obtained in large-scale commercial field applications." In statistical terminology the meaning of correlation is somewhat more restricted. Correlation is measured on a scale of -1.0 to +1.0 and refers to the strength of the linear relationship between two variables. A value of 0 implies no linear relationship; a value of ± 1.0 implies a perfect linear relationship (i.e., $y = a + bx$, where x and y are the variables whose correlation is ± 1.0 and a and b are constants).

2. Correlation as a General Descriptor

Many of the papers reviewed use correlation in the more general sense; a smaller number apply the term in the stricter statistical sense. Several examples of the general use are found in Goodrich's review (9) of reports on 19 field projects in which carbon dioxide miscible injection was used to enhance oil recovery. In a study of mechanisms of oil displacement by Holm and Josendal (12), the term correlation is used to refer to the degree of agreement between theoretical and experimental data. They compare the predicted value of pressure required for miscible displacement to that obtained in actual laboratory floods (in slim tube tests) and report a "good agreement." Myhill and Stegemeier (15) apply the term correlation in analyzing the performance of an energy balance model they have developed for steam drive prediction. Under this model, oil recovered is a function of steam zone volume which in turn is a function of reservoir properties, injection procedures, and steam properties. They report oil/steam ratios calculated by means of their simple mathematical model "correlate well" (have a high degree of similarity of results) with experience from field steam-drive projects and with laboratory physical model experiments.

3. Correlation Coefficients

Researchers who compute values of correlation coefficients (designated " r ") and discuss in a quantitative manner the significance of relationship provide useful additional information to their readers, and their presentation enables the interested reader to investigate the inter-

pretation in more depth. For example, the strength of alternative relationships or predictive models can be compared within one paper or from paper to paper. Gerbacia (7), who presents a formal statistical design for the efficient formulation of experiments to evaluate surfactant systems, includes a table showing the values of the simple linear correlation coefficients relating the dependent variables in his analysis to the independent variables. Only those pairs of variables (one dependent and one independent) for which the correlation was statistically significant are shown. (For his sample size of 15, coefficients whose absolute value is 0.50 or greater are significant at the 0.05 level.)

In their survey and analysis of data from micellar-polymer field tests, Lake and Pope (14) routinely present the correlation coefficients when comparing various variables (slug size, surfactant concentration, etc.) to recovery efficiency. They briefly define "significance" in the context of correlation coefficients and cite a statistics text as a source for additional explanation. The standard statistical test for correlation is to hypothesize that the linear correlation between two variables is zero (i.e., they are uncorrelated). When the absolute value of r is large (how large it must be depends on the sample size and the significance level chosen), the hypothesis of zero correlation is rejected and the alternative hypothesis, that the variables are correlated, is accepted.

The same micellar-polymer data are further analyzed by Holm (11). He takes exception to some of the conclusions of Lake and Pope, mainly on the grounds of certain data selected or omitted in their correlations. He suggests, for example, that more consistent or up-to-date values exist for some of the fields. Several of his points are quite convincing. In one case, however, a careful analysis of the correlation coefficients shows his argument to be less strong than it might at first appear. In considering the relationship between recovery efficiency and slug size times surfactant concentration, he proposes a correlation based only on oleic slug data which yields a correlation coefficient of $r = 0.59$ as an alternative to the use by Lake and Pope of both oleic and aqueous

slug data (correlation $r = 0.36$). Neither of these correlations turns out to be statistically significant at the 0.05 level; most of the increase in r under the Holm method is offset by the reduction in the sample size when the aqueous data are eliminated. (The probabilities of observing an r as large or larger than that reported if the variables are uncorrelated are, respectively, about 20% and 15% under the Lake and Pope and the Holm data.) Thus, in this example the explicit nature of the presentation of the correlation relationship allows the reader to pursue and evaluate the line of reasoning presented.

Another example of the value of detailed correlation information is found in the fireflood data of Chu (4). He draws attention to the very low coefficient ($r = 0.022$) measured between fuel content and water-air ratio even though laboratory experiments and projects within a specific reservoir show a strong negative correlation. He attributes the lack of significant correlation in these data to widely varying reservoir properties. An examination of the raw data, however, shows that because of missing information only thirteen out of the 39 observations in his sample had values for both fuel content and water-air ratio and that for only two of these thirteen is the water-air ratio different from zero. The failure to show a negative correlation is, therefore, more probably due to the small sample size.

C. REGRESSION

1. Background

Regression analysis is a technique for expressing one variable (the dependent variable) as a mathematical function of one or more other variables (the independent variables). A simple regression involves only one independent variable; in multiple regression the dependent variable is expressed in terms of two or more independent variables. The most common type of regression model is a least squares linear regression. Linear means that the equation relating the variables is a straight line (e.g.,

for a multiple regression with three independent variables, $y = a + b_1x_1 + b_2x_2 + b_3x_3$ where the x 's are the independent variables and the a 's and b 's are constants). Least squares means that the line chosen is that which minimizes the sum of the squares of the distances between the value of the dependent variable predicted by the equation of the line and the values actually observed for the dependent variable. A characteristic of least square regression to be borne in mind when using this technique is that outliers (observed points that are far from most of the other observations) have a strong influence upon the equation computed. Non-linear regression relationships can be obtained in many ways, for example, by including independent variables raised to a power (x_1^2 , x_2^3 , etc.) or by including products of independent variables (x_1 times x_2).

2. Statistical Tests

There are several types of statistical statements that can be made using the output of a regression analysis. Consider a simple bi-variate example, $y = a + bx$. The linear correlation between x and y can be tested as described in the previous section, by computing the t value from the correlation coefficient, r , between x and y . A related measure is r^2 ("r-squared"), also called the coefficient of determination. This value is the proportion of the total variance of y that is "explained"⁵ by the linear relationship with x . In other words, if $r^2 = .74$ then 74 percent of the uncertainty surrounding the observed y values in this sample is eliminated by a knowledge of x and the constants in the regression equation, a and b .

5. The variance of y is the sum of the squares of the distance between the individually observed y 's and their average, $\bar{y}$, divided by the number of observations. If you were asked to predict a future y value without any additional information, a good bet would be to guess $\bar{y}$. If you know the x value, however, and the equation relating x and y , a better bet would be the value lying on this line for the given x . The observed y values could still differ from this line but the variance from the line (the sum of the squares of the distances from the line divided by the number of observations) would be less than the variance from $\bar{y}$. This amount of reduction in variance (expressed as a percentage) obtained by knowing and predicting with the line is said to be the "explained" variance.

The statistical statements in the case of multiple regression are analogous to those of the bivariate example although the calculations are a bit more complex. The hypothesis that there is a multiple correlation different from zero between y and all the x 's considered at once can be tested. The "multiple r^2 " is the proportion of the total variance of y explained by the regression equation with all the x 's.

Besides testing for the existence of a non-zero correlation and measuring the reduction in variance due to the regression equation, the precision of the regression equation as a predictor can be computed. This value, called the standard error of estimate (SEE), is a measure of the expected variability in an actual y and its computed value based on the regression line. (It is the standard deviation between the actual y and the computed y .) For example, an SEE of 0.08 may be obtained. Assuming the observed y values to be normally distributed around the regression line, then a confidence statement can be made (e.g., the true value of y lies within $\pm$ one SEE of the calculated y with 68 percent confidence).

The uncertainty surrounding the coefficients in the equation, the a and the b values, can also be computed. In addition, the b coefficients can be transformed to "beta" values which are standardized values such that their magnitude indicates the relative importance of their associated x 's to the computation of the y value. (Without this transformation the size of any coefficient, b , depends in part on the units in which the x happens to be measured and is not necessarily an indicator of the importance of that x compared to other x 's in the equation. For example, an equation involving thickness measured in feet would automatically have a larger coefficient than the same equation with thickness measured in meters.)

The use of these statistical statements is discussed further as appropriate in the context of the particular article being reviewed.

3. Graphical Fits to Data

A relationship between variables need not necessarily be expressed as an equation. Gates and Ramey (6) in their article on in-situ

combustion propose a relationship between oil displaced and volume burned apparently derived by curve fitting by eye to six points (four field data points and two boundary condition points in their Figure 1).

In a more recent work, "Correlation of Gelation Times for Polymer Solutions Used as Sweep Improvement Agents" by Terry, Huang, Green, Michnick and Willhite (17), data are fitted by eye with a straight line to produce the relationship between gelation time and initial polymer concentration (for a number of constant dichromate-reducing agent concentrations). Most of the experimentally derived points lie on the lines drawn; the remaining points are very close to the lines.

4. Bivariate Regression Models

Regression equations are called "bivariate" when only two variables are considered. The dependent variable (the variable to be predicted) is expressed in terms of a single independent variable (although in some cases the independent variable appears as both a simple and a squared term). In a report on crude oil steam distillation in steam flooding, Wu and Elder (20) apply regression techniques to analyze laboratory steam distillation yields of sixteen crude oils obtained from various parts of the United States. They develop a number of different bivariate regression equations (including linear, logarithmic linear, and second order polynomial) to predict steam distillation yield for each of a range of levels of V_w/V_{oi} (volume of water over volume of initial oil). To provide a rough estimate of steam distillation yield, they recommend a second order polynomial equation with crude oil viscosity expressed as a logarithm as the best bivariate relationship. This recommendation is based on the low standard error of estimates (ranging from 2.8 percent to 4.5 percent) obtained with these equations at different V_w/V_{oi} levels.

The second choice of Wu and Elder for a yield predictor is API gravity. Their data show that the linearity of the relationship between steam distillation yield and API gravity increases with API gravity up to 33°API. Above that level the relationship changes to one of negative correlation. To accommodate this downturn in yield with increasing API

gravity, Wu and Elder tried fitting a second order polynomial in API gravity to the yield data. This regression, however, fits less well than their initial linear regression for low values of API gravity. Consequently, over the entire range the data are expressed as well by the linear as by the polynomial relationship between API gravity and yield. An alternative approach would be to treat the relationship as a discontinuous one, expressed by a line with positive slope for API gravity values less than 33°API and by a line with negative slope above that level.⁶ In this study, however, the number of observations above 33°API is insufficient for developing the second linear equation.

Yellig and Metcalfe (21) have carried out laboratory tests to develop a linear equation to predict CO₂ minimum miscibility pressures (MMP). CO₂ MMP is an important parameter for screening and selecting reservoirs for CO₂ injection projects. For highest recovery a candidate reservoir must be capable of withstanding an average reservoir pressure greater than the CO₂ MMP. Yellig and Metcalfe show CO₂ MMP as a linear function of temperature, except where the bubble point pressure of the reservoir oil is greater than the computed CO₂ MMP. In the latter case the CO₂ MMP is set equal to the bubble point pressure. They compare the efficacy of this method to two earlier proposals from the literature. On the basis of smaller residuals (the difference between the predicted and observed values of CO₂ MMP under the various methods) they recommend their approach.

6. Physically the high API gravity fluids are richer in light hydrocarbons (such as CH₄ and C₂H₆). Consequently, one might expect on physical grounds a difference in behavior between low API and high API gravity fluids when steam distillation is attempted. The process moves from lowering high viscosities by temperature rise to steam-hydrocarbon gas displacement.

Another study of the relationships of reservoir characteristics and operating conditions to oil recovery is found in Gomaa's work (8) on steamflood recovery. By using input values from a specific reservoir and the numerical steamflood simulator of K. H. Coates, W. D. George, and B. E. Marcum, Gomaa investigates via sensitivity runs the effect upon recovery of such characteristics as porosity and reservoir thickness and operating factors such as time and net heat injected. Most of the relationships are curvilinear.

5. Multivariate Models

A number of the articles discussed in this review make use of multiple regression models in which the dependent variable is a function of more than one independent variable. Lake and Pope (14), for example, present two multivariate equations for estimating recovery efficiency in micellar-polymer field tests. In one, recovery is expressed as an equation linear in mobility buffer slug size and log-linear in capillary number. In the second equation, recovery is expressed in terms of average mobility buffer polymer concentration and capillary number. Lake and Pope provide full information on the statistical significance of these equations. For example, in the first equation the hypothesis of a zero multiple correlation is stated to be rejected at the 0.001 significance level. The alternative hypothesis, a non-zero multiple correlation, is therefore, accepted. The standard error of estimate (here called the mean deviation) in recovery efficiency is 9 percent. The multiple r value is given as $r = 0.79$. A somewhat more useful number would be r^2 (0.62) which indicates that 62 percent of the variability in recovery efficiency for these observations is explained by this equation.

A parametric study of the CO_2 huf-n-puf process by Patton, Coats, and Spence (16) provides an example of a multiple regression equation with six independent variables. Data for this study were generated by a numerical simulation of the cyclic CO_2 production process. The simulator predicts incremental oil recovery as a function of nine operating and reservoir parameters. A multiple regression analysis was used to relate the efficacy (STB incremental oil/MCF CO_2 injected) of the CO_2

cyclic simulation to six of the parameters. For each of these six independent variables, both a linear and a quadratic relationship with efficacy were analyzed; however, the quadratic relationship was significant for only one of the independent variables. The overall significance of the full equation is discussed by presenting the r^2 value (which they call the coefficient of regression). The value obtained is 0.74 indicating that 74 percent of the variation in the data has been explained.

Brigham, Satman, and Soliman (2) use multiple regression techniques in an analysis of in-situ combustion field projects and pilots. They wish to predict recovery versus volume injected, and they begin with an engineering approach, combining heat balance and material balance considerations to identify the necessary parameters (independent variables) and their modes of interaction. The initial description of the relationship among the variables is augmented by using multiple linear regression to determine the effect of adding more variables. In their final formulation, recovery (the dependent variable) is adjusted to account for the fuel burned and the independent variables include cumulative air injected, oxygen utilization, net thickness of formation, oil saturation, oil viscosity, and porosity. The equation includes several multiplicative terms (products of two or more independent variables, also called "interaction terms") and one squared term. The fit of the derived equation to the data (field results) is expressed in what appears to be the standard error of estimate (it is referred to as the "standard deviation").

Chu's two papers on fireflood field projects (3 and 4) include examples of multiple regression models as well as the simple correlation coefficients discussed earlier. In one case Chu defines an indicator variable y to rate the success of a project ($y = 1$, technical and economic success; $y = 0$, technical success only; $y = -1$, unsuccessful), and then develops a multiple regression equation to express y as a continuous variable in terms of depth, porosity, permeability, thickness, viscosity, and oil saturation. The equation contains two interaction terms. Some

information on its significance is indicated by listing the multiple correlation coefficient. In (4), Chu cites three approaches for determining air requirements including a multiple linear regression equation for air requirement computed from the field data as a function of thickness, oil saturation, and permeability. The multiple correlation coefficient for this equation is 0.969 and the fit is described as "extremely good." The significance of a correlation value, however, depends as was mentioned earlier on the sample size as well as the magnitude of the correlation coefficient. In this instance, because of missing data, only seven observations figured in the calculation. The "degrees of freedom" are further lowered by the fact that there are three independent variables in the equation. Carrying out a test of the hypothesis that the multiple r is different from zero, we find that this hypothesis can be accepted only if the significance level of 25 percent (rather than the traditional 5 percent) is used.

Johnson and Pollin (13) investigate the measurement and correlation of CO_2 miscibility pressures, with added emphasis on variables besides temperature, namely the role of oil properties and composition. Using slim tube experiments they develop and test a CO_2 MMP equation that is a curvilinear function of reservoir temperature, oil gravity, oil molecular weight, and injection gas composition. As a means of comparing this method to other approaches they plot the predicted versus experimental values obtained for a sample of 30 observations. They cite the standard deviation obtained for the ratio of the predicted to the experimental values as being equal to 0.06. This can be compared to the values of 0.13, 0.27, and 0.23 computed by Yellig and Metcalfe (21) for their own and two other methods.

An imaginative application of multiple linear regression analysis is found in the work of Vinatieri and Flemming (18) on the use of pseudo-components to represent the phase behavior of surfactant systems. Noting that surfactant systems for tertiary recovery usually contain at least five components (oil, water, surfactant, cosurfactant, and electrolyte) and that the isothermal, isobaric phase diagram of these systems can be represented

in four-dimensional space, the authors propose the use of pseudocomponents to lower the dimensional space to a degree permitting physical representation of the phase diagram. To select the best set of pseudocomponents, they employ regression analysis. Any set of five pseudocomponents will contain all the information of the original components. A set limited to four pseudocomponents will lose some information but can be shown in three dimensions by a quaternary phase diagram. The "best" set of five pseudocomponents is that where the contribution of one pseudocomponent is minimized (so that it can be dropped with the least loss of information). For example, in the analysis of samples from a pilot surfactant flood, five initial components are identified: crude oil, water, isobutyl alcohol, petroleum sulfonate, and NaCl. Vinatieri and Flemming report that they used multiple regression to compute many different sets of pseudocomponents which are in each case linear combinations of these initial components. They do not give the details of this intermediate step in their model development; however, they present the results of the regression analysis for the set of pseudocomponents they found to be the "best" in the sense defined above. The resulting system is described by four pseudocomponents: aqueous, surfactant, oil, and salt. The labels of the pseudocomponents reflect the identity of the initial components that are the major constituents of the pseudocomponents.

In a similar manner, Vinatieri and Flemming apply regression techniques to reduce further the number of pseudocomponents and to construct other pseudocomponent sets having particular compositions of interest. These transformations make it easier to visualize aspects of the apparent phase behavior of the system, but, of course, to the degree that information is lost during the transformation they represent approximations to the actual system behavior.

A final example of the use of a multiple regression technique as an intermediate step in a somewhat complex analysis is found in the paper of Davis, Tyler, Brost, and Hasking, entitled "Evaluation of Surfactant EOR Potentials Using a Scaling Law Interpretation of Core Flood Residual Oil Saturation Profiles" (5). The scaling law referred to by Davis et al

is their hypothesis that surfactant flooding is (approximately) a volumetric, linearly scaleable process; in other words, a given pore volume slug of surfactant will produce the same compositions and saturation distributions in a core of any physical size and shape. This slug size relationship can then be combined with information about the reservoir and used for an initial screening of surfactant candidates.

As part of the demonstration of the volumetric linear scaling, the authors investigate by regression analysis the effect of geometric and microscopic variables on laboratory water floods and surfactant floods. An initial set of eleven physical variables was combined to produce seven "similarity groups" of dimensionless variables. A step-wise multiple regression of recovery efficiency (the dependent variable) with these dimensionless groups as the independent variables showed that only three of the groups contributed significantly to the equation explaining recovery efficiency and that none of these three represented core dimensions, aspect ratios, or shape. Furthermore, two of the groups (capillary number and viscosity ratio) represent microscopic behaviors that scale volumetrically. This observation and the small standard error of estimate for the regression equation support the hypothesis of volumetric linear scaling.

D. MULTIPLE ANALYSIS OF VARIANCE

Simple or one-way analysis of variance was mentioned earlier as a method for testing for differences in the mean value of a variable (for instance, reservoir thickness) across a number of different groups or samples (for instance, fields grouped as successful, marginal, or unsuccessful fireflood projects). A somewhat more complex technique, multiple analysis of variance, can be used when the groups are established on the basis of more than one factor. For example, Gerbacia (7) uses this approach in designing and analyzing a laboratory experiment for the study of properties influencing crude oil displacement in a micellar recovery process.

Gerbacia wishes to determine the effect of three factors -- petroleum sulfonate concentration, alcohol chain length, and alcohol-sulfonate ratio -- on a number of dependent variables related to recovery efficiency, for example, interfacial tension. The measurements of interfacial tension are assigned to a group based on their value on each of three factors. Alcohol chain length is a variable taking on only three values. The other factors, which take on values over a continuous range, are broken down into groups (in this example three levels are chosen for each factor) by an arbitrary categorization of the values. A test can then be made to see whether interfacial tension is significantly different across groups. Since there is more than one grouping factor, the importance of each (called the "simple effects") to differences in interfacial tension can be estimated. The method also facilitates the determination of the effects, if any, of interactions between the factors, e.g., whether the effect of sulfonate concentration and alcohol chain length upon interfacial tension is greater than the sum of the effects of these factors taken separately.

Gerbacia makes sophisticated use of this technique for the efficient formulation of his experiment. A variation⁷ of the standard factorial design (where the dependent variable is measured for every combination of the different levels of the factors) enables him to reduce the number of observations needed to estimate the simple and interaction effects. He then expresses the effects in terms of a quadratic equation by carrying out a step-wise multiple regression analysis. Gerbacia points out that this approach, which produces response surfaces, has been used in other fields for process optimization and characterization. A drawback of the method is that the small sample size leaves the deductions vulnerable to experimental error since each observation has a strong influence on the outcome.

7. G. E. P. Box and D. W. Behnken, "Some New Three Level Designs for the Study of Quantitative Variables," Technometrics, Vol. 2, No. 4, Nov. 1960, pp. 455-475.

E. PROBABILISTIC METHODS

1. Background

Statistical inference in general and hypothesis testing in particular are based on probabilistic concepts. Besides this role of probability in the interpretation of an analysis, however, probability can also play a part in the analysis itself. Three examples of the explicit treatment of uncertainty in the design and execution of an analysis of EOR data are reviewed here. The probabilistic techniques are: decision rules based on frequency distributions; decision trees for estimating and updating a probability distribution for enhanced oil reserves; and risk analysis of EOR pilot tests by means of Monte Carlo simulation.

2. Frequency-Based Decision Rules

In (4), Chu presents a fireflood screening procedure he has devised based on observed frequency distributions of values for a number of variables (reservoir characteristics) over successful and aborted projects. He selects as a screening variable any variable whose distribution is such that for every value beyond some breakpoint the number of occurrences for successful projects is always more (or always less) than the number of occurrences for aborted projects. For example, one such variable is the fraction of oil saturation. At all values above 0.45, the successful projects in his sample outnumber unsuccessful ones. The value 0.45 can, therefore, be used as a screening breakpoint.

An implicit assumption of this approach is that the occurrences of successful and unsuccessful projects have equal weighting. An alternative scheme is to give a different weight to the successful and unsuccessful projects since in the sample used here there are many fewer unsuccessful than successful projects. A technique that can be used to incorporate both the information on different sample sizes and the observed frequency distributions of the variable over successful and unsuccessful projects is Bayes Theorem. By following this method not only can a new project be classified as more likely to be a success or to be a failure based on the measured value of some screening variable and the

historical data on previous projects, but also the probabilities associated with the success or failure are computed. For example, using Chu's frequency profile for the reservoir characteristic "oil saturation fraction times porosity fraction" and assuming the observed value of this characteristic to be 0.10 for a new reservoir, Bayes Theorem gives a probability of 88 percent that the project will be unsuccessful and 12 percent that it will be successful.

3. Decision Diagrams and Probability Assessments

Another example of the explicit treatment of uncertainty is provided by Hasiba, Wilson, and Martinelli (10) who illustrate a method for incorporating probability judgements into the computation of enhanced recovery reserves. The authors use hypothetical data on five reservoirs and concentrate on the uncertainty surrounding the values of "oil in place" and the "recovery efficiency." Three values, a most likely, a high, and a low value, are estimated for these two variables for each reservoir. Probabilities are then assessed subjectively for each value; for example, the probability of achieving a recovery fraction of 0.40 at a particular reservoir was assessed to be 30 percent. The format of a decision tree or diagram provides a convenient way to assemble the probability assessments and to carry out computations. The probability of a particular level of reserves is a function of the probabilities of different oil in place values and recovery efficiencies. This information is summarized as a cumulative probability distribution of enhanced oil reserves, which shows the probability of enhanced reserves equal to or greater than a given level for a range of values. Using a single estimate of total costs for each reservoir and dividing by the different levels of reserves, this probability distribution over amount of reserves can be changed to a distribution over cost per barrel to produce the reserves. By comparing this cost distribution to different possible selling prices, reservoirs can be classified as economic or uneconomic.

Hasiba et al suggest a "51 percent probability of success" decision rule in designating the classification of a reservoir. In other words, if the probability that the cost per barrel is less than or equal to a given price is 51 percent or larger, then the project is economic. An alternative approach would be to compute the expected cost (mathematical expectation) per barrel from the distribution and to consider a project economic if this expected cost was less than the price. This method has the advantage of taking account not only of the probability of success but also of the amount to be gained. A corporation, for example, would be justified in considering projects with less than a 50 percent chance of success if their potential payoffs were large enough. These two approaches are equivalent when the probability distribution of the cost per barrel is symmetrical, but they can give different results for skewed distributions.

Finally, the authors combine the distributions of reserves for the different reservoirs predicted to be successful at a given price to produce a distribution for total corporate reserves.

This example illustrates a standard approach to probabilistic modeling. First, the different basic sources of uncertainty are identified. In the model each of these sources of uncertainty is acknowledged and treated to a greater or lesser degree depending on the importance of the variable and the scope of the model. The uncertainty surrounding some variables may be ignored by substituting a single, "best guess" value. Other variables may be given several representative values, without having probabilities assigned to these. For the most important variables, however, probability assessments are in order. These estimates are made by further subdividing or "decomposing" the variables of interest into manageable candidates for assessment. In this study by Hasiba et al, the desired information or output of the model is the corporation's amount of economically producible enhanced recovery reserves. The basic uncertainties are the economics (cost and price) and the amount of recoverable oil. Probability values are not assigned to cost in this case. A single best estimate of total cost is made for each project. Selling price for recovered oil is treated by the "scenario" approach, that is, by repeating

the analysis for each of three different possible price levels, without explicitly determining the likelihood of the different scenarios. The amount recoverable, on the other hand, is treated probabilistically by decomposition into recoverable amount per project and, within a project, into oil in place and recovery efficiency. Subjective probability assessments made at this detailed level are subsequently combined mathematically to obtain the probability distribution of the corporate reserves summed over all economic projects.

4. Risk Assessment

The term risk assessment is currently in common use in many fields. It generally refers to an approach to project or policy evaluation in which specific account is taken of the major uncertainties (uncontrollable factors, events, or actions) and of the possible consequences of different resolutions of these uncertainties. In its ultimate form, risk assessment requires that any uncertainty be expressed as a probability and that consequences, both monetary and non-monetary, be presented in a numerical form. The complex reservoir simulation models, familiar to EOR researchers, represent a type of risk analysis. A study of these models, however, is beyond the scope of this review. We limit our consideration to macro-level models of a few of the uncertainties.

Anderson (1) applies risk analysis to the decision on pilot testing for EOR projects. The purpose of the analysis is to estimate the economic impact of the pilot outcome (the change in the expected value of reserves, for example, and the reduction in the variability about this value) for different required rates of return on investment. Both engineering and economic estimates are systematically combined using a computerized Monte Carlo simulation technique in order to compute the economic outcome of the pilot. Repeated runs of the simulation permit the computation of an expected value of the pilot's economic outcome and a probability distribution about this value. An advantage of Anderson's method is that it includes in the economic impact the cost of the unsuccessful pilots (simulation runs where the sampled value of reserves, for example, is too low for commercialization).

Anderson illustrates the use of this technique for a hypothetical surfactant waterflooding problem. As with any risk model, an early step in the specification of the inputs is to decide which uncertainties will be treated explicitly (i.e., have probability distributions assigned) and which will be treated deterministically (i.e., given a single value). In this example amount of reserves, amount of chemicals required, price per pound, and oil price are all given probability distributions. Deterministic variables include certain costs (e.g., capital equipment), reservoir characteristics (e.g., porosity), and production plan (e.g., pattern type). The effect of changes in the deterministic variables upon the pilot's economic outcome can be tested by "sensitivity analysis." In a sensitivity analysis, the calculation is repeated holding all factors constant except the one whose effect is being investigated. The latter is varied over a range of probable values and the effect on the model outcome is noted. No explicit assignment of probability to these different values is made. A variable, however, whose variation causes large changes in the outcome is a candidate for further study and perhaps incorporation into the probabilistic part of the model.

Another use of the risk analysis approach to evaluating recovery projects is found in Williams, Brown, and Ramey (19b). In this mathematical model for appraising thermal drive projects, probability assessments are made for the economic parameters, for example, price per barrel of oil, operating cost per unit of oil production, and well intangible costs. Assumptions as to the type of probability distributions involved and their statistical independence simplify the calculations; the uncertainties can be combined analytically without the need for Monte Carlo simulation techniques. The output of this model is a discounted net present value of the cash flow of the project for various technical and economic scenarios. This discounted net present worth is then graphed against the injection rate of steam or compressed air in order to obtain an optimal injection rate.

CHAPTER IV

ADVANCES AND TRENDS

This review of the use of statistical techniques in the analysis of EOR data over the past ten years shows:

- (1) A trend toward the use of more complicated and advanced techniques,
- (2) An increasingly sophisticated application of traditional techniques,
- (3) Application of these techniques to problems in
 - (a) thermal processes
 - (b) miscible processes
 - (c) micellar-polymer floods,
- (4) Application to laboratory, field, and simulation data, and
- (5) Statistical analysis of both engineering and economic data.

A general tendency toward a more quantitative description of the results using specific statistical tests is observed. For example, rather than saying that two variables "correlate well" researchers now tend to give the numerical value of the correlation coefficient and in some cases to carry out the statistical test showing the level of significance for which the observed correlation can be judged to be different from zero. In looking at relationships among variables, there is a tendency to move from simple bivariate models where one variable is shown as a function of a single other variable to multiple variate models, both linear and non-linear. In line with this tendency to look for more subtle relationships among variables is the use of variable transformations and the investigation of interactions among variables.

There are a number of notable examples of the use of more advanced techniques in the analysis of EOR data. One such technique, Monte Carlo simulation, takes into account explicitly the uncertainty surrounding the value of some of the parameters. The use of probabilistic techniques has led some researchers to incorporate subjective probability assessments

in their analyses. Such assessments are a way of providing probabilistic inputs to a model on variables for which historical frequency data are not readily available. The pitfalls of subjective probability assessment have been widely studied in research in other fields. Elicitation techniques have been developed to minimize assessor bias.⁸ In addition to the willingness to combine subjective and objective probability assessments in a single model, this review also shows an increase in the development of decision models which combine economic and engineering factors.

To make the best use of statistical analysis, it is necessary to consider in the beginning or early stages of a study the type of statistical analysis that will be applied to the data obtained. Such statistical planning includes, for example, deciding upon the hypotheses that will be tested in order to ensure that the required data are collected. In extreme cases, the statistical techniques may drive the entire analysis. In such a case, we speak of the statistical techniques providing the experimental design. In Gerbacia's study (7), for example, the desire to study the simple and interaction effects of certain independent variables upon a dependent variable (and to gain information for this study in the most economical fashion) determined the selection of the analysis of variance design. This, in turn, determined the variable values at which measurements would be taken.

In addition to the tendency toward the use of more advanced and complicated statistical techniques, the review showed an increasing sophistication in the application of all techniques. An example of this sophistication is the inclusion of a discussion of the rationale for using different techniques in the research report. Such a discussion might include a statement of the underlying assumption about the independence of

8. Morgan, M. G., Henrion, M. and Morris, S. C., "Expert Judgments for Policy Analysis," Brookhaven National Laboratory Publication BNL51358 UC13 (General, Misc., and Progress Report (Nonnuclear) TIC4500).

the observations or the probability distributions of variables being estimated. In reporting on the analysis, researchers call attention to surprising results and, while giving their own explanations, alert the readers to the need for considering alternative explanations. An example of such a consideration of surprising data would be the inclusion of a discussion of "outliers" in a regression analysis.

In addition to describing the underlying assumptions of a technique and identifying any surprising results, some researchers help the readers by describing negative results, that is, by discussing what parts of the analysis failed to show significant effects. For example, they may discuss variable transformations that failed to yield an improvement in the establishment of linear relationships. Finally, the conscientious researcher recognizes and discusses the extent to which reported results can be generalized. Such a discussion may include highlighting the underlying assumptions about the distributions of variables and specifying the ranges of variable values from which the model has been developed and over which it can reasonably be extended.

APPENDIX A
STATISTICAL TEXTS AND GLOSSARY OF STATISTICAL TERMS

A. STATISTICAL TEXTS

Many researchers find that referring to more than one statistical text book is an effective way to review statistical concepts and the details of applying statistical techniques. The following list of selected texts presents the authors' recommendations of additional statistical sources. Many of the texts listed have been widely and successfully used in college courses on statistics. Along with these classic works we include some newer publications whose clarity of presentation will appeal to some readers.

1. Specialized Books

Stanley, L. T., Practical Statistics for Petroleum Engineers. Tulsa, OK: The Petroleum Publishing Co., 1973.

Grayson, C. J., Jr., Decisions Under Uncertainty: Drilling Decisions by Oil and Gas Operators. Norwood, MA: The Plimpton Press, 1960.

Nie, N. H., Hull, C. H., Jenkins, J. G., Steinbrenner, K., and Bent, D. N., SPSS: Statistical Package for the Social Sciences. New York: McGraw-Hill, 1975. (Documentation for computer programs).

2. General Statistical Texts (Introductory)

Cochran, W. G., Sampling Techniques, 3rd ed. New York: Wiley, 1977.

Cochran, W. G., and G. M. Cox, Experimental Designs, 2nd ed. New York: Wiley, 1957.

Cox, D. R., Planning of Experiments. New York: Wiley, 1958.

Freund, J. E., Mathematical Statistics, 3rd ed. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1980.

Hodges, J. L., Jr. and E. L. Lehmann, Basic Concepts of Probability and Statistics, 2nd ed. Holden-Day, Inc., San Francisco, 1970.

Hoel, Paul G., Elementary Statistics, 4th ed. John Wiley and Sons, Inc., NY, 1976.

Khazanie, Ramakant, Elementary Statistics, 2nd ed. Holden-Day, Inc., San Francisco, 1970.

Kreyszig, E., Introductory Mathematical Statistics. Principles and Methods. New York: Wiley, 1970.

McClave, James T. and Frank H. Dietrick, II, Statistics. Dillen Publishing Co., San Francisco, 1979.

Mendenhall, W., Introduction to Probability and Statistics, 5th ed. Wadsworth Publishing Co., Inc., Belmont, CA, 1979.

Mosteller, F., R. E. K. Rourke, and G. B. Thomas, Jr., Probability with Statistical Applications. Addison-Wesley Publishing Co., Inc., Reading, MA, 1961.

Scheffe, H., The Analysis of Variance, 2nd ed. New York: Wiley, 1963.

Spiegel, Murray R., Schaum's Outline Series: Theory and Problems of Statistics. McGraw-Hill Book Co., NY, 1961.

Steel, Robert G. D. and James H. Torne, Principles and Procedures of Statistics: A Biometrical Approach, 2nd ed. McGraw-Hill Book Company, NY, 1980.

Walpole, Ronald E., Introduction to Statistics, 3rd ed. Macmillan Publishing Co., Inc., NY, 1977.

Wonnacott, T. H. and R. J. Wonnacott, Introductory Statistics, 2nd ed. John Wiley and Sons, Inc., NY, 1972.

3. Advanced Statistical Texts

Cramer, H., Mathematical Methods of Statistics. Princeton Univ. Press, Princeton, NJ, 1964.

DeGroot, Morris H., Probability and Statistics. Addison-Wesley Publishing Co., Reading, MA, 1975.

Feller, W., An Introduction to Probability and Its Applications, Vol I, 3rd ed. New York, Wiley, 1968.

Graybill, F. A., An Introduction to Linear Statistical Models, Vol I, McGraw-Hill Book Company, NY, 1961.

Hogg, Robert V. and Allen T. Craig, Introduction to Mathematical Statistics, 4th ed. Macmillan Publishing Co., Inc., NY, 1978.

Lindgren, Bernard W., Statistical Theory, 3rd ed. Macmillan Publishing Co., Inc., NY, 1976.

Parzen, E., Modern Probability Theory and Its Applications. New York: Wiley, 1960.

Wilks, S. S., Mathematical Statistics. John Wiley and Sons, Inc., NY, 1962.

B. GLOSSARY OF STATISTICAL TERMS

These definitions are designed as reminders rather than to provide full explanations of statistical concepts or tools. For more details, text books of the type cited in Part I.B. above should be consulted.

averages. See mean, median, and mode.

Bayes Theorem - A useful formula for up-dating a probability value on the basis of additional (sample) data. Specifically, an initial Prob (x) becomes

$$\text{Prob (x|data)} = \frac{\text{Prob (data|x) Prob (x)}}{\text{Prob (data|x) Prob(x) + Prob (data|\neg x) Prob (\neg x)}}$$

Where

$\neg x$ signifies "not x" and Prob (a|b) means probability of a given b.

beta weights - Standardized regression coefficients. Computed by multiplying the ordinary regression coefficients of x_j by the standard deviation of x divided by the standard deviation of y, the dependent variable. Equivalent to computing the regression coefficient b for x and y variables standardized to have unit variance (variance = 1.00). The latter standardization is accomplished by transformations in which every

x_i is divided by the standard deviation of x and every y_i is divided by the standard deviation of y .

bivariate - a relationship involving two variables, e.g., a simple linear regression equation.

confidence interval - when estimating a value based on sample information, for example a coefficient b_1 in a regression equation, limits on the uncertainty surrounding the estimate can be established if certain assumptions are made. For instance, we may compute that with probability 0.95 the true value of b_1 falls within some range of its estimate. This is called the 95 percent confidence interval for b_1 .

correlation - a linear relationship. The correlation coefficient measures the strength of the linear relationship between two variables on a scale from -1.0 to + 1.0.

decision tree, decision diagram - a procedure for specifying and evaluating complex decision situations where several decisions are taken in sequence and where the later decisions may depend upon earlier decisions and upon the outcome of uncontrollable intervening events. The decision tree shows the flow over time of possible decision choices and event outcomes. It facilitates the incorporation into the decision of probabilities, costs, and benefits occurring at different points in time.

degrees of freedom - a parameter needed when carrying out hypothesis tests using certain statistics (e.g., t-tests and F-tests) and related to the number of observations and variables. The procedure for computing degrees of freedom is given in statistics texts in the explanations of the tests.

dependent variable - in a regression analysis or an analysis of variance, the variable being studied whose value is thought to be predictable to

some degree by considering other variables called the independent variables.

F statistic - a statistic whose distribution, like that of the t-statistic, is well known and tabulated. It is particularly useful for hypothesis tests involving variances.

factorial design - in an analysis of variance where the effect upon a variable of interest (dependent variable) of more than one classification variable (factor) is to be measured, the method of setting up the experiment or measurements to insure that all combinations of all levels of all factors will be considered. For example, if the effect upon oil displaced of 3 different surfactants and 2 different injection methods were studied, the factorial design would require an oil displacement measurement for each combination of surfactant and injection method, six in all.

frequency distributions - the sorting or grouping of sample values or observations into categories according to their size. Some categories may have many observations. For example, the frequency distribution of household incomes in a town grouped by \$5000 intervals would have many observations in the \$15,000-\$20,000 category. When displayed graphically the frequency distribution is called a histogram.

homogeneity of variances (also called "homoscedasticity") - the term used to mean that the population variances of two (or more) variables are equal. Because of sampling effects, two populations may have equal variances even though the variances computed for samples drawn from the populations differ somewhat.

hypothesis - a statement about a population of variables to be evaluated on the basis of sample data.

independent variables - in a regression analysis or an analysis of variance, the variable or variables which are used to predict another variable known as the dependent variable.

inference - the activity of making judgments (evaluating hypotheses) about populations of variables on the basis of statistics drawn from samples of the variables.

interaction - in a regression equation, the terms which contain more than one of the independent variables. For example, in the equation,

$$y = a + b_1x_1 + b_2x_2 + b_3x_1x_2$$

the fourth term, $b_3x_1x_2$, is an interaction term. Its inclusion in the equation suggests that the effect upon y of x_1 and x_2 is more than the sum of the effects of these two independent variables taken separately (the second and third terms in the equation).

interaction effects - in an analysis of variance, the effect upon some variable of interest (the dependent variable) of changes in other variables (independent or classification variables) taken in combination, two or more at a time.

level of significance - a value, usually chosen to be 0.05 or 0.01, for use in hypothesis testing. A hypothesis is rejected if the probability of occurrence for the statistic of interest (given that the hypothesis is true) is less than the significance level. For example, using a t test we can show that for a sample size of 15, a correlation coefficient (r) of 0.50 or greater is significant at the 0.05 level.

mean - the most commonly used average. It is computed by adding up the values of all the observation and dividing by the number of observations. Also called the expected value when referring to a population.

median - the middle value in a set of observations. Half of the observations have lower values, half have higher values. The 50th percentile.

mode - the most frequently observed value in a set of observations.

Monte Carlo simulation - a procedure for determining the long run average or "expected" behavior of a system involving many uncertain and (possibly) interacting variables. Repeated trials or runs through the system are made with the variable values each time established by chance from probability distributions describing their uncertainty. The total effect of system outcome is noted each time and then these values averaged over all the trials to obtain the expected outcome. Also used for determining probabilities.

multiple R^2 - in a multiple linear regression analysis, the percentage of the total variation in y that is attributable to ("explained by") the regression equation. Its equation is

$$R^2 = \sum (y_{\text{observed}} - \bar{y})^2 / \sum (y_{\text{computed}} - \bar{y})^2$$

where $\bar{y}$ is the mean value of y and the summations are over all the observations.

multivariate - a technique involving more than one independent variable. The terms multivariate regression analysis and multiple regression analysis are used interchangeably.

normally distributed - a variable whose values in the population follow the normal or gaussian distribution. This bell-shaped probability distribution curve has the formula:

$$f(x) = (1/\sigma\sqrt{2\pi}) \exp^{-(1/2)} ((x-\mu)/\sigma)^2$$

where σ is the standard deviation of x and μ is the mean of x.

outlier - an unusually high or low value in a set of observations.

pair-wise differences - differences between variables considered two at a time, for example, the means of two variables.

probability assessments - determining the probability values of discrete events or the probability distributions of continuous variables by quantifying the subjective judgments of experts. A method for assessing probability distributions, for example, is to ask experts to estimate the median value of the distribution and the 0.01, 0.25, 0.75 and 0.99 percentiles. A smooth curve is fit to these points to approximate the whole distribution.

probability elicitation (see probability assessment)

quadratic - an expression in which the highest power to which a variable is raised is 2. For example,

$$y = a + b_1 x + b_2 x^2$$

is a quadratic equation.

residual - the difference between the observed value of a dependent variable and the value obtained as an estimate for that variable using a regression equation containing one or more independent variables. Examining the residuals is useful in evaluating a regression equation. For example, if the residuals compared to the values of one of the independent variables are small for most of the range of the independent variable and then suddenly become large, it is an indication that the equation should be applied only over a limited range.

sensitivity runs - repeated calculations of the output of a model while varying the inputs (usually one variable at a time).

simple effects - in an analysis of variance, the effect upon some variable of interest (the dependent variable) of changes in other variables (independent or classification variables) taken one at a time.

standard deviation - a measure of the amount of scatter or dispersion in a sample of measurements. The standard deviation is the positive square root of the variance.

$$s.d. = \sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 / (n-1)}$$

where x_i are the observed sample measurements, n is the number of observations and $\bar{x}$ is their mean value.

standard error of estimate (SEE) - in a regression analysis, the standard deviation of the actual y_i (observed) from the computed (predicted) values of y , the dependent variable. The equation is

$$SEE = \sqrt{\sum (y_{\text{computed}} - y_{\text{actual}})^2 / (n-2)}$$

where n is the number of observations.

standardized values - a useful transformation of variable values. For example, variables standardized to have a mean value of zero are obtained by subtracting from all observations in the sample the sample mean. Similarly variables can be standardized to have a variance equal to 1.0 (called "a unit variance") by dividing every observation by the sample standard deviation.

step-wise multiple regression - a method of selecting the order in which independent variables will be entered into a least-squares, linear regression equation. The dependent variable is expressed first as a function of one independent variable, then as a function of that independent

variable and one other independent variable, and so on until all independent variables appear in the equation. The criterion for selection of the variable to be added at each step is that variable whose inclusion in the estimating equation causes the greatest reduction in the sum of squares of the difference between the observed and estimated values of the dependent variable.

student's t statistic - a statistic whose distribution is known and tabulated. Its value can be computed and used in a wide variety of hypothesis tests, including tests about means, and regressions.

transformation - the conversion of data to a more manageable form by means of a mathematical operation. For example, taking the logarithm of each observation to get a more linear expression for data that have a wide range and curvilinear shape.

variance - a measure of the dispersion or scatter in a set of observations. The standard deviation is the square root of the variance.

$$\text{variance} = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}$$

where x_i are the observations, $\bar{x}$ is their mean value, and n is the number of observations.

z statistic - for large samples (more than 25 observations) this statistic can be used in testing for the difference between two means. It is more powerful than the student's t statistic.

APPENDIX B
BIBLIOGRAPHY WITH ABSTRACTS

1. ANDERSON, M. L., "Application of Risk Analysis to Enhanced Recovery Pilot Testing Decisions," J. Pet. Tech. (December, 1979), pp. 1525-1530, 9 References.

ABSTRACT

Increasing U.S. dependence on high-priced imported oil has focused attention on maximizing recovery from existing oil fields. Recovery methods that were previously uneconomical now can be justified in many cases. These advanced recovery techniques usually follow reservoir exploitation by primary and secondary waterflooding or pressure maintenance methods. Consequently, they have been called tertiary recovery, but more recently the term enhanced oil recovery (EOR) has come into use.

Examples of EOR processes include surfactant or low-tension waterflooding, generally used in light-oil reservoirs, and thermal methods such as steam flooding or in-situ combustion, generally used in heavy-oil reservoirs. One common characteristic of EOR processes is the requirement for high front-end investment. For chemical waterflooding processes, if the project is a failure for any reason, the investment in chemicals is lost completely and surface facilities value is reduced substantially.

Prospective EOR projects are preceded by a pilot test to reduce risk of commercial failure and consequent investment loss. This is not the only reason for conducting pilot tests. Pilot test results also are needed to provide information for design of the commercial operation.

Industry, with and without U.S. DOE support, currently is conducting a number of EOR pilots, and more will be started in future years. Many tests are described in the literature. Government and industry have a common interest in maximizing the number of pilots that are successful by selecting the best EOR process for reservoirs with the highest profit potential. This paper shows how this goal can be accomplished by applying risk analysis prior to pilot test initiation. It also describes a risk analysis algorithm and illustrates its application with a hypothetical example involving a decision to pilot test a surfactant waterflooding process. Risk analysis results are compared with a conventional economic sensitivity analysis. As will be demonstrated, an important risk analysis output is an unbiased estimate of probability of success of the pilot test that, along with the economic results, can provide the basis for project selection and scheduling. Finally, conclusions are drawn on the merits of risk analysis for aiding pilot test decision-making.

2. BRIGHAM, W. E., SATMAN, A. and SOLIMAN, M. Y., "Recovery Correlations for In-Situ Combustion Field Projects and Application to Combustion Pilots," J. Pet. Tech. (December, 1980), pp. 2132-2138, 9 References.

ABSTRACT

During the last three decades, the injection of heat-bearing fluid into a reservoir has gained considerable usage as an enhanced oil recovery mechanism. Crude oils with low API gravity and high viscosity do not respond satisfactorily to conventional recovery processes. Since oil viscosity is highly temperature dependent, the performance of these reservoirs can be improved significantly by raising the reservoir temperature through the addition of heat. In-situ combustion is one of the processes that can increase oil recovery through heat addition.

Oil recovery predictions for in-situ combustion projects would provide a basis for calculating air-injected/oil-produced ratios (AOR's), oil rates, oil recovery, and economic limits. There is a possibility that such predictions could be achieved by describing the movement of heat and fluids analytically, and such approaches have been tried; however, no analytic model has been developed that completely describes the movement of heat and fluids.

Numerical modeling has been an alternative way of describing in-situ combustion; however, due to the complexities of the process, the multidimensional geometry, and the cost of running the more complex models, no approach to recovery prediction has been entirely satisfactory.

It appeared that the solution to this dilemma was to attempt to correlate field results. Our approach was to base our correlating parameters primarily on those terms that occur in heat and material balances of combustion and only then to add additional variables on a purely statistical correlation basis. Although some screening guides in the literature attempt to define which projects may be successes or failures, these guides make only a yes/no evaluation or apply only to certain fields. Therefore, there is a clear need to develop a simple model to predict the oil recovery to be expected from in-situ combustion.

3. CHU, C., "A Study on Fireflood Field Projects," paper SPE 5821 prepared for SPE-AIME Symposium on Improved Methods for Oil Recovery, Tulsa, Okla., March 22-24, 1976, pp. 321-332, 60 References.

ABSTRACT

For the recovery of medium- to high-viscosity crudes, the fireflood process and its variations have been practiced in a wider geographical area than steam stimulation and steamflood. This study reviews more than 40 domestic and foreign firefloods, develops equations relating fireflood performance to reservoir properties, and establishes criteria for screening prospects for the application of the fireflood process.

Regression equations developed in this study will allow the prediction of fuel content and air-oil ratio for a fireflood with known information on porosity, oil saturation and other properties.

Two different approaches have been used to establish screening guides for firefloods. The first approach compares the reservoir and crude properties in successful firefloods with those in unsuccessful firefloods and determines which of these properties form statistically significant bases for differentiating successes from failures. The resulting screening guide states that a reservoir is a good fireflood prospect if it has porosity of 22% or greater, oil saturation 50% or higher, oil content greater than 1000 Bbl/AF, API gravity of 24° or less, and viscosity less than 1000 centipoise. The criterion on maximum viscosity is based on the consideration that steamflood is preferable to fireflood for very high viscosity crudes. The second approach defines a variable y to serve as a measure of project success and failure. The variable ranges from a value of -1 denoting an unsuccessful project to +1 which represents total success. An equation was developed by regression analysis to express this variable y as a function of reservoir and crude properties. The screen guide resulting from this approach stipulates that to ensure economic success, the composite variable y should be greater than 0.27 and viscosity again should be less than 1000 cp. These two screening guides have been applied to 39 firefloods and should be useful for pointing out reservoirs that show promise to be economic successes.

4. CHU, C., "State-of-the-Art Review of Fireflood Field Projects," paper SPE/DOE 9772 presented at the SPE/DOE 1981 Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Okla., April 5-8, 1981, pp. 29-37, 76 References.

ABSTRACT

This paper embodies a state-of-the-art review of fireflood field projects. Based on reservoir data on 25 selected successful fireflood projects and 9 aborted projects, a new screening guide has been developed for firefloods. A new regression equation was also developed which will allow prediction of air requirements with known reservoir characteristics. Methods of predicting other performance variables such as fuel content, sweep efficiency, oil recovery and air-oil ratio are discussed. Industry experience on project design is reviewed in regard to the choice between dry and wet combustion and determination of pattern type and size, air injection rate, water-air ratio and completion intervals. Special well completions needed for fireflood are reviewed as well as the various ignition methods. Operational problems plaguing the fireflood projects, which include poor injectivity or productivity, corrosion, erosion, emulsion and explosion hazards, are discussed along with their remedies.

5. DAVIS, Jr., L. A., TYLER, T. N., DALE, F. B., HASKING, H. K., "Evaluation of Surfactant EOR Potentials Using a Scaling Law Interpretation of Core Flood Residual Oil Saturation Profiles," Paper SPE/DOE 9780 presented at the 1981 SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Okla., April 5-8, 1981, pp. 123-128, 15 References.

ABSTRACT

The screening of surfactant candidates for a given reservoir can be improved by using linear core flood residual oil saturation profiles measured along the core after chemical flooding. A surfactant formulation's functional relation of oil recovery with slug size can be calculated from a single core flood with the assumption of a relaxed scaling law. This slug size relation can then be combined with knowledge of the reservoir to provide an improved means of initially screening surfactant candidates.

A volumetric linear scaling approach is developed from laboratory core flood data. Residual oil saturation profiles measured in reservoir material with a microwave absorption instrument support this approximate scaling relation. A statistical analysis of 32 linear core flood water floods and surfactant slug floods is presented as additional verification. The limits of this scaling law are defined, with emphasis on the role of mixing and dispersion.

The procedure for using saturation profiles to calculate oil recovery as a function of slug size is developed and a test case presented. A recovery relation derived from a single core flood saturation profile is compared with that determined by multiple conventional core floods.

As an example, a recovery versus slug size relation is assumed for a layered linear flood. High core flood oil recovery at one volume throughput is shown to be an insufficient criterion for surfactant system selection. The flow distribution of surfactant and the entire oil recovery versus slug size relation can be dominant factors in the overall performance. The use of saturation profiles is a more efficient means of obtaining the recovery relations and allows introduction of reservoir flow distribution properties as an integral part of the initial surfactant screening process.

6. GATES, C. F. and RAMEY, Jr., H. J., "Engineering of In-Situ Combustion Oil Recovery Projects," paper SPE 7149 presented at SPE-AIME 1978 California Regional Meeting, San Francisco, California, April 12-14, 1978, pp. 1-7, 13 References.

ABSTRACT

The oil recovery-volume burned method of making engineering calculations for in-situ combustion projects provides a means for calculating air-oil ratios, oil rates as a function of oil recovery and economic limits. The results match both laboratory and field data better than frontal displacement calculations, which assume constant air-oil ratio. During the early life of in-situ combustion projects, the air-oil ratio may be much less than indicated by frontal displacement calculations, because of oil recovery from unburned sands adjacent to the burned sand. As a consequence, air compression costs per barrel would be much less, as indicated by the oil recovery-volume burned method. Initial oil rates depend upon the initial oil and gas saturation. Maximum profit from in-situ combustion may be realized by early application in the life of a reservoir. Results of oil recovery-volume burned calculations have correlated well with field applications of the in-situ combustion process.

7. GERBACIA, W., "The Evaluation of Surfactant Systems for Oil Recovery Using Statistical Design Principles and Analysis," paper SPE 7070 presented at the SPE-AIME Fifth Symposium on Improved Methods for Oil Recovery, Tulsa, Okla., April 16-19, 1978, pp. 345-351, 23 References.

ABSTRACT

A statistical response surface design procedure was used to investigate the effect of petroleum sulfonate concentration, alcohol chain length, and the alcohol-sulfonate ratio on salt tolerance, conductivity, viscosity, interfacial tension, and oil recovery properties of aqueous surfactant solutions. This procedure greatly reduced the number of data points which were required to develop significant correlations.

Regression analysis of the data showed that calcium tolerance was chiefly dependent on sulfonate concentration, and to a smaller extent, on the alcohol chain length, and specific conductance and sulfonate concentration. Viscosity was found to increase with the hydrocarbon chain length of the alcohol and the ratio of alcohol to sulfonate. The interfacial tension was dependent only on the sulfonate concentration within the limits of the variables studied. None of the surfactants produced very low interfacial tensions (10^{-2} dyne/cm) with the crude oil used in the investigation, nor were high displacement efficiencies observed.

8. GOMAA, E. E., "Correlations for Predicting Oil Recovery by Steamflood," Soc. Pet. Eng. J. (February, 1980) pp. 325-332, 11 References.

ABSTRACT

Heavy-oil properties that classify as candidates for steamflooding often need to be screened for priority ranking due to budget, manpower, development, and permitting limitations. Also, sensitivity studies often are run on steamflood projects to determine the effects of various operating strategies on project performance and economic feasibility. Steamflood performance predictions required in such screening and sensitivity studies certainly can be made using one or more of the analytical and empirical models available in the literature. Numerical reservoir models that simulate the process of steamflooding also can be used to make the required predictions. While these analytical and/or numerical models could suffice, they generally require somewhat lengthy computations and necessitate the use of a computer.

There is a need for a simplified easy-to-use method for predicting steamflood performance. This paper describes the development of such a method and its basis, procedures, and limitations of applicability.

9. GOODRICH, John H., "Review and Analysis of Past and Ongoing Carbon Dioxide Injection Field Tests," paper SPE 8832, presented at the First Joint SPE-DPE Symposium on Improved Oil Recovery, Tulsa, Okla., April 20-23, 1980, pp. 221-228, 53 References.

ABSTRACT

Under a contract with the U.S. Department of Energy, Gruy Federal, Inc. has prepared comprehensive review reports for 19 projects in 16 fields in which carbon dioxide miscible injection was used to enhance oil recovery. Information from the geological and engineering literature, raw data from public records, and limited information supplied by project operators allowed nonproprietary review and analysis of seven full-scale (i.e., commercial intent) field projects and 12 pilot projects. Abbreviated summaries of the field reviews for the full-scale projects are presented in this paper. Analysis and synthesis of the data and information from the field projects is also related to published CO₂ flooding technology.

These data indicate that injection of CO₂ is a technically efficient enhanced oil recovery process over a wide range of geologic and reservoir conditions. Hence, published technical guidelines for judging applicability of CO₂ injection are probably too restrictive.

10. HASIBA, H. H., WILSON, Jr., L. A. and MARTINELLI, J. W., "How to Organize and Plan Enhanced Recovery Efforts," World Oil (January 1977), pp. 91-95.

ABSTRACT

Method adds probability to engineering data on reserves, recovery, expected costs and oil prices in a wrap-up of company's enhanced recovery prospects. Listing of projects, expected reserves and probabilities for success lets planners make best possible decisions.

11. HOLM, L., W., "Status of Micellar-Polymer Field Tests - Another View -," Petroleum Engineer International, (April, 1980), pp. 100-116, 13 References.

ABSTRACT

Petroleum Engineer International published an article in its November 1979 issue (p. 38) by Larry Lake and Gary Pope, University of Texas, which analyzed results of micellar-polymer field tests. Although the authors were careful to point out the limited number of tests conducted, the incompleteness of some tests, and the viscous instability of some floods, they used standard statistical techniques such as least-square line-fitting, correlation coefficients and confidence levels to analyze the data.

I have serious concern about some of the conclusions and implications of this study and the way in which the conclusions were derived. Several were based upon the authors' selection of certain field tests and certain data from those field tests to obtain correlations. Some of the data were from incomplete field tests. Also, correlations were obtained using data from two cases not presented on a consistent basis.

12. HOLM, L. W. and JOSENDAL, V. A., "Mechanisms of Oil Displacement by Carbon Dioxide," paper SPE 4736 prepared for the SPE-AIME Improved Oil Recovery Symposium, Tulsa, Okla., April 22-24, 1974, pp. 15-22, 17 References.

ABSTRACT

CO₂ can enhance the recovery of oil from porous rock by 1) solution gas drive, 2) swelling oil and reducing its viscosity and 3) miscible effects.

The most efficient use of carbon dioxide as an oil recovery agent is obtained at flooding pressures where miscible type displacement is achieved. The extraction of hydrocarbons (C₃ to C₃₀) from the crude oil in place by CO₂ at these pressures promotes a displacement efficiency which approaches 100%. This high displacement efficiency can be obtained at flooding temperatures below about 200°F and pressures below 3000 PSI with any crude oil containing appreciable hydrocarbons in the gasoline-light gas-oil range. Also, the process is applicable to water flooded reservoirs which have been depleted of their gas and LPG components. The presence of methane in the injected CO₂ or in the reservoir oil reduced the overall recovery efficiency of the displacement process.

A simple correlation is presented to determine the optimum displacement pressure for CO₂ floods. Information presented on the size and composition of the CO₂-hydrocarbon transition zone during a CO₂ flood shows how the selection of this pressure may be adjusted to obtain improved conformance of the flood.

13. JOHNSON, J. P. and POLLIN, J. S., "Measurement and Correlation of CO₂ Miscibility Pressures," Paper SPE/DOE 9790 presented at the 1981 SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Okla., April 5-8, 1981, pp. 269-274, 22 References.

ABSTRACT

At sufficiently high injection pressures, non-hydrocarbon gases become miscible with crude oil and are capable of displacing petroleum fluids from a porous rock matrix with high efficiency. This report details the experimental methods used to determine CO₂ minimum dynamic miscibility pressures (MDMP) and describes the relationship between the onset of miscible fluid flow and static-cell PVT behavior.

An accurate empirical correlation will be presented which predicts the MDMP for a wide variety of live oils and stock oils with pure and diluted CO₂. This correlation, requiring only the oil gravity, molecular weight, reservoir temperature and injection gas composition, shows substantially better agreement with experiment than methods previously published. To the extent that the MDMP represents an optimum field operating pressure during tertiary oil recovery processes, the correlation can be used for rapid estimation of injection gas costs.

14. LAKE, L. W. and POPE, G. A., "Status of Micellar-Polymer Field Tests," Petroleum Engineer International (November, 1979), pp. 38-60, 92 References.

ABSTRACT

There are 44 planned, current and completed micellar-polymer field tests reported in the literature. The tests range in size from 0.625 acres (Louden) up to 407 acres (Marathon's M-1) with several of the larger projects being labeled by their operators as demonstration projects rather than tests. The study shows strong correlations between recovery and mobility buffer size and the ratio of viscous to capillary forces. Poor correlations are noted with surfactant slug size.

In this article we assume familiarity with the basic objective of micellar-polymer flooding - to mobilize trapped oil by lowering interfacial forces. This is accomplished by injecting an interfacially active surfactant slug driven successively by a mobility control agent (polymer-thickened water) and then by chase water. Readers interested in more technical details are referred to the preceding article by Poettmann and Hause.

A micellar-polymer test is any project which injects surfactants to produce oil. This definition encompasses tests (Borregos, for example) which did not use a mobility control agent, but omits tests, such as West Ranch or the various Marathon minitests, which did not have a producer. The rationale for this is that the survey will be more complete if it is restricted to producing tests, as there are several minitests that have not been reported in the literature. This survey is based entirely on public literature sources.

15. MYHILL, N. A., and STEGEMEIER, G. L., "Steam-Drive Correlation and Prediction," J. Pet. Tech. (February, 1978), pp. 173-182, 19 References.

ABSTRACT

During the past 15 years, steam-injection processes have become an important means of exploiting heavy oil reserves. Traditionally, these processes have been classified as either steam soaks or steam drives. With combinations, such as pre-soaking drive wells and partially driving steam soaks, the distinction is not always applicable. Furthermore, our experience suggests that oil/steam ratios from most mature processes converge to a value determined only by reservoir and steam properties and time.

To date, the steam-soak process has proven the more attractive, partly because the immediate response allows an early evaluation of a reservoir and partly because oil rates from initial soak cycles tend to be better than later cycles. Successful steam soaks are limited to reservoirs where natural recovery mechanisms (gravity drainage, pressure depletion, and solution gas drive) are ineffective because of the low oil mobilities.

Successful steam drives require (1) good conformance, (2) a means of starting the process because high oil saturations can limit injectivity severely and prevent effective initial reservoir heating, and (3) sustained high injectivity throughout the process life. Unlike steam soaks, steam drives do not respond until built-up oil banks and heat reach the production wells. Because peak production rates may not be observed for several years after the start of injection, piloting is expensive and expansion to full scale is somewhat hazardous. For these reasons, screening methods that predict ultimate oil/steam ratio are useful in planning new projects or in modifying existing ones.

In the past, steam injection has been applied to a wide spectrum of reservoir conditions, many of which have proven unsuitable. In retrospect, we can explain the varied response with a simple mathematical model that incorporates reservoir and steam properties in the prediction. This paper describes the model and compares predictions from it with laboratory and field results.

16. PATTON, J. T., COATS, K. H. and SPENCE, K., "A Parametric Study of the CO₂ HUF-n-PUF Process," paper SPE 9228 presented at the SPE-AIME 54th Annual Fall Technical Conference & Exhibition, Las Vegas, Nevada, September 23-26, 1979, pp. 2-5, 10 References.

ABSTRACT

Cyclic CO₂ stimulation of a production well, especially in viscous oil reservoirs, is developing as a method of rapidly producing tertiary oil and obtaining valuable data. History matching provides confirmation of CO₂ - crude interactions, measured in the laboratory, that can increase the accuracy of CO₂ flood predications.

Profitability of the process is enhanced by proper control of key operating parameters. The most important are:

- (a) CO₂ injected per cycle
- (b) number of cycles
- (c) back pressure during projection

Reservoir parameters dictate the selection of commercial applications. The dominant factors are:

- (a) viscosity of the oil
- (b) oil swelling and viscosity reduction due to CO₂ dissolving in the crude
- (c) trapped gas saturations
- (d) fluid saturation
- (e) permeability
- (f) wettability

In the absence of published field data, this study utilized a numerical simulator to predict incremental oil recovery as a function of the above operating and reservoir parameters. Multiple regression analysis was then used to relate the efficacy (STB incremental oil/MCF CO₂ injected) of the CO₂ cyclic stimulation process to six parameters.

Under ideal conditions one extra barrel of stock tank oil is produced for each MCF of CO₂ injected. Efficacy decreases with both number of cycles and volume injected.

17. TERRY, R. E., HUANG, C., GREEN, D. W., MICHNICK, M. J., WILLHITE, G. P., "Correlation of Gelation Times for Polymer Solutions Used as Sweep Improvement Agents," J. Pet. Tech. (April 1981), pp. 229-235, 20 References.

ABSTRACT

Gelled polymers are being used increasingly to redirect or modify reservoir fluid movement in the vicinity of injection or production wells for the purpose of improving water/oil ratios. To date, little has been reported about the chemistry of the in-situ gelling process that involves a multivalent metal ion, a reducing agent, and a polymer. This paper reports results of a study of the relationship between process parameters and gelation time, which is defined as the time required for the solution to reach a specified viscosity. The gelation time is determined by continuous monitoring of the viscosity following addition of the chemical reactants. The varied parameters in the investigation include polymer type and concentration, chromate concentration, and reducing-agent type and concentration. Five different polyacrylamide polymers were used including polyacrylamides that were hydrolyzed to different degrees, an anionic copolymer, and a cationic copolymer. Sodium bisulfite and thiourea were used as reducing agents. It was determined that for a given polymer-reducing agent system, the reciprocal of gelation time is a linear function of the reciprocal of the polymer concentration for a fixed metal ion concentration. The slope of the straight line is a function of the degree of polymer hydrolysis, the existence of the anion or cation functional groups, and type of reducing agent used.

18. VINATIERI, J. E. and FLEMING, III, P. D., "The Use of Pseudocomponents in the Representation of Phase Behavior of Surfactant Systems," J. Pet. Tech. (October 1979), pp. 289-300, 12 References.

ABSTRACT

A new method is developed to represent the phase behavior of multicomponent systems. This method uses fewer pseudocomponents than true components, but unlike conventional methods in which pseudocomponents are often chosen arbitrarily, the method uses regression analysis to find a "best" set of pseudocomponents.

The method is applied to two surfactant systems of the type used for tertiary oil recovery. One system contains a crude oil (from the North Burbank Unit, Osage County, OK) and the other contains a pure hydrocarbon, 1-phenyltetradecane. For both systems the representation in terms of the pseudocomponents chosen by the regression analysis is significantly more faithful than that obtained by conventional methods.

Since the considerations discussed here are general, they should be applicable to a wide range of phase studies in multicomponent systems. For example, they should be illuminating when applied to oil recovery by gas injection (carbon dioxide, natural gas, etc.), and to extraction processes, as well as to surfactant systems.

- 19a. WILLIAMS, R. L., RAMEY, JR., H. J., BROWN, S.C., SANYAL, S. K., and RAGHAVAN, R., "An engineering Economic Model for Thermal Recovery Methods," paper SPE 8906 presented at the SPE-AIME 50th Annual California Regional Meeting, Los Angeles, California, April 9-11, 1980, pp. 1-12, 34 References. (A short version of this paper is given in reference 19b.)

ABSTRACT

An economic model for thermal recovery has been developed. This paper evaluates the optimum recovery rates and production schedule under both steam drive and in-situ combustion processes, possible future production, and the economics of each method based on today's prices.

The recovery model for steam injection is based on the work of Ramey and Raghavan which presented a computer program to determine surface steam line and wellbore heat losses, vertical heat losses to the adjacent formation, an oil recovery schedule, and associated steam injection calculations. The recovery model of in-situ combustion is based on the Gates and Ramey method of making engineering calculations of air-oil ratios and oil rates as a function of oil recovery.

Once recovery rates for steam drive and in-situ combustion are obtained, a cash flow analysis may be made. Capitalization and operating costs are considered and income is discounted to net present worth. Thus, an engineer may be able to use this method to help evaluate which processes would be more profitable for a particular reservoir.

- 19b. WILLIAMS, R. L., BROWN, S. L. and RAMEY, Jr., H. J., "Economic Appraisal of Thermal Drive Projects - A New Approach," paper SPE 9358 presented at the SPE-AIME 55th Annual Fall Technical Conference and Exhibition, Dallas, Texas, September 21-24, 1980, pp. 1-3, 10 References.

ABSTRACT

Because of rapid increases in oil prices, oil companies have begun to re-evaluate recovery projects that were once considered economically unattractive. High on the list of new investment opportunities are thermal oil recovery projects. The combination of price increases, investment incentives (such as tax credits and subsidies by the Federal government), and proven superior recovery performance over other enhanced oil recovery methods has made many thermal recovery projects appear economically attractive.

To evaluate a thermal recovery project, reservoir, production, and economic parameters must either be known or assumed. Many numerical models have been developed to simulate existing projects and match actual production data. However, these models are often unduly complex and employ assumptions which reduce their applicability to a particular reservoir. Also, computer time and costs may prohibit an in-depth study of a reservoir.

Because thermal recovery projects require a substantial capital investment, a detailed reservoir and economic analysis is imperative in order to optimize oil production and revenue, maximize profits, and attain a good rate of return on investment. This paper presents a method to facilitate the estimation of oil recovery by either continuous steam injection or in-situ combustion, and generate a cash flow estimate based on the production schedule of each process.

It is assumed that the reservoir parameters are known, or can be obtained from conventional logging and laboratory methods. A synthesis of heat and mass balance equations presented in the literature is used to estimate oil production. A discounted cash flow is generated based on a probability distribution of the oil price, fuel price, capital costs, and operating costs. Discounted net present worth is graphed against the injection rate of steam or compressed air, and an optimal injection rate can be determined.

This method was developed to allow management to decide whether steam injection or in-situ combustion will be the most economically attractive process in the field. Parameters such as injection rates, pattern size and type, and efficiency may be changed either to describe a particular field application or to optimize the production schedule of a heavy oil recovery project. Application of this to existing projects shows that for different parameters, either in-situ combustion or continuous injection will be the more economically attractive in the field.

20. WU, C. H. and ELDER, R. B., "Crude Oil Steam Distillation in Steam Flooding," Final Report, DOE/ET/12357-3 (August 1980), 130 pp., 23 references.

ABSTRACT

Steam distillation yields of sixteen crude oils from various parts of the United States have been determined at a saturated steam pressure of 200 psig. Study made to investigate the effect of steam pressure (200 to 500 psig) on steam distillation yields indicates that the maximum yields of a crude oil may be obtained at 200 psig. At a steam distillation correlation factor ($\frac{V_w}{V_{oi}}$) of 15, the determined steam distillation yields range from 12 to 56% of initial oil volume for the sixteen crude oils with gravity ranging from 12 to 40° API.

Regression analysis of experimental steam distillation yields shows that the boiling temperature (simulated distillation temperature) at 20% simulated distillation yield can predict the steam distillation yields reasonably well: the standard error ranges from 2.8 to 3.5% (in yield) for $\frac{V_w}{V_{oi}} \leq 5$ and from 3.5 to 4.5% for $\frac{V_w}{V_{oi}} > 5$. The oil viscosity (cs) at 100°F can predict the steam distillation yields with standard error from 3.1 to 4.3%. The API gravity can predict the steam distillation yields with standard error from 4.4. to 5.7%. Characterization factor is an unsatisfactory correlation independent variable for correlation purpose.

21. YELLIG, W. F. and METCALFE, R. S., "Determination and Prediction of CO₂ Minimum Miscibility Pressures," J. Pet. Tech. (January, 1980) pp. 160-168, 8 References.

ABSTRACT

Miscible recovery of reservoir oil can be achieved by carbon dioxide (CO₂) injection at pressure levels above a certain minimum. The lowest pressure required for miscible displacement of a given reservoir oil will be defined as the minimum miscibility pressure (MMP). Knowledge of the CO₂ MMP is important during screening and selection of reservoirs for miscible CO₂ injection projects and it is necessary for prediction and evaluation of their performance as a result of CO₂ injection.

This paper presents a procedure for determining the CO₂ MMP for a given reservoir oil and proposes that it be considered an industry standard for determining CO₂ MMP. This procedure consists of performing CO₂ displacements at various pressure levels in a slim, sand-packed tube. The CO₂ MMP is then determined using the data collected from the displacement tests. The paper also presents a correlation for predicting the CO₂ MMP for a given reservoir oil based on the reservoir temperature and the bubble point pressure of the oil. The CO₂ MMP is estimated from the reservoir temperature and then corrected if it is lower than the bubble point pressure of the reservoir oil. This correlation is based on CO₂ MMP data for various synthetic and naturally occurring reservoir oils and was found to predict known values with greater accuracy than the available published correlations.

APPENDIX C
COMPLETE LISTING OF
ARTICLES IDENTIFIED IN THE LITERATURE SEARCH

The preliminary set of citations identified in this literature search contained a total of 184 items from two sources. Source 1, "Petroleum Abstracts," was searched for articles dealing with the topic defined as "mathematical analysis of tertiary recovery operations." Source 2, files of the U.S. Department of Energy (D.O.E.), was searched for references on "enhanced recovery and statistics." The DOE File search yielded nine articles and 38 references to data compiled in tables in DOE Energy Information Administration reports. The citations of tabulated data consisted of actual and projected values for gas and oil production under various economic assumptions and recovery methods.

The pertinent articles dealing with the use of statistical methods have already been discussed in the main body of the report. This Appendix provides a full listing of all the identified articles for interested readers. The abstracts of the articles have been deleted to save space, however Table C-1 provides a categorical description of the types of mathematical techniques represented in the articles that were not deemed, on the basis of the information in the abstract, to be examples of statistical methods.

Table C-1. Categorical Description of Articles Not Using Statistical Methods

<u>Category</u>	<u>Percentage</u>
Mathematical Analysis of Laboratory Data	
General Mathematical Models	10
Numerical Analysis	5
Finite Difference Models	5
Thermo or Fluid Dynamics	35
SUBTOTAL	55
Reservoir Simulation Models	5
Descriptive Pilot or Field Data	10
Macro-Economic Models	10
Miscellaneous	20
	<hr/>
TOTAL	100

SOURCE 1
PETROLEUM ABSTRACTS FILE

Au, A. D. K., A. Behie, B. Rubin and K. Vinsome (computer Modelling Group); TECHNIQUES FOR FULLY IMPLICIT RESERVOIR SIMULATION; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9302, 12 pp, 1980.

Anderson, M. L. (Mobil Res & Develop Corp); APPLICATION OF RISK ANALYSIS TO ENHANCED RECOVERY PILOT TESTING DECISIONS; SPE OF AIME ECON & EVALUATION SYMP. (Dallas, 2/20-22/77) PROC. pp 233-242, 1977 (SPE-6352).

ANDERSON, M. L. (Mobil Res & Develop Corp); APPLICATION OF RISK ANALYSIS TO ENHANCED RECOVERY PILOT TESTING DECISIONS; SPE OF AIME ECON. & EVALUATION SYMP. (Dallas 2/20-22/77) PROC. pp 233-242, 1977 (SPE-6352).

Baker, L. E. (Amoco Production Co.) and K. D. Luks (Notre Dame Univ.); CRITICAL POINT AND SATURATION PRESSURE CALCULATIONS FOR MULTICOMPONENT SYSTEMS; 53RD ANNU. SPE OF AIME FALL TECH. CONF. (Houston, 10/1-3/78) PREPRINT No. SPE-7478, 12 pp, 1978 [R] SOC. PETROL. ENG. J. v. 20, No. 1, pp 15-24, Feb. 1980.

Batycky, J. P., B. B. Maini and D. B. Fisher (Petroleum Recovery Inst.); SIMULATION OF MISCIBLE DISPLACEMENT IN FULL DIAMETER CARBONATE CORES; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9233, 12 pp, 1980.

Bennett, K. B., C. H. K. Phelps, H. T. Davis and L. E. Scriven (Minnesota Univ.); MICROEMULSION PHASE BEHAVIOR: OBSERVATIONS, THERMODYNAMIC ESSENTIALS, MATHEMATICAL SIMULATION; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9351, 16 pp, 1980.

Brown, V. R. R., A. A. Lorenz and W. M. Prevost (General Electric Co.); A UNIQUE INSULATION SYSTEM FOR STEAM INJECTION ENHANCED RECOVERY AND GEOTHERMAL WELLS; 50TH ANNU. SPE OF AIME CALIF. REG. MIG. (Los Angeles, 4/9-11/80) PREPRINT No. SPE-8913, 6 pp, 1980.

Boghossian, D. M. (Energy Resources Co., Inc.); ENHANCED OIL RECOVERY BY IMPROVED WATERFLOODING; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNO. SYMP. (Tulsa, 8/22-24/79) PROC. v. 1, pp D-1/1 - D-1/19, 1979 (CONF-790805-P1).

Baker, L. E. (Amoco Production Co.) and K. D. Luks (Notre Dame Univ.); CRITICAL POINT AND SATURATION PRESSURE CALCULATIONS FOR MULTICOMPONENT SYSTEMS; 53RD ANNU. SPE OF AIME FALL TECH. CONF. (Houston, 10/1-3/78) No. SPE-7478, 12 pp, 1978.

Bossler, R. B. (Texas A&M Univ.); A METHOD OF DETERMINING CRUDE OIL REMAINING IN A RESERVOIR AT THE END OF A WATER-FLOODING OPERATION; PROD. MON. v. 30, No. 10, pp 12-20, Oct. 1966.

Bureau of Mines, CARBON DEPOSITION FOR THERMAL RECOVERY OF PETROLEUM, eds. H. R. Johnson and E. L. Burwell (Morgantown, West Virginia, September 1965).

Bureau of Mines, THE LIQUID HYDROCARBON PRODUCTION IN THE UNITED STATES, 1946-75 AND 1980 PROJECTED, HIGHLIGHTING ENHANCED RECOVERY, eds. M. Carrales, Jr. and V. T. Funk (Washington, D. C., 1977).

California University, Lawrence Berkeley Laboratory, RANDOM CHOICE METHOD FOR CALCULATING FLUID DISPLACEMENT IN A POROUS MEDIUM, eds. N. Albright, C. Anderson, P. Concus (NTIS, PC A02/MF A01) (Berkeley, California, June, 1980).

Chu, C. (Getty Oil Co.); A STUDY ON FIREFLOOD FIELD PROJECTS; SPE OF AIME IMPROVED OIL RECOVERY SYMP. (Tulsa, 3/22-24/76) PREPRINT No. SPE-5821, 17 pp, 1976. J. Petrol. Technol. v. 29, pp 111-120, Feb. 1977.

Chu, C. (Getty Oil Co.); A STUDY OF FIREFLOOD FIELD PROJECTS; SPE OF AIME MID-CONTINENT SECT. IMPROVED OIL RECOVERY SYMP. (Tulsa, 3/22-24/76) PREPRINT No. SPE-5821, pp 321-337, 1976. J. Petrol. Technol. v. 29, pp 11-120, Feb. 1977.

Clampitt, R. L., and P. D. Fleming III (Phillips Petroleum Co.); RESEARCH DIGS INTO MICELLAR FLOODING PROCESSES; OIL AND GAS J. v. 78, No. 2, pp 91-94, 1/14/80 (ISSN 00201388).

Cole, F. W. (Amoco Energy Corp); VOLUMETRIC METHODS AND PRODUCTION DATA; DETERMINATION OF RESIDUAL OIL SATURATION [Unnumbered Publ.] Interstate Oil Compact Comm., Oklahoma City; pp 72-88, June 1978.

Colorado School of Mines, Department of Petroleum Engineering, CRUDE OIL STEAM DISTILLATION IN STEAM FLOODING: FINAL REPORT, eds. C. H. Wu and R. B. Elder (NTIS, PC A07/MF A01) (Colorado, August 1980).

Conner, W. D. (Columbia Gas Transmis Corp.), 5TH ANNU. U.S. EPT. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v. 2, pp 0-6/7 - 0-6/12, 1979 (CONF-790805-P2). [R] SPE OF AIME EASTERN REG. MTG. (Charleston, W. Va., 10/31/79-11/2/79) Preprint No. SPE-8740, 10 pp, 1979.

Conner, W. D. (Columbia Gas Transmis Corp.), 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 2, pp 9-6/1 - 0-6/12 1979 (CONF-790805-P2). [R] SPE OF AIME EASTERN REG. MTG. (Charleston, W. Va, 10/31/79-11/2/79 Preprint No. SPE-8740, 10 ppm 1979.

Craig, F. F., Jr. (Pan American Petr Corp.); A CURRENT APPRAISAL OF FIELD MISCIBLE SLUG PROJECTS; SPE OF AIME MID-CONTINENT SEC IMPROVED OIL RECOVERY SYMP. (Tulsa, Okla., 4/13-15/69) PREPRINT No. SPE-2418, pp 109-118, 1969. J. Petrol. Technol. v. 22, pp 529-536, May 1970.

Crawford, P. B. (Texas Petroleum Res Comm.); ENGINEERING NEW OIL RECOVERY METHODS PETROL. ENG. v. 41, No. 4, pp 49-52, April 1969.

Deiber, J. A. and W. R. Schowalter (Princeton Univ.); FLOW THROUGH TUBES WITH SINUSOIDAL AXIAL VARIATIONS IN DIAMETER; A. I. Ch. E. J. v. 25, No. 4, pp 638-645, July 1979 (ISSN 0011541).

Department of Natural Resources, MICHIGAN'S OIL AND GAS FIELDS, 1979 (Lansing, Michigan, 1980).

Dominguez, J. G. D.; Kansas Univ. Ph. D. Thesis, PHASE BEHAVIOR OF MICROEMULSION SYSTEMS WITH EMPHASIS ON EFFECTS OF PARAFFINIC HYDROCARBONS AND ALCOHOLS, 260 pp, 1977; Abstr. No. 77-28, 859, DISS. ABSTR. INT., SECT. B v. 38, No. 7, pp 3301-B - 3302-B, Jan. 1978.

Donaldson, E. C., and R. F. Kendall (Energy Res & Develop Adm) and F. S. Manning (Tulsa Univ.); DISPERSION AND TORTUOSITY IN SANDSTONES; 51ST ANNU. SPE OF AIME FALL MTG. (New Orleans, 10/3-6/76) PREPRINT No. SPE-6190, 16 pp, 1976.

Doughty, D. A. (U. S. Dept. Energy); ISOPIESTIC COMPOSITIONS OF AQUEOUS IONIC SURFACTANT SYSTEMS AS A MEASURE OF PREFERENTIAL INTERACTIONS. APPLICATION TO THE DETERMINATION OF MICELLE AGGREGATION; J. Phys. Chem. v. 83, No. 20, pp 2621-2628, 10/4/79 (ISSN 00223054).

Dullien, F. A. L. and G. K. Dhawan; CHARACTERIZATION OF PORE STRUCTURE BY A COMBINATION OF QUANTITATIVE PHOTOMICROGRAPHY AND MERCURY POROSIMETRY; J. COLLOID INTERFACE SCI. v. 47, No. 2, pp 337-349, May 1974.

Elkins, L. E. (Amoco Production Co.); OIL RECOVERY-PAST TRENDS, FUTURE EXPECTATIONS, AND TECHNOLOGICAL REQUIREMENTS; ANNU. API PROD. DIV. MTG. (Los Angeles, 5/3/-5/71) PAP. pp 165-180, 1971.

Elkins, L. E. (Amoco Production Co.); NEW RECOVERY PLANS KEY TO 60 BILLION BARRELS, WORLD OIL v. 172, No. 7, pp 69-72, June 1971.

Elkins, L. R. (Sohio Petroleum Co.); RESULTS - RECOMMENDATIONS; DETERMINATION OF RESIDUAL OIL SATURATION [Unnumbered Publ.] Interstate Oil Compact Comm., Oklahoma City; pp 262-290, June 1978.

Fassihi, M. R., W. E. Brigham and H. J. Ramey, Jr. (Stanford Univ.); THE REACTION KINETICS OF IN-SITU COMBINATION; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9454, 15 pp, 1980.

Fleming, P. D. III and J. E. Vinatieri (Phillips Petroleum Co.); MULTIVARIATE OPTIMIZATION OF SURFACTANT SYSTEMS FOR TERTIARY OIL RECOVERY; 53RD SPE OF AIME FALL TECH. CONF. (Houston, 10/1-3/78) PREPRINT No. SPE-7582, 8 pp, 1978.

Friedman, F. and W. F. Ramirez (Colorado Univ.); A SINGLE PHASE MODEL OF MECHANISMS EFFECTING MISCIBLE SURFACTANT OIL RECOVERY; CHEM. ENG. SCI. v. 32, No. 7, pp 687-694, 1977.

Friedman, F.; FLOW OF A MISCIBLE SURFACTANT IN A BEREA SANDSTONE; Colorado Univ. Ph. D. Thesis, 191 pp, 1976; Abstr. No. 77-11, 299, DISS. ABSTR. INT., SECT. B v. 37, No. 12, Pt. 1, p 6240-B, June 1977.

Funasaki, N. and S. Hada (Kyoto Coll Pharm); COEXISTENCE OF TWO KINDS OF MIXED MICELLES; J. PHYS. CHEM. v. 84, No. 7, pp 736-744, 4/3/80 (ISSN 00223654).

Gates, C. F. (Mobil Oil Corp.) and H. J. Ramey, Jr. (Stanford Univ.); A METHOD FOR ENGINEERING IN-SITU COMBUSTION OIL RECOVERY PROJECTS; J. PETROL. TECHNOL. v 32, No. 2, pp 285-294, Feb. 1980 (SPE 7149) (ISSN 01492136).

Gerbacia, W. (Chevron Research Co.); THE EVALUATION OF SURFACTANT SYSTEMS FOR OIL RECOVERY USING STATISTICAL DESIGN PRINCIPLES AND ANALYSIS; 5TH SPE OF AIME MID-CONTINENT SECT. IMPROVED METHODS FOR OIL RECOVERY SYMP. (Tulsa, 4/16-19/78) PROC. pp 345-354, 1978 (SPE-7070).

Godsey, J. E. (Stiles Godsey Engineering, Inc.); WATERFLOOD PLANNING POINTERS; PETROL. ENG. v. 44, No. 11, pp 82, 95, Oct. 1972.

Gomaa, E. E. (Standard Oil Co. California); CORRELATIONS FOR PREDICTING OIL RECOVERY BY STEAMFLOOD; J. PETROL. TECHNOL. v. 32, No. 2, pp 325-332, Feb. 1980 (SPE-6169) (ISSN 01492146)

Goodrich, J. H. (Gruy Federal Inc.); REVIEW AND ANALYSIS OF PAST AND ONGOING CARBON DIOXIDE INJECTION FIELD TESTS; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROC. pp 221-234, 1980 (SPE/DOE-8832).

Grant, M. and R. C. Desai (Toronto Univ.); SURFACE TENSION OF A SIMPLE FLUID: MANY BODY POTENTIAL; J. CHEM. PHYS. v. 72, No. 3, pp 1482-1486, 2/1/80 (SSN 00219606).

Grantz, R. E. (Amoco Production Co.); WATERFLOOD HISTORY MATCH STUDY OF THE TORCHLIGHT TENSLEEP MICELLAR PILOT; SPE OF AIME ROCKY MOUNTAIN REG. MTG. (Casper, Wyo., 5/14-16/80) PREPRINT No. SPE-9046, 10 pp, 1980.

Gula, M. M. and E. A. Gula (Oklahoma State Univ.); BIODEGRADABILITY OF COMPOUNDS USED IN ENHANCED OIL RECOVERY; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROCv. 3, pp E-2/1 - E-2/7, 1979 (CONF-790805-P3)

Guerrero, E. T (Tulsa Univ.); RELEVANCE OF GRADUATE PROGRAMS -- UNIVERSITY VIEWPOINT; SPE OF AIME ENG. MANPOWER CONF. (Houston, 6/6-7/78) Proc. 14 pp, 1978.

Hales, H. B. and A. S. Odeh (Mobil Res & Develop Corp.); AN IMPROVED METHOD FOR SIMULATING IDEAL LOW-TENSION FLOODING PROCESSES; SOC. PETROL. ENG. J. v 16, No. 2 pp 53-56, April 1976 (SPE-5674).

Harmsen, G. J. (Nederlandse Aard Mij BV); STEAM FLOODING IN A WATER DRIVE RESERVOIR IN THE SCHOONEBEEK FIELD IN THE NETHERLANDS; 10TH WORLD PETROL. CONGR. (Bucharest, 1979) Proc. v 3, pp 275-282, 1980 (ISB 0-85501-472-5)

Hasiba, H. H. (Gulf Oil Corp), J. W. Martinelli (Gulf Oil Canada Ltd) and L. A. Wilson, Jr. (Gulf Sci & Technol Co); HOW TO ORGANIZE AND PLAN ENHANCED RECOVERY EFFORTS; WORLD OIL v 184, No. 1, pp 91-95, Jan. 1977.

Haynes, S. J., M. F. Fontaine and Teasdale, T. S. (Texaco, Inc); THE CHARCO REDONDO STEAM FLOOD PILOT DATA ANALYSIS; SPE OF AIME MID-CONTINENT SECT. IMPROVED OIL RECOVERY SYMP. (Tulsa, 3/22-24/76) PREPRINT No. 5823, pp 345-356, 1976.

Hirasaki, G. J. and R. C. Nelson (Shell Development Co) and H. R. van Domselaar (Shell Internat Res Mij BV); EVALUATION OF THE SALINITY GRADIENT CONCEPT IN SURFACTANT FLOODING; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROCS. pp 143-158, 1980 (SPE/DOE-8825).

Holm, L. W. (Union Oil Co California); STATUS OF MICELLAR-POLYMER FIELD TESTS: ANOTHER VIEW; PETROL. ENG. v 52, No. 5, pp 100, 106, 108, 110, 112, 114, 116, April 1980 (ISSN 00316466).

Holm, J. W. and V. A. Josenda1 (Union Oil Co California); MECHANISMS OF OIL DISPLACEMENT BY CARBON DIOXIDE; SPE OF AIME IMPROVED OIL RECOVERY SYMP. (Tulsa, 4/22-24/74) PREPRINT No. SPE-4736, pp 15-30, 1974. J. PETROL. TECHNOL. v. 26, pp 1427-1438, Dec. 1974.

Ikoku, C. U. and H. J. Ramey, Jr. (Stanford Univ); TRANSIENT FLOW OF NON-NEWTONIAN POWER-LAW FLUIDS IN POROUS MEDIA; SPE OF AIME CALIF. REG. MTG. (San Francisco, 4/12-14/78) PREPRINT No. SPE-7139, 16 pp, 1978. U. S. Dep. Energy Fossil Energy Rep. No. SAN-1265-9, 270 pp, Feb. 1979. [R] Diss. Abstr. Int., Sect. B v 39, No. 3, p 1443-B, Sept. 1978. [R] Soc. Petrol. Eng. J. v 19, No. 3, pp 164-174, June 1979.

Iskarder, F. F.; A PROBABILISTIC ANALYSIS OF THE ECONOMICS OF OIL RECOVERY FROM THE ATHABASCA TAR SANDS; Tulsa Univ. Ph. D. Thesis, 193 pp, 1980; Abstr. No. 8016314, DISS. ABSTR. INT., SECT. B. v 41, No. 1, p 315-B, July 1980 (ISSN 041942).

Ivanhoe, L. F. (Occidental Petroleum Corp); WHERE IN THE WORLD WILL WE GET OUR OIL IN THE 1980's?; 55TH ANNU. AAPG-SEG PACIFIC SECT. MTG. (Bakersfield, Calif. 4/9-11/80) TECH. PROGRAM PREPRINT 24 pp + 4 pp reprint, 1980.

Jensen, O. K.; NUMERICAL MODELING WITH A MOVING COORDINATE SYSTEM: APPLICATION TO FLOW THROUGH POROUS MEDIA; Washington Univ. Ph. D. Thesis 207 pp, 1980; Abstr. No. 8013538, DISS. ABSTR. INT. SECT. B v 40, No. 12, Pt. 1, p 5748-B, June 1980 (ISSN 04194217).

Jensen, O. K. (Chevron Research Co); AN AUTOMATIC TIMESTEP SELECTION SCHEME FOR RESERVOIR SIMULATION; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9373, 8 pp, 1980.

Jean, Y. and H. J. Ache (Virginia Polytechnic Inst & State Univ); DETERMINATION OF CRITICAL MICELLE CONCENTRATIONS IN MICELLAR AND REVERSED MICELLAR SYSTEMS BY POSITRON ANNIHILATION TECHNIQUES; J. Amer. CHEM. SOC. v 100, No. 3, pp 984-985, 2/1/78.

Johnson, D. R. and R. L. Fox (Sandia Labs); EXAMINATION OF TECHNIQUES FOR THERMALLY EFFICIENT DELIVERY OF STEAM TO DEEP RESERVOIRS; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROC. pp 85-93, 1980 (SPE/DOE-8820).

Jou, D., C. Perez-Garcia and J. M. Rubi (Barcelona Univ); VARIATIONAL SOLUTIONS FOR THE TWO-STREAM MIXING OF POWER-LAW FLUIDS; v 35, Nos. 5-6, pp 393-407, 1979 (ISSN 00036994).

Kalter, R. J. and W. E. Tyner (Cornell Univ); ENHANCED OIL RECOVERY: THE IMPACT OF POLICY OPTIONS; Rep. No. STAFF PAPER-77-27, NSF/RA-770324, 29 pp, July 1977; PB-276, 763/OGA; Abstr., GOV. REP. ANNOUNCE. INDEX v 78, No. 9, pp 149-150, 4/28/78 (ISSN00979007).

Kazemi, H., L. S. Merrill and J. R. Jargon (Marathon Oil Co); PROBLEMS IN INTERPRETATION OF PRESSURE FALL OFF TESTS IN RESERVOIRS WITH AND WITHOUT FLUIDS BANKS; 42ND ANNU. SPE OF AIME CALIF. REG. MTG. (Los Angeles, ELES, 11/4-5/71) PREPRINT No. SPE-3696, 16 pp, 1971. J. PETROL. TECHNO. v 24, pp 1147-1156, Sept. 1972.

Kennedy, J. L.; STUDY ANALYZES EFFECT OF OIL PRICE ON ENHANCED RECOVERY'S FUTURE ROLE; OIL GAS J. v 74, No. 52, pp 185-191, 12/27/76).

Kinney, G. T.; REAL NEW-OIL PRICE SEEN FALLING TO \$9.81 BY '79; OIL GAS J. v 73, No. 48, pp 65-68, 12/1/75.

Kovalev, A. G., Kachalov, O. B., Pokrovskii, V. V., STATISTICAL EVALUATION OF THE EFFECT OF CERTAIN FACTORS ON THE EFFECTIVENESS OF THE DISPLACEMENT OF OIL BY WATER (In Russian), Neft. Khoz., No. 1 (January 1975) pp. 30-32.

Lake, L. W. and G. A. Pope (Texas Univ); STATUS OF MICELLAR-POLYMER FIELD TESTS; PETROL. ENG. v 51, No. 13, pp 38, 42-44, 48, 50, 52, 56, 58, 60, Nov. 1979 (ISSN 00316466).

Lake, L. W., J. R. Johnston and G. L. Stegemeir (Shell Development Co); SIMULATION AND PERFORMANCE PREDICTION OF A LARGE-SCALE SURFACTANT/POLYMER PROJECT; 53RD ANNU. SPE OF AIME FALL TECH. CONF. (Houston, 10/1-3/78) PREPRINT No. SPE-7471, 12 pp, 1978.

Langston, J. D. (Exxon Co); A NEW LOOK AT THE U. S. OIL AND GAS POTENTIAL: EXPLORATION AND ECONOMICS OF THE PETROLEUM INDUSTRY [Book] Matthew Bender, New York; v 14, pp 33-50, 1976.

LaPue, Moore & Schafer Staff; ANALYSIS AND ASSESSMENT OF ENHANCED OIL RECOVERY BASELINE DATA: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS. FINAL REPORT; Rep. No. ERDA 76-155/1, 38 pp, 10/1/76; Abstr. No. 2260, ENERGY ABSTR. POLICY ANAL. v 3, No. 7, p 407, July 1977.

Larson, R. G. (Bell Telephone Inc); CONTROLLING NUMERICAL DISPERSION BY VARIABLY TIMED FLUX UPDATING IN TWO DIMENSIONS; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9374, 12 pp, 1980.

Layton, D. R. (Anadarko Production Co); HOW TO GET ADDITIONAL OIL FROM A WATERED-OUT FLOOD; WORLD OIL v 170, No. 1, pp 53-56, Jan. 1970.

Lee, S. T., W. H. Chen and W. E. Culham (Gulf Research & Develop Co) and R. H. Jacoby (Pennsylvania State Univ); EXPERIMENTAL AND THEORETICAL STUDIES ON THE FLUID PROPERTIES REQUIRED FOR SIMULATION OF THERMAL PROCESSES; 54TH ANNU. SPE OF AIME TECH. CONF. (Las Vegas, 9/23-26/79) PREPRINT N. SPE-8398, 20 ppm 1979.

Limon, J. T.; A NUMERICAL INVESTIGATION OF MICELLAR FLOODING IN ONE AND TWO DIMENSIONAL SYSTEMS; Tulsa Univ. Ph. D. Thesis, 113 pp, 1978; Abstr. No. 7810325, DIS. ABSTR. INT., SECT. B v 39, No. 6, p 2946-B, Dec. 1978 (ISSN 04194217).

Majumdar, S. R. (Calgary Univ) and D. H. Michael (London Univ Coll); THE INSTABILITY OF PLANE PENDENT DROPS; J. COLLOID INTERFACE SCI. v 73, No. 1, pp 186-192, Jan. 1980 (ISSN 00219797).

Malcolm, J. D. and C. D. Elliott (Newfoundland Memorial Univ); INTERFACIAL TENSION FROM HEIGHT AND DIAMETER OF A SINGLE SESSILE DROP OR CAPTIVE BUBBLE; CAN. J. CHEM. ENG. v 58, No. 2, pp 151-153, April 1980 (ISSN 0084034).

McCormick, C. L., H. H. Neidlinger, R. D. Hester and G. C. Wildman (Southern Mississippi Univ); RANDOM-AND GRAFT-COPOLYMERS FOR UTILIZATION IN ENHANCED OIL RECOVERY - SYNTHESIS AND SOLUTION BEHAVIOIR; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 1, pp D-4/1 - D-4/26, 1979 (CONF-790805-P1).

McNabb, D.; TEXAS OPERATORS PUSHING ENHANCED RECOVERY; OIL GAS J. v 72, No. 36, pp 37-40, 9/9/74.

McNally, R.; DEVELOPMENT DRILLING AT ALL-TIME HIGH; PETROL. ENG. v 52, No. 1, pp 21-24, Jan. 1980 (ISSN 00316466).

Meldau, R. F. (Husky Oil Ltd); GAS-STEAM INJECTION IN HEAVY OIL WELLS; 50TH ANNU. SPE. OF AIME CALIF. REG. MTG. (Los Angeles, 4/9-11/80) PREPRINT No. SPE-8911, 12 pp, 1980.

Mills, P. L., W. P. Wu and M. P. Dudukovic (Washington Univ, St. Louis); TRACER ANALYSIS IN SYSTEMS WITH TWO-PHASE FLOW; A. I. Ch. E. J. v 25, No. 5, pp 885-890, Sept. 1979 (ISSN 00011541).

Miron, R. L., J. E. Peterson, T. L. Kilgore, M. T. Shannon, T. Bates (Shell Oil Co) et al.; COALINGA POLYMER DEMONSTRATION PROJECT, EAST COALINGA FIELD, FRESNO COUNTY, CALIFORNIA; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 1, pp D-2/1 - D-2/22, 1979 (CONF 790805-P1).

Missel, R. J., N. A. Mazer and G. B. Benedek (Massachusetts Inst. Technol), C. Y. Young (Brandeis Univ) and M. C. Carey (Harvard Univ); THERMODYNAMIC ANALYSIS OF THE GROWTH OF DODIUM DODECYL SULFATE MICELLES; J. PHYS. CHEM. v 84, No. 9, pp 1044-1057, 5/1/80 (ISSN 00223654).

Moffit, P. D. (Phillips Petroleum Co) and D. E. Menzie (Oklahoma Univ); WELL INJECTION TESTS OF NON-NEWTONIAN FLUIDS; SPE OF AIME ROCKY MT REG. MTG. (Cody, Wyo., 5/17-19/78) PREPRINT No. SPE-7177, 8 pp, 1978.

Morgantown Energy Research Center; OPTIMIZATION OF CARBON DEPOSITION EXPERIMENTS IN THERMAL OIL RECOVERY BY STATISTICAL ANALYSIS; eds. A. W. Effinger and L. A. Schrider (Bureau of Mines, Morgantown, West Virginia, November 1979).

Myhill, N. A. (Shell Development Co); A CHECK ON NUMERICAL THERMAL SIMULATION; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROC. pp 111-117, 1980 (SPE/DOE-8822).

Naiki, M.; NUMERICAL SIMULATION OF POLYMER FLOODING INCLUDING THE EFFECTS OF SALINITY; Texas Univ. Ph. D. Thesis, 390 pp, 1979; Abstr. No. 792833, DISS. ABSTR. INT., SECT. B v 40, No. 7, p 3346-B, Jan. 1980 (ISSN 04194217).

Nghiem, L. X., D. K. Fong and K. Aziz (Computer Modeling Group); COMPOSITIONAL MODELING WITH AN EQUATION OF STATE; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9306, 14 pp, 1980.

Nicksic, S. W. (Chevron Research Corp); SECONDARY RECOVERY OF GAS AND OIL; ENERGY SOURCES: v 1, No. 2, pp 237-247, Winter 1974.

Nolan, J. B., R. Ehrlich and R. B. Crookston (Gulf Research & Develop Co); APPLICABILITY OF STEAMFLOODING FOR CARBONATE RESERVOIR; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROC. pp 95-110, 1980 (SPE/DOE-8821).

Oh, S. G.; INTERFACIAL EFFECTS IN OIL RECOVERY; Northwestern Univ. Ph. D. Thesis, 295 pp, 1978; Abstr. No. 7903333, DISS. ABSTR. INT., SECT. B v 39, No. 8, p 3992-B, Feb. 1979 (ISSN 04194217).

Orr, F. M., Jr. A. D. Yu and C. L. Lien; PHASE BEHAVIOR OF CO₂ AND CRUDE OIL IN LOW TEMPERATURE RESERVOIRS; 1ST JOINT SPE/DOE ENHANCED OIL RECOVERY SYMP. (Tulsa, 4/20-23/80) PROC. pp 17-32, 1980 (SPE-DOE-8813) [R] U. S. DEP. ENERGY INT. ENERGY AGENCY ENHANCED OIL RECOVERY WORKSHOP (Bartlesville, Okla., 4/24/80) PROC. pp 227-242, 1980.

Pang, R. W. (Phillips Petroleum Co) and B. H. Caudle (Texas Univ); MODELING OF A MICELLAR-POLYMER PROCESS; 5TH SPE OF AIME INT. OILFIELD & GEOTHERM. CHEM. SYMP. (Stanford, Calif., 5/28-30/80) PREPRINT No. SPE-9009, pp 307-324, 1980.

Patton, J. T. (CBI Inc), K. H. Coats (INTERCOMP Inc) and K. Spence (US Dept. Energy); A PARAMETRIC STUDY OF THE CO₂ HUF-n-PUF PROCESS; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9228, 8 pp, 1980.

Pease, R. W., E. N. Durham and J. A. Watson (Gruy Federal Inc) and J. McGhee; ASSESSMENT OF POTENTIAL INCREASED OIL PRODUCTION BY POLYMER-WATERFLOOD IN NORTHERN AND SOUTHERN MID-CONTINENT OIL FIELDS. FINAL REPORT; U. S. Dep Energy Rep. No. BETC/0026-10, 123 pp, Sept. 1979.

Perry, G. E. and C. M. Kidwell (Shell Oil Co); WEEKS ISLAND "S" SAND RESERVOIR B GRAVITY STABLE MISCIBLE CO₂ DISPLACEMENT, IBERIA PARISH, LOUISIANA; 5TH ANNU. U.S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 2, pp N-1/1 - N-1/15, 1979 (CONF-790805-P2) [R] U. S. DEP. ENERGY INT. ENERGY AGENCY ENHANCED OIL RECOVERY WORKSHOP (Bartlesville, Okla., 4/24/80) PROC. pp 184-202, 1980.

Pope, G. A. (Texas Univ); THE APPLICATION OF FRACTIONAL FLOW THEORY TO ENHANCED OIL RECOVERY; SOC. PETROL. ENG. J. v 20, No. 3, pp 191-205, June 1980 (SPE-7660) (ISSN 00379999).

Ramirez, W. F. and L. C. Denoyelle (Colorado Univ) and F. Friedman and P. J. Shuler (Chevron Research Co); ADSORPTION AND INTERFACIAL TENSION DYNAMICS OF SURFACTANTS IN POROUS MEDIA; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9280, 11 pp, 1980.

Renfro (ARCO Oil & Gas Co); SHEEP MOUNTAIN CO₂ PRODUCTION FACILITIES - A CONCEPTUAL DESIGN; J. PETROL. TECHNOL. v 31, No. 11, pp 1462-1468, No. 1979 (SPE-7796) (ISSN 01492136).

Regaldo, A. J. R.; NUMERICAL SIMULATION OF STEAM INJECTION INTO A COMPACTING RESERVOIR UNDER NON-NEWTONIAN FLOW CONDITIONS; Pennsylvania State Univ. Ph. D. Thesis, 230 pp, 1980; Abstr. No. 8015833, DISS. ABSTR. SECT. B v 41, No. 1, p 315-B, July 1980 (ISSN 04194217).

Ruckenstein, E. (New York State Univ, Buffalo); THERMODYNAMICS OF MICROEMULSIFICATION WITH IONIC SURFACTANTS; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9281, 8 pp, 1980.

Ruckenstein, E. and R. Krishnam (New York State Univ. Buffalo); THE EQUILIBRIUM RADIUS OF MICROEMULSIONS FORMED WITH IONIC SURFACTANTS; J. COLLOID INTERFACE SCI. v 75, No. 2, pp 4/6-492, June 1980 (ISSN 00219797).

Rump, W. M., A. E. Cover, M. N. Shah (Pullman Kellogg Inc); COST AND AVAILABILITY OF CARBON DIOXIDE FOR ENHANCED OIL RECOVERY; 4TH ANNU. DOE ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING METHODS SYMP. (Tulsa, 8/29-31/78) PROC. v 1B, pp C-3/1 - C-3/11, 1978.

San Filippo, G. P. and L. G. Guckert (Pennzoil Co); PROGRESS OF THE PILOT CARBON DIOXIDE FLOOD IN THE ROCK CREEK - BIG INJUN FIELD, ROANE COUNTY, WEST VIRGINIA; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 2, pp 0-5/1 - 0-5/6, 1979 (CONF-790805-P2).

Satman, A. (Stanford Univ), M. Eggenschwiler (INTEVEP) and H. J. Ramey, Jr. (Stanford Univ); INTERPRETATION OF INJECTION WELL PRESSURE TRANSIENT DATA IN THERMAL OIL RECOVERY; 50TH ANNU. SPE OF AIME CALIF. REG. MTG. (Los Angeles, 4/9-11/80) PREPRINT No. SPE-8908, 10 pp, 1980.

Sauty, J. P., (Bureau Rech Geol Min (Fr)); AN ANALYSIS OF HYDRODISPERSIVE TRANSFER IN AQUIFERS; WATER RESOURCES RES. v 16, No. 1, pp 145-158, Feb. 1980 (ISSN 00431397).

Sigmund, P. M. (HYCAL Energy Res Labs Ltd), K. Aziz and L. X. Nghiem (Computer Modeling Group), R. Mehra (Calgary Univ) and J. I. Lee (Petro Canada); LABORATORY CO₂ FLOODS AND THEIR COMPUTER SIMULATION; 10TH WORLD PETROL. CONGR. (Bucharest, 1979) PROC. v 3, pp 243-250, 1980 (ISD 0-85501-472-5).

Slattery, J. C. (Northwestern Univ); INTERFACIAL TRANSPORT PHENOMENA; CHEM. ENG. COMMUN. v 4, Nos. 2-3, pp 149-166, 1980.

Slattery, J. C., J. D. Chen (Northwestern Univ), C. P. Thomas and P. D. Fleming III (Phillips Petroleum Co); SPINNING DROP INTERFACIAL VISCOMETER; J. COLLOID INTERFACE SCI. v 73, No. 2, pp 483-499, Feb. 1980 (ISSN 00219797).

Smith, D. H., and S. A. Templeton (Oak Ridge Natl Lab); EFFECTS OF COSURFACTANT ON HYDROCARBON SOLUBILIZATION IN THE SYSTEM p-XYLENE/DECANOL/SODIUM OCTANOATE/WATER; J. COLLOID. INTERFACE SCI. v 68, No. 1, pp 59-69, Jan. 1979 (ISSN 00219797).

Swift, S. C. and L. P. Brown (Cities Service Oil Co); INTERFERENCE TESTING FOR RESERVOIR DEFINITION: THE STATE OF THE ART; SPE OF AIME MID-CONTINENT SECT. IMPROVED OIL RECOVERY SYMP. (Tulsa, 3/22-24/76) PREPRINT No. SPE-5809, pp 165-175, 1976.

Talash, A. W. (Mobil Res & Develop Co); EXPERIMENTAL AND CALCULATED RELATIVE PERMEABILITY DATA FOR SYSTEMS CONTAINING TENSION ADDITIVES; SPE OF AIME MID-CONTINENT SECT. IMPROVED OIL RECOVERY SYMP. (Tulsa, 3/22-24/76) PREPRINT No. SPE-5810, pp 177-188, 1976.

Thomas, C. P., W. K. Winter and P. D. Fleming III (Phillips Petroleum Co); APPLICATION OF A GENERAL MULTIPHASE, MULTI-COMPONENT CHEMICAL FLOOD MODEL TO TERNARY, TWO-PHASE SURFACTANT SYSTEMS; 52ND ANNU. SPE OF AIME FALL TECH. CONF. (Denver, 10/9-12/77) PREPRINT No. SPE-6727, 16 pp, 1977.

Todd, M. R. and C. A. Chase (Intercomp Rsce Dev Eng Inc); A NUMERICAL SIMULATOR FOR PREDICTING CHEMICAL FLOOD PERFORMANCE; 5TH SPE OF AIME RESERVOIR SIMULATION SYMP. (Denver, 1/31/79-2/2/79) PREPRINT No. SPE-7689, pp 161-174, 1979.

Tracy, P. (Oklahoma Univ); PETROLEUM DATA SYSTEM: SCOPE AND APPLICATIONS; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 2, pp J-6/1 - J/-6/7, 1979 (CONF-790805-P2).

Uraiet, A., R. Raghavan and G. W. Thomas, (Tulsa Univ); DETERMINATION OF THE ORIENTATION OF A VERTICAL FRACTURE BY INTERFERENCE TESTS; J. PETROL. TECHNOL. v 29, pp 73-80, Jan. 1977 (SPE-5845).

Vinatieri, J. E. and Fleming, P. D. III; USE OF PSEUDOCOMPONENTS IN THE REPRESENTATION OF PHASE BEHAVIOR OF SURFACTANT SYSTEMS; SOC. Pet. Eng. J.; V 19, No. 5 (October, 1979) pp 289-300.

Verma, V. B.; A THEORETICAL INVESTIGATION OF FORWARD COMBUSTION IN A ONE DIMENSIONAL SYSTEM; Tulsa Univ. Ph. D. Thesis, 113 pp, 1978; Abstr. No. 7812311, DISS. ABSTR. INT., SECT. B v 39, No. 2, pp 938-B - 399-B, Aug. 1978 (ISSN 04194217).

Vinatieri, J. E., and P. D. Fleming III (Phillips Petroleum Co); USE OF PSEUDOCOMPONENTS IN THE REPRESENTATION OF PHASE BEHAVIOR OF SURFACTANT SYSTEMS; 5TH SPE OF AIME MID-CONTINENT SECT. IMPROVED METHODS FOR OIL RECOVERY SYMP. (Tulsa, 4/16-19/78) PROC. pp 215-232, 1978 (SPE-7057) [R] SOC. PETROL. ENG. J. v 19, No. 5, pp 289-300, Oct. 1979.

Wall, S. N. (Goteborg Univ) and G. E. A. Aniansson (Chalmers Univ Technol); NUMERICAL CALCULATIONS ON THE KINETICS OF STEPWISE MICELLE ASSOCIATION; J. PHYS. CHEM. v 84, No. 7, pp 727-736, 4/3/80 (ISSN 00223654).

Wang, F. H. J. (General Motors Corp) and J. L. Duda, E. E. Klaus, S. K. Fan and S. T. Ju (Pennsylvania State Univ); A SYSTEMATIC STUDY OF FACTORS INFLUENCING THE FLOW OF POLYMER SOLUTIONS IN POROUS MEDIA; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 1, pp D-5/1 - D-5/23, 1979 (CONF-790805-P1).

Ward, J. S. and F. D. Martin (New Mexico Petr Res Center); PREDICITON OF VISCOSITY FOR PARTIALLY HYDROLYZED POLYACRYLAMIDE SOLUTIONS IN THE PRESENCE OF CALCIUM AND MAGNESIUM IONS; 5TH SPE OF AIME INT. OILFIELD & GEOTHERM. CHEM. SYMP. (Stanford, Calif., 5/28-30/80 PREPRINT No. SPE-8978, pp 21-31, 1980.

Weinbrandt, R. M. (Aminoil Inc); IMPROVED OIL RECOVERY BY ALKALINE FLOODING IN THE HUNTINGTON BEACH FIELD; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 1, pp C-4/1 - C-4/10, 1979 (CONF-790805-P1).

Wesson, T. C., (US Dept Energy); HOW TO DETERMINE RESIDUAL OIL SATURATION; PETROL. ENG. v 51, No. 15, pp 25-26, 28, 30, 34, 36, Dec. 1979 (ISSN 00316466).

White, T. M. and R. F. Lindsay (Gulf Explor & Prod Co); ENHANCED OIL RECOVERY BY CO₂ MISCIBLE DISPLACEMENT IN THE LITTLE KNIFE FIELD, BILLINGS COUNTY, NORTH DAKOTA; 5TH ANNU. U. S. DEP. ENERGY ET AL. ENHANCED OIL & GAS RECOVERY & IMPROVED DRILLING TECHNOL. SYMP. (Tulsa, 8/22-24/79) PROC. v 2, pp N5/1 - N-5/19, 1979 (CONF-790805-P2).

Williams, R. L. (Getty Oil Co) S. L. Brown and H. J. Ramey, Jr. (Stanford Univ); ECONOMIC APPRAISAL OF THERMAL DRIVE PROJECTS - A NEW APPROACH; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9358, 6 pp, 1980.

Williams, R. L., S. C. Brown and S. K. Sanyal (Stanford Univ) and R. Raghavan (Tulsa Univ); AN ENGINEERING ECONOMIC MODEL FOR THERMAL RECOVERY METHODS; 50TH ANNU. SPE OF AIME CALIF. REG. MTG. (Los Angeles, 4/9-11/80) PREPRINT No. SPE-8906, 17 pp, 1980.

Yanoski, J. L. and T. A. Mccracken (Amoco Production Co); A NINE-POINT FINITE DIFFERENCE RESERVOIR SIMULATOR FOR REALISTIC PREDICTION OF UNFAVORABLE MOBILITY RATIO DISPLACEMENTS; 4TH SPE OF AIME NUMERICAL SIMULATION OF RESERVOIR PERFORMANCE SYMP. (Los Angeles, 2/19-20/76) PREPRINT No. SPE-5734, pp 209-229, 1976.

Yellig, W. G. and R. S. Metcalfe (Amoco Production Co); DETERMINATION AND PREDICTION OF CO₂ MINIMUM MISCIBILITY PRESSURES; J. PETROL. TECHNOL. v 32, No. 1, pp 160-168, Jan. 1980 (SPE-7477) (ISSN 01492136).

Yellig, W. F. and R. S. Metcalfe (Amoco Production Co); DETERMINATION AND PREDICTION OF CO₂ MINIMUM MISCIBILITY PRESSURES; 53RD ANNU. SPE OF AIME FALL TECH. CONF. (Houston, 10/1-3/78) PREPRINT No. SPE-7477, 12 pp, 1978.

Yortsos, Y. C. (Southern California Univ) and A. S. Fokas (California Inst Technol); AN ANALYTICAL SOLUTION FOR LINEAR WATERFLOOD INCLUDING THE EFFECTS OF CAPILLARY PRESSURE; 55TH ANNU. SPE OF AIME FALL TECH. CONF. (Dallas, 9/21-24/80) PREPRINT No. SPE-9407, 16 pp, 1980.

Yuferov, Yu. K., L. P. Dmitriev, Yu. A. Stukanogov, A. F. Vaslavskii; ACCOUNTING FOR THE ANISOTROPY OF A BED DURING THE WORKING OF OIL DEPOSITS WITH UNDERLYING WATER (In Russian), Neftepererab Neftekhim No. 9 (Moscow 1978) pp 7-8.

SOURCE 2

U.S. DEPARTMENT OF ENERGY FILES, 47 REFERENCES
OF WHICH 9 (SHOWN HERE) WERE ARTICLES AND 38 WERE DATA TABULATIONS

Bureau of Mines, "Carbon Deposition for Thermal Recovery of Petroleum," eds. H. R. Johnson and E. L. Burwell (Morgantown, West Virginia, September 1965).

Bureau of Mines, "The Liquid Hydrocarbon Production in the United States, 1946-75 and 1980 Projected, Highlighting Enhanced Recovery," eds. M. Carrales, Jr. and V. T. Funk (Washington, D.C., 1977).

California University, Lawrence Berkeley Laboratory, "Random Choice Method for Calculating Fluid Displacement in a Porous Medium," eds. N. Albright, C. Anderson, P. Concus (NTIS, PC A02/MF A01) (Berkeley, California, June, 1980).

Colorado School of Mines, Department of Petroleum Engineering, "Crude Oil Steam Distillation in Steam Flooding: Final Report," eds. C. H. Wu and R. B. Elder (NTIS, PC A07/MF A01) (Colorado, August 1980).

Department of Natural Resources, "Michigan's Oil and Gas Fields, 1979" (Lansing, Michigan, 1980).

Kovalev, A. G.; Kachalov, O. B.; Pokrovskii, V. V., "Statistical Evaluation of the Effect of Certain Factors on the Effectiveness of the Displacement of Oil by Water" (In Russian), Neft. Khoz., No. 1 (January 1975) pp. 30-32.

Morgantown Energy Research Center, "Optimization of Carbon Deposition Experiments in Thermal Oil Recovery by Statistical Analysis," eds. A. W. Effinger and L. A. Schrider (Bureau of Mines, Morgantown, West Virginia, November 1979).

Vinatieri, J. E. and Fleming, P. D. III, "Use of Pseudocomponents in the Representation of Phase Behavior of Surfactant Systems," Soc. Pet. Eng. J., Vol. 19, No. 5 (October, 1979) pp. 289-300.

Yuferov, Yu. K.; Dmitriev, L. P.; Stukanogov, Yu. A.; Vaslayvskii, A. F., "Accounting for the Anisotropy of a Bed During the Working of Oil Deposits with Underlying Water" (In Russian), Neftepererab Nefiekhim, No. 9 (Moscow, 1978) pp. 7-8.

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