SCREENING TESTS

for

ENHANCED OIL RECOVERY PROJECTS*

by David B. Burnett and Michael W. Dann
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ABSTRACT

Laboratory Screening Tests are suggested to evaluate potential enhanced oil recovery projects. Standardized procedures are used to study the feasibility of (1) miscible/CO_2 projects, (2) thermal processes, and (3) chemical processes.

The Screening Tests are divided into four sections: crude oil characterization, injection water studies, reservoir core characterization, and displacement studies in porous media.

These Screening Tests augment geologic and engineering studies and supplement (but do not replace) the more commonly known core analysis programs.

INTRODUCTION

Interest in Enhanced Oil Recovery has increased dramatically with the advent of governmental incentive programs, increased crude prices, and the shortage of U. S. oil supply. Because of this impetus, industry engineering, research, and technical service personnel are having to evaluate more potential prospects in shorter periods of time than ever before.

To help those who are performing feasibility studies of potential enhanced oil recovery projects, a set of Screening Tests has been developed. These tests are a series of laboratory measurements using fluids and cores from a candidate reservoir. The laboratory test procedures are based on those published in the technical literature.

The Screening Tests begin with relatively inexpensive, rapid, and direct measurements. The Screening programs become more complex as the tests continue. The final series of tests, in addition to serving as screening criteria, are actually part of the process design of a particular oil recovery technique.

These laboratory studies provide data that augment geologic and engineering studies. It is stressed that fundamental core analysis data is required at the beginning of any reservoir engineering study--including enhanced oil recovery projects. Such data as oil saturations and determination of permeability and porosity are essential: their determination and evaluation have been published previously.[1,2]

Enhanced oil recovery processes that are discussed in this paper are shown in Table 1. Three major classifications are made:

1. Gas Injection Processes (Miscible/CO_2)
2. Thermal Processes
3. Chemical Processes

The Screening Tests are divided into four sections:

A. Crude Oil Characterization
B. Injection Water Studies
C. Reservoir Core Characterization
D. Displacement Studies in Porous Media

Each section of the Screening Tests is designed to measure certain fundamental characteristics of the candidate reservoir. In some cases, the tests are employed to determine if the proposed project meets the criteria required of an enhanced oil recovery process. In other cases, data is collected to use in published correlations that predict oil recovery performance.

The laboratory tests are taken from the technical literature. While details of testing techniques are not described, comprehensive references are given. In addition, each section also contains references to reviews of technology and field projects. Where possible, references are given to correlations that predict oil recovery.

Even though many of the tests are similar for various processes, the organization of this paper will allow highlights and special tests to be placed in the overall screening protocol.

MISCIBLE/CO_2 PROCESSES

In terms of displacement efficiency, miscible processes are the most efficient oil recovery technique. Miscible flooding is of particular utility in reservoirs where water injection processes are not practical because of water quality problems, reservoir sensitivity, or the presence of low permeability zones.

Miscible processes are utilized because of the efficiency of the solvent in displacing the crude oil from the reservoir matrix. Almost any solvent, if conditions permit, can be used in a conditionally miscible or first contact miscible displacement. Because of its availability, its inexpensive cost, and its performance in oil recovery processes, carbon dioxide (CO_2) has become the most important miscible solvent. Since the majority of projects exhibit conditional miscibility between crude oil and CO_2, this section will discuss these processes only.

Miscibility between CO_2 and crude oil is a function of reservoir temperature, reservoir oil composition, and the composition of the injected gas.

There are several types of laboratory tests which have been developed to evaluate potential CO_2 flooding projects. Orr described techniques designed to characterize the crude oil-CO_2 system.[3]

Other recommended tests are described below.

Oil Characterization Tests

Oil characterization tests can be used to measure fundamental physical properties of the crude oil. Table 2 lists useful types of tests to be used for crudes that are potential CO_2 flooding candidates. The basic sediment and water test (BS&W) is routinely performed to insure sample quality. The test for asphaltenes is used to indicate the precipitation tendency of the crude.

The Watson characterization factor is used to predict solubility, swelling and viscosity behavior of the crude oil.[4,5]

Data from the characterization tests can be used to predict minimum miscibility pressure (MMP) as determined by slim tube tests.[7,8,9] Fig. 1 shows MMP as a function of reservoir temperature and oil character.

Burnett, Alston and Lim[10] and more recently Metcalfe[11] evaluated the effect of impurities on MMP. Other research showed that MMP can be adjusted to fit reservoir conditions.[12,13] Fig. 2 shows that the effect of light hydrocarbons upon MMP.

Slim tube screening and appropriate PVT tests should be performed to test CO_2-reservoir oil systems so that the predictions can be tested against experimental data.

Injection Water Study

When water injection is utilized with miscible/CO_2 processes, it is appropriate to test injection water quality. Tests are shown in Table 3. Since these tests are also appropriate for chemical flooding processes, and since testing is more often required for those projects, these programs are discussed later.

Reservoir Core Characterization and Displacement Studies in Porous Material

When miscible conditions prevail, displacement efficiency is a function of reservoir rock properties.[14] Screening tests utilizing reservoir cores are required because core heterogeneity, dead end pore space, and tortuosity will strongly affect residual oil saturation. When displacement tests using short reservoir core plugs are required, special techniques can be utilized to establish CO_2-oil transition zones upstream of the test core.[15]

Core plugs can also be stacked into composite core allowing longer flow paths for the displacement to proceed. Table 6 shows a comparison of these techniques along with direct injection into a core plug. It is seen that under the test conditions employed, little difference was noted in the procedures.

Predictive techniques for oil recovery using CO_2 based on experimental data are generally limited to numerical simulations. One method for simulating mobility behavior of the CO_2 slug is the one-fourth power mixing rule. An early graphical technique using this technique to predict oil recovery is given by Claridge[16].

THERMAL PROCESSES

Thermal oil recovery processes offer some of the most cost efficient enhanced oil recovery processes currently known.[17] These processes, involving the input of heat energy along with ancillary aids, are generally preferred for shallow oil reservoirs containing fairly viscous crude oils. Process efficiency, whether the potential project is insitu combustion or a steamflood, is dependent upon both reservoir oil properties and reservoir rock properties. Recommended Screening Tests to measure those properties are described herein.

IN-SITU COMBUSTION

Of the various in-situ combustion techniques, forward combustion processes are the most commonly found types.18,19 In this process, air is injected into a well, ignition is caused to occur at the input well, and a combustion zone is propagated through the reservoir rock to producing wells. Improved oil recovery is caused by a combination of effects. The light ends of the crude are driven off by the heat ahead of the combustion front. Connate water is vaporized and aids heat transfer beyond the combustion zone. A mobile oil bank is formed and is recovered at the production wells ahead of the fire front.

It has been found that the injection of water with air improves efficiency. The water injection technique scavenges heat from behind the burn zone and transfers the energy to the area of high oil saturation ahead of the combustion front. Tests have shown that oil recovery is higher, and maximum reservoir temperatures tend to be lower with water injection. The technique also reduces air injection requirements.[20,21]

Many factors affect the application and limits of the in-situ combustion oil recovery process. The character of both the crude oil and the reservoir rock are important variables. Screening tests are therefore selected to:

1. indicate whether in-situ combustion is applicable to the reservoir in question
2. provide basic laboratory data to use in oil recovery prediction techniques

Such screening tests are detailed below.

Oil Characterization

Basic oil characterization tests are performed, as discussed before, in order to verify the quality of the crude sample furnished for testing. Other characterization tests give qualitative indications of the possible efficiency of in-situ combustion. These tests are listed in Table 2.

Various investigators have shown how the key variables are affected by the composition of the crude.[19,21,22,23] The gravity of the crude oil can be used to estimate process requirement. The relationship between gravity and fuel and air injection requirements is shown in Fig. 3.[20] Care must be taken in using the relationship; recent studies have shown that more subtle characterization tests show variance in process efficiency when correlated with gravity.[24]

Injection Water Study

When water injection is combined with in-situ combustion, the Screening Tests listed in Table 3 are recommended to insure adequate water quality. The recommended studies include water analysis, bacteriological testing, and source water filterability studies.

Reservoir Core Characterization

Characteristics of the reservoir rock material are important parameters and may dominate the in-situ combustion process. Table 4 lists the Screening Tests recommended for typical projects.

The petrographic tests consist, in part, of X-ray diffraction testing to determine the amount and type of clays and other minerals in the reservoir rock. If relatively large quantities of clay materials are found, then other tests are scheduled. When the reservoir rock matrix is found to contain large amounts of clay, the combustion process is reportedly more efficient.[25]

Thermal properties testing also aids in screening the reservoir. Values for thermal conductivity and specific heat of the reservoir rock can be determined directly rather than relying on generalized correlations.[26]

Displacement Studies in Porous Media

Combustion characteristics of the crude oil in reservoir rock are determined by in-situ combustion tests. The percentage of crude oil used as fuel and the quantity of air required to burn the oil determines whether the combustion process is practical. Laboratory tests measure this efficiency.

Typical test data is shown in Table 6. The device used to gather this information has been described previously.[27]

The experimental data can be used to predict ultimate oil recovery and recovery rate for a proposed field project. Brigham, et al. have developed a correlation that uses the fraction oxygen utilized and fuel burned (along with basic reservoir data) to predict recovery rates and ultimate recovery.[28]

STEAMFLOODING

Steamflooding processes are employed in reservoirs having crudes of all ranges of API gravity.[29] When crude oil is heated by steam, viscosity is reduced significantly and flow efficiency is improved. When contacting oils of more moderate gravity, steam will tend to distill light components from the crude and to create a solvent bank ahead of the steam front causing an increase in displacement efficiency. The effectiveness of steam injection will vary not only upon the crude oil properties, but also upon the reservoir rock properties and the thermal properties of the steam. Laboratory tests, by taking into account all of these factors, provide a direct measurement of the displacement efficiency of the process at the temperature and pressure conditions which would be used in the field project. The Screening Tests are discussed below.

Oil Characterization Tests

Recommended Screening Tests to characterize crude oil are the same as used for in-situ combustion projects. These are shown in Table 2.

Oil viscosity as a function of temperature is a key measurement: viscosity can be interpolated or extrapolated by using Braden's correlation.[30]

Injection Water Study

A source of water suitable for boiler feed water must be identified early in the screening process. Routine water analysis for the common ions, determination of suspended solids, scaling and corrosion tendencies must all be determined. Recommended screening tests are given in Table 3.

Water quality criteria and ion exchange water softening procedures are described by Elias et al.[31]

Reservoir Core Characterization

The characteristics of the reservoir are an integral part of steamflood process efficiency.

Screening Tests are given in Table 4.

In addition to the petrographic studies and thermal properties tests discussed in the previous section, thermal properties test data are needed for both overlying and underlying rock strata as an aid in estimating heat loss from the pay zone.

Displacement Studies in Porous Media

Injection tests in reservoir core provide a direct measurement of the residual oil saturation after steamflooding (Table 5). Steam quality can be specified, and together with the steam temperature, determine the pressure of the injected steam.

Laboratory steamflooding tests also provide a measurement of the permeability to steam of the rock sample at its final oil saturation. This data can be used to estimate the rate at which steam can be injected into the field. The steam injection rates will determine the rate of heat energy transferred to the reservoir and ultimately will determine the lifetime of the project.

Steam permeability data may also show the effect of clay minerals. When exposed to steam, many geological formations with high concentrations of clays experience severe matrix permeability reduction.[32] In addition to the deleterious effect of clay minerals reacting with steam, dissolved minerals can reprecipitate and cause plugging.[39] If such sensitivity is known, then corrective measures can be planned.[32,34]

Core flooding tests using hot water are ordinarily performed to show the effectiveness of the process in areas of the reservoir unswept by steam. A comparison of steamflooding to hot water flooding is shown in Table 6.

Data from the laboratory Screening Tests can be used to predict oil recovery in a proposed field project. Gomaa[35] correlates oil recovery to net heat injected. This correlation has been developed into a computer program for the TI 59 calculator.[36]

CHEMICAL PROCESSES

Chemical enhanced oil recovery techniques discussed in this section are shown in Table 1. Polymer flooding, caustic flooding, and micellar/polymer flooding are all evaluated with similar Screening Tests, however, the various chemical techniques are discussed separately in order to highlight the differences of each type of process.

CAUSTIC FLOODING

Caustic or alkaline flooding has been found to be an effective oil recovery process in certain types of reservoirs. A review of field projects is given by Johnson.[37]

Caustic flooding involves the injection of high pH chemicals that react with acidic components of crude oils.[38] The reaction creates transient low interfacial tensions between the aqueous caustic solution and the in-place oil. The low interfacial tensions facilitate oil mobilization in the same manner as micellar/polymer processes. However, the caustic processes create a surface active chemical in-situ rather than the chemical being injected in a microemulsion slug.

For a caustic flood to perform effectively, certain conditions must be met. The crude oil must contain certain organic acids in order to react with injection chemical.[39] There must be a source of water that is compatible with high pH chemicals and the reservoir rock matrix must be insensitive to the injection of the water/chemical solution.

The Screening Tests measure these criteria early in the design program.

Crude Oil Characterization

As before, the first Screening Test is oil characterization. Crude oil quality is of utmost importance for these and other chemical processes. The standard quality tests are recommended plus an additional test for amines (oil field corrosion inhibitors that cause false tests for acid number and affect interfacial tension and rock wettability).

The acid number of the crude oil represents a direct measurement of the amount of organic acid material in the crude oil available for reaction with caustic.[40]

Because wettability alteration has been suggested as one mechanism for oil mobilization in caustic flooding, contact angle measurements are recommended to measure the wettability characteristics of the crude oil. The Screening Test recommended in Table 2 are advancing and receding contact angle measurements by the technique of Treiber, Archer, and Owens.[41]

Injection Water Study

For caustic flooding, water quality standards similar to those for steamflooding are required. Additionally, the introduction of the high pH chemical (caustic) into water containing significant quantities of calcium or magnesium ions is certain to cause precipitation of the hydroxides. If precipitates are formed, then caustic effectiveness is lessened and fluid injectivity is impaired.

As mentioned, water softening tests using ion exchange techniques can determine if treatment of source waters is feasible.

Table 2 shows one of the more significant Screening Tests -- interfacial tension testing. Although classified as an oil characterization test, interfacial tension behavior is strongly dependent upon water solubility and is discussed here.

Transient low IFT tests are measured using the spinning drop technique.[42] These tests are performed to study not only the effect of caustic concentration, but also the effect of brine salinity upon interfacial tension. Results from these studies help define the conditions to be used for subsequent oil recovery tests in reservoir cores.

Reservoir Core Characterization

It is essential to determine the quantity, type, and significance of clays in reservoir formations being considered for caustic flooding. The response of some reservoirs is dominated by clays.[43] In addition to the deleterious effects of clays on caustic slugs, the minerals have significant effect on the estimation of reservoir properties such as porosity, water saturations, permeability, and well log responses. The suggested Screening Tests, therefore, evaluate the presence of clays by a variety of techniques.

Petrographic tests provide a direct measurement of clays. Data is supplemented by cation exchange capacity test data.[44,45]

Water sensitivity tests are performed to determine the alteration in permeability caused by a change in water salinity. Tests are adapted from Hewitt.[46] Fig. 4 gives guidelines for the magnitude of permeability change caused by the presence of clays.

Caustic consumption tests are quantitative measurements of the reaction of the alkaline material with the reservoir rock. Testing procedures are taken from Jennings, et al.[40]

Displacement Studies in Porous Media

Secondary or tertiary oil recovery core tests are performed in reservoir cores to evaluate caustic flooding effectiveness. Experimentation can be done with fresh, native-state, or restored core plugs.

Ordinarily, caustic oil recovery processes do not result in oil bank formation; tertiary oil is, instead, produced at high water-oil ratios and produced emulsions are common. The most useful experimental data is the final oil saturation after caustic flooding (as determined by core solvent extraction techniques) and relative permeability to water before and after caustic flooding. Typical recovery data is shown in experiment No. 5, Table 6.

The industry, as yet, has not reached a consensus on the theory of caustic flooding so that there are few mechanistic theories to develop oil recovery correlations.[47] Additionally, few field projects are available to develop empirical techniques of oil recovery predictions. Currently, the best approach is to develop projected field performance with numerical simulation.

The best and most recent reference to such a project is Edinga et al.[48]

POLYMER FLOODING

Injection of polymer solutions to enhance oil production has been used for a number of years. A review by Chang[49] has discussed field projects. Polymers are generally used to alter the mobility of water injected either as an "improved waterflood" or as drive agents in micellar flooding. Proper mobility control design will insure that the fluids injected in the oil recovery process will provide maximum volumetric sweep efficiency. When properly used, polymers will reduce the flow (the mobility) of injected water through the formation.

Polymers as mobility control agents should be used in caustic flooding processes as well as micellar processes so as to control the flow of the chemical solution through the formation. Screening Tests for all of these systems are discussed below.

Oil Characterization

The most important screening test is, of course, the viscosity of the crude oil at reservoir conditions. When used with the data derived from relative permeability testing, mobility ratios can be determined for optimum flow behavior. This is discussed later.

Injection Water Studies

It is of utmost importance to identify and develop a satisfactory source of injection water for any chemical flooding process, polymer flooding included.

These Screening Tests are the most important of all the polymer tests. The characteristics of the injection water will determine the performance of the polymer solution.

There are several key tests in Table 3.

Rheological tests with polymer solutions are used to measure viscosity characteristics of various products. The tests also show the relative performance of various types of polymers. Standard techniques well characterized in the literature are used for screening.[50]

Reservoir Core Characterization

The key screening tests for reservoir rock characterization are petrographic studies and water sensitivity tests. (Table 4)

Injection waters selected for polymer projects first should be tested in reservoir cores. These experiements insure that there are no incompatibility problems between the source brine and the reservoir rock matrix. These tests have been discussed earlier.

Core tests with polymer solutions serve to measure injectivity behavior of the prototype system. The tests are typically performed in clean water-saturated reservoir cores. Injection rates typical of near well bore conditions are used. Polymer solutions meeting the screening criteria will show good injectivity behavior with no appreciable plugging. It is recommended that several polymer types and grades be evaluated in order to identify systems with optimum performance for subsequent core tests.

Because of the importance of fluid mobility ratios in chemical flooding processes, a significant Screening Test is the determination of water-oil relative permeability. In most cases steady-state tests using fresh or restored state reservoir cores are recommended as the most accurate curves. With this data and with the fluid properties, "unit mobility ratios" can be calculated.[51]

Displacement Studies in Porous Media

Polymer solutions alone do not significantly improve displacement efficiency. Oil recovery stems from improvement in sweep efficiency. Model studies used to predict polymer flood oil recovery performance require more than injectivity data. It is, therefore, necessary to determine the performance of a test polymer solution in reservoir core as a function of concentration and at varying frontal advances (shear rates).

Multistep tests are performed under reservoir conditions to choose optimal polymer concentration and to collect required data for subsequent simulation studies.

MICELLAR/POLYMER FLOODING

Micellar/polymer processes are the most promising and widely adaptable of the enhanced oil recovery techniques. These chemical processes have been studied for a number of years and numerous field pilots have been tried. A review has been given by Gogarty[52] and later by Lake and Pope[53] with the assistance of Holmes.[54] These processes, when properly designed will maximize both volumetric sweep efficiency and displacement efficiency in the candidate reservoir.

It has only been recently that empiricism has given way to straightforward design. Studies have provided a better understanding of the fundamental mechanisms of the chemical behavior of microemulsions in oil recovery. Research studies in the mechanism of oil recovery are showing that microemulsions formulated to give "middle phase behavior" tend to give the best oil recovery performance.[55,56,57] Investigative work is revealing the conditions that must be met to achieve and maintain such systems in flow through porous media. The importance of effective mobility control has been shown, both within the microemulsion slug and for the polymer drive behind it. Laboratory testing criteria have been developed to evaluate both polymers and surfactants more rapidly and more effectively than in the past.[58] It is now possible to design and evaluate both micellar systems polymer mobility control agents early in the screening of an oil reservoir for chemical flooding. These prototype systems are a fundamental part of the screening tests.

Crude Oil Characterization

Equivalent alkane carbon number (EACN) is used to characterize the reservoir oil.[59] With oil properties determined, and reservoir temperature and brine properties known, a prototype microemulsion system can be developed. A successful prototype slug is one which exhibits middle phase behavior when diluted with crude oil and formation brine.

Viscosity of the slug is adjusted by varying the concentration and characteristics of the surfactant and co-surfactant in the formulation. Fig. 5 shows the effect of co-surfactant concentration upon Maraflood™ slug viscosity. This technology developed by Marathon Oil Company avoids the use of polymers in the microemulsion slug to achieve proper mobility control.[57] (Pope et al.[60] and Chiou and Kellerhals[61] most recently have reported polymer-surfactant incompatibilities.)

Injection Water Studies

Water analytical studies are one key to the success of a micellar system design. Selection of the brine to be used has already been discussed in the section on polymer flooding.

Reservoir Rock Characterization

Screening tests for micellar flooding are selected to measure the same characteristics of the reservoir as previous processes.

A key addition to the list involves the measurement of the capillary number of the reservoir core as a function of oil saturation.[62,63] The curve in Fig. 6 shows capillary number versus oil saturation for Baker dolomite compared to the value for Berea reported by Guptra and Trushenski.

Displacement Studies in Porous Media

Prototype microemulsion slugs typically are evaluated in a series of tertiary oil recovery core tests. These tests should be conducted in reservoir rock rather than outcrop sand.

If large diameter core can be obtained, radial core tests offer the most direct procedure.[64] Such tests allow the experiment to be conducted at rates which match or approach field rates (less than 1 ft/day). A typical test is summarized in Table 6.

If larger diameter core is not available, stacked reservoir plugs can be used to create composite long linear cores. Oil recovery data provide measurements of the relative fractions of oil and water flowing in the oil bank and the mobility of the flowing oil water bank. These data together with the oil recovery efficiency are typically used in chemical flooding numerical simulators.

DISCUSSION

For the first time, comprehensive Screening Tests have been presented to test the suitability of enhanced oil recovery in a candidate reservoir. The tests are not meant to be a complete testing program--the technology is too complex for a cookbook approach. Rather they are a compilation of practices and techniques utilized by the industry over the years to define reservoir parameters governing a recovery process.

All of the procedures are only a guideline, however. It is expected that skilled investigators can readily adapt and modify them to fit his or her particular need and requirements.

CONCLUSIONS

1. Laboratory Screening Tests are an essential part of enhanced oil recovery.

2. By measuring fundamental rock and fluid properties, Screening Test data support more elaborate modeling studies.

3. By coordinating Screening Tests, several oil recovery processes can be evaluated simultaneously for a candidate reservoir.

4. By performing an orderly Screening program, critical design criteria can be determined early and testing is completed sooner providing better quality data.

5. By following a coordinated Screening program, the mistakes and omissions typifying "short cut studies" can be avoided.

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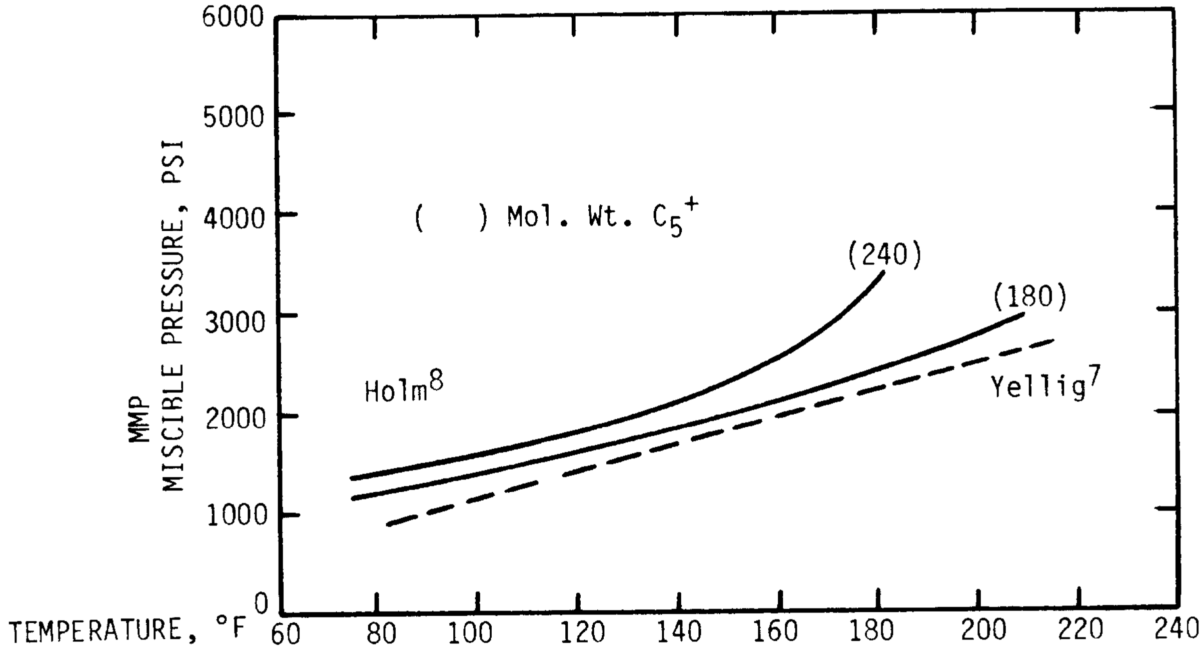


FIGURE 1—PREDICTION OF MMP FOR CO_2-OIL DISPLACEMENT STUDY SCREENING TESTS

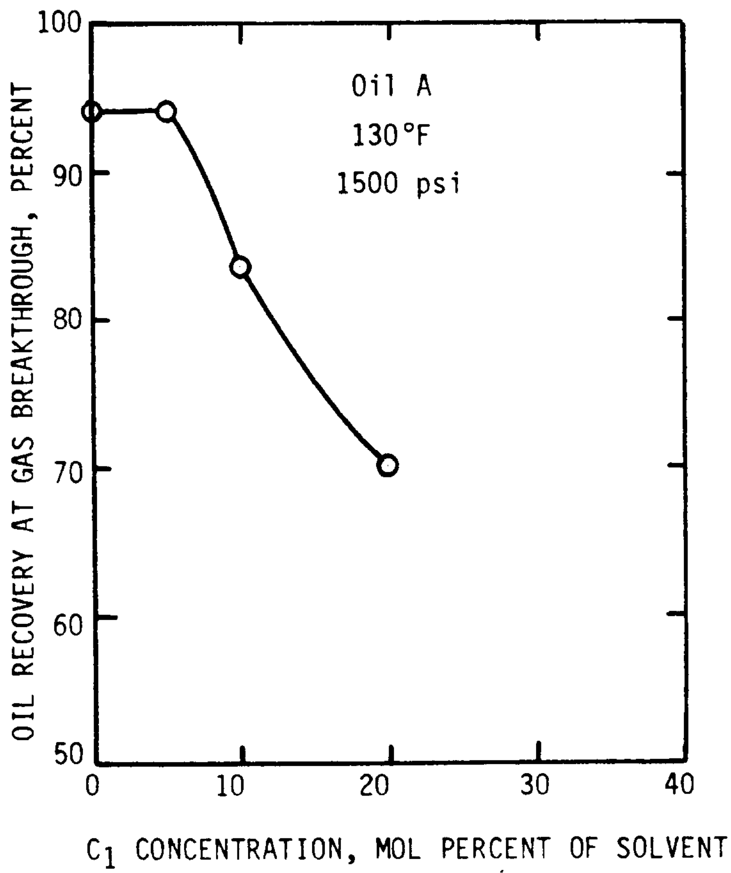


FIGURE 2a—EFFECT OF LIGHT HYDROCARBONS UPON MMP AS DETERMINED BY SLIM TUBE DISPLACEMENT STUDY SCREENING TESTS

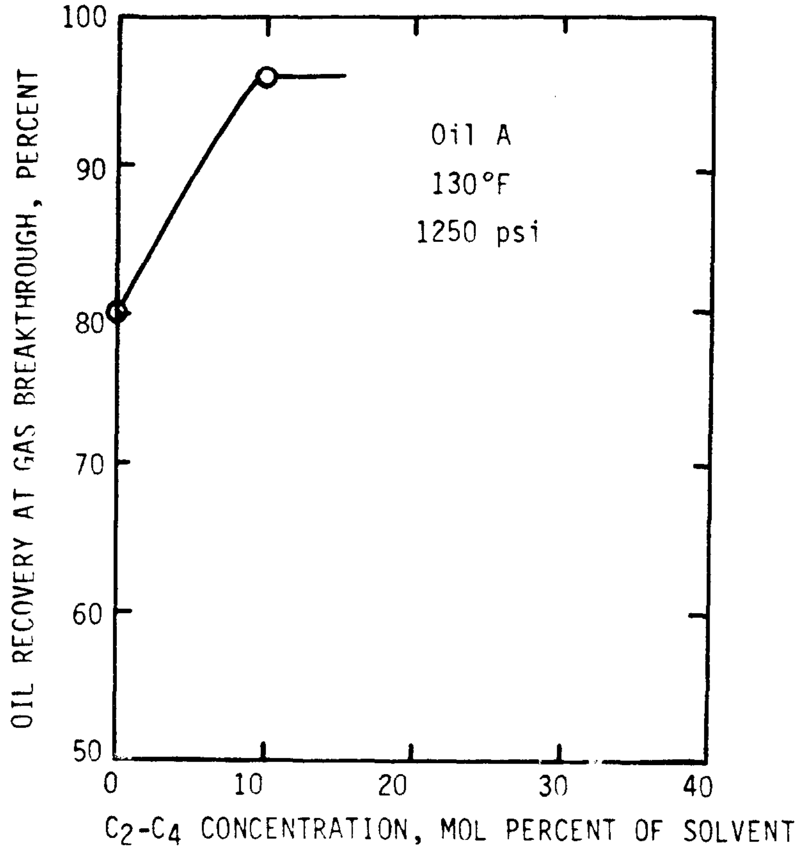


FIGURE 2b—EFFECT OF LIGHT HYDROCARBONS UPON MMP AS DETERMINED BY SLIM TUBE DISPLACEMENT STUDY SCREENING TESTS

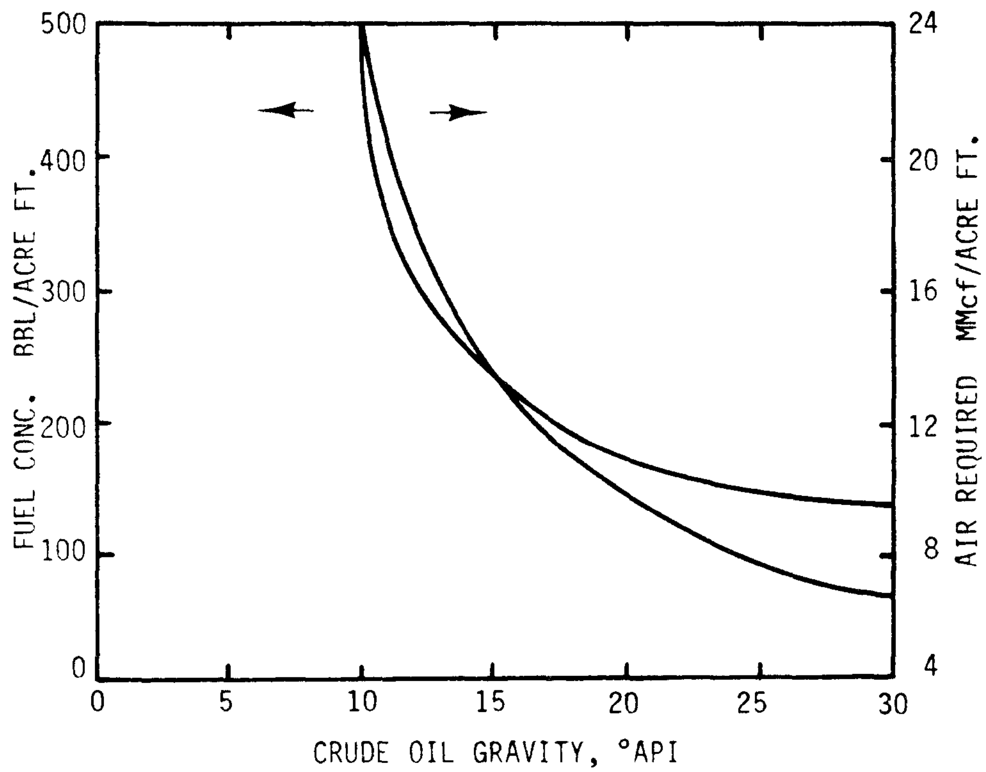


FIGURE 3—AIR AND FUEL REQUIREMENTS FOR IN-SITU COMBUSTION SCREENING TEST (REF. 20)

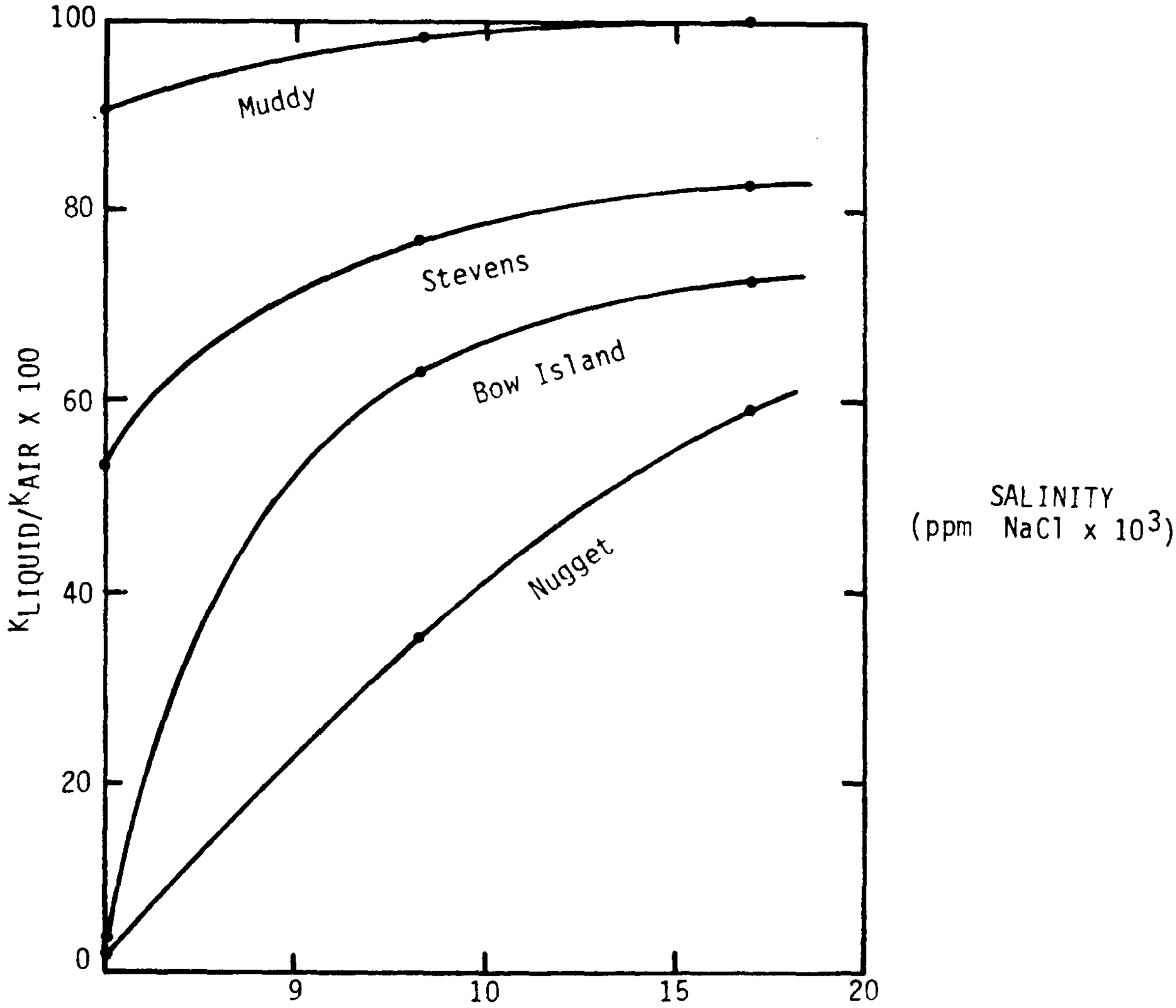


FIGURE 4—PERMEABILITY RATIOS OF LOW, MODERATE AND HIGHLY SENSITIVE RESERVOIR CORES (Ref. 46)

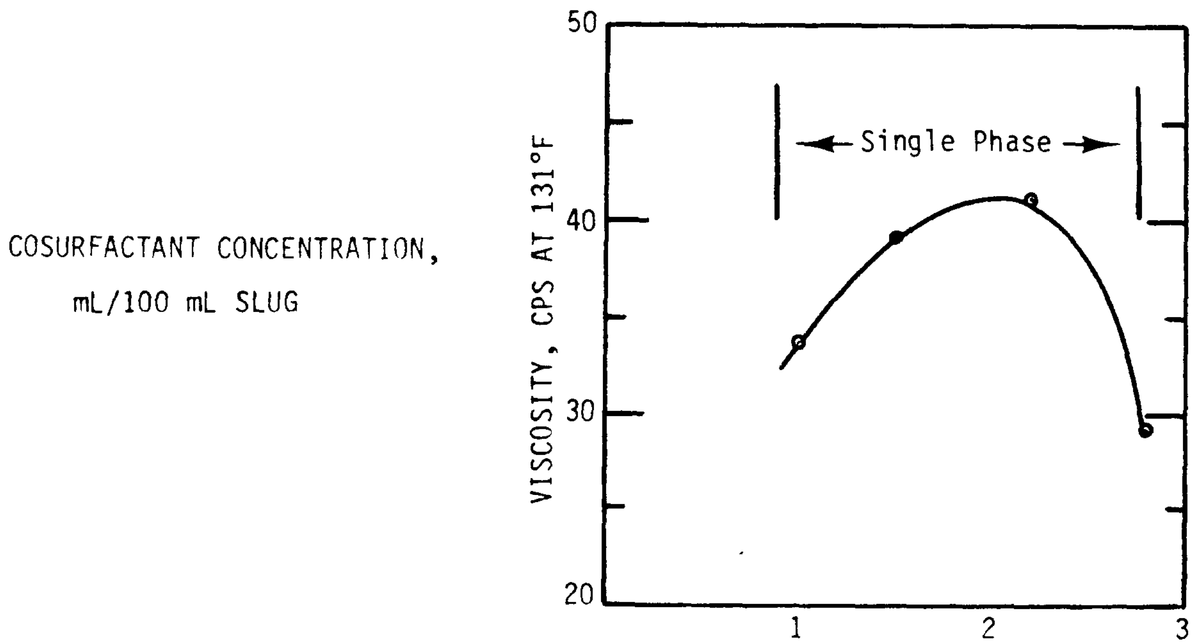


FIGURE 5—VISCOSITY OF PROTOTYPE SLUG INJECTION WATER SCREENING TEST

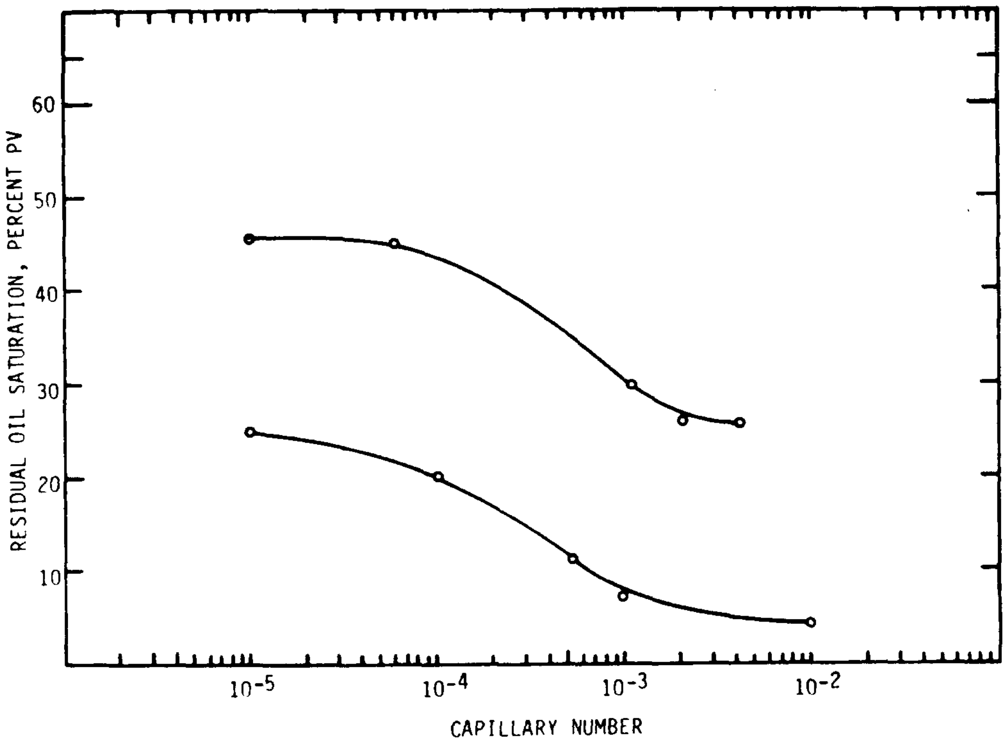
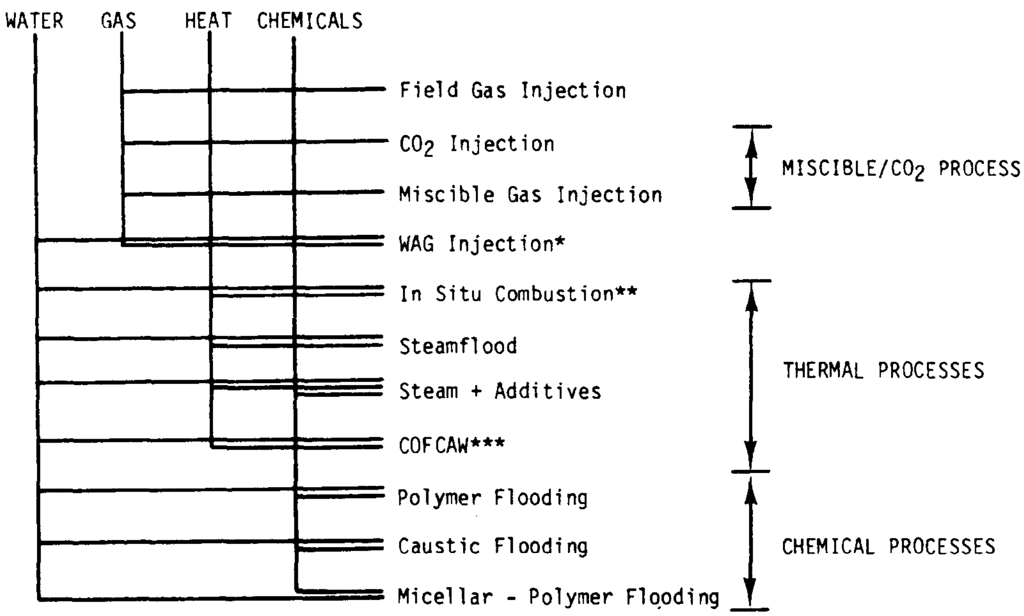


FIGURE 6—FINAL OIL SATURATION VS. CAPILLARY NUMBER CORE CHARACTERIZATION SCREENING TEST

TABLE 1—CLASSIFICATION OF IMPROVED OIL RECOVERY TECHNIQUES



*Water and Gas Alternate Injection
**Fire Flood by Air Injection or Air and Water Injection
***AMOCO Fire Flood Process. Combination of Forward Combustion and Water Injection

TABLE 2—CRUDE OIL CHARACTERIZATION

I. Basic Tests*
- BS&W
- Amines
- Acid Number
- Asphaltenes
- Viscosity
- API Gravity
- Equivalent Molecular Weight

II. Indicator Tests
- Prediction of Minimum Miscibility Pressures (CO_2)
- Determination of Watson Characterization Factor (CO_2)
- Contact Angle
- Interfacial Tension Tests (Caustic)
- Equivalent Alkane Carbon Number (Microemulsions)
- Low Temperature Oxidization and Fuel Deposition (Thermal)

*ASTM Part 23 - Petroleum Products and Lubricants, 1980

TABLE 3—INJECTION WATER STUDIES

- Water Analysis
- Water Compatibility Behavior
- Water Quality Tests
- Rheology Studies (Polymers)
- Bacteriological Studies
- Phase Behavior Tests (Microemulsions)
- Water Softening Tests

TABLE 4—RESERVOIR CORE CHARACTERIZATION

- Petrographic Studies
  (X-Ray, SEM, Lithology)
- Cation Exchange Capacity
- Injection Water Sensitivity
- Relative Permeability
  - Unit Mobility Determination
- Determination of Capillary Number
- Thermal Properties
- Chemical Adsorption Studies

TABLE 5—DISPLACEMENT STUDIES IN POROUS MEDIA

- Slim Tube CO_2 Tests
- In-Situ Combustion Tests
- Steamflood Oil Recovery
- Steam Permeability
- Hot Water Flooding
- Secondary Oil Recovery Tests
- Tertiary Oil Recovery Tests
- Polymer Injection Tests

TABLE 6—DISPLACEMENT STUDIES OF POROUS MEDIA; COMPARISON OF TECHNIQUES

Oil Sample	Reservoir Rock	Screening Test	Terminal Conditions: Oil Saturation, Percent Pore Space	Terminal Conditions: Final Permeability, Millidarcies	Cumulative Oil Recovered, Percent: Pore Space	Cumulative Oil Recovered, Percent: Original Oil in Place
A	Carbonate A	Miscible/CO_2: Direct Injection	18.5	-	69.0	89.0
A	Carbonate A	Miscible/CO_2: Indirect Injection	21.4	-	54.8	71.9
B	Carbonate B	Miscible/CO_2: Indirect Injection	14.1	1.5	20.7	59.5
B	Berea Sandstone	Miscible/CO_2: Indirect Injection	0.50	-	24.8	98.0
C	Sandstone A	Chemical Flood: Caustic Injection	41.0	3.6	5.0	8.2
C	Sandstone A	Chemical Flood: Microemulsion Slug	15.0	7.0	55.0	79.0
D	Sandstone B	Thermal Recovery: Steam Flood, 450°F	18.4	312	31.5	63.1
D	Sandstone B	Thermal Recovery: In-Situ Combustion	*	[218 BbL/Ac.Ft. Fuel Consumption; 15.7 MMCF/Ac. Ft]		
E	Sandstone C	Thermal Recovery: Steam Flood, 400°F	10.8	64	28.2	72.2
E	Sandstone C	Thermal Recovery: Hot Waterflood, 250°F	39.2	27	-	-

*Alternate Calculation