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INSTRUMENTATION AND OPERATIONAL
REQUIREMENTS FOR PILOT-SCALE CO₂
ENHANCED OIL RECOVERY PROJECTS

MASTER

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W. D. Lyle, Jr.
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ABSTRACT

This report describes an instrumentation system to monitor a miscible displacement pilot flood under carefully controlled conditions. The primary focus is on CO₂ flooding but the results apply equally well to other types of miscible floods. Included are discussions of the physical processes in a CO₂ flood, a review of existing CO₂ floods, instrumentation available, site selection and characterization, operation of the flood, simulator evaluation, and cost estimates for this type of project. Throughout the report it is emphasized that determination of residual oil saturation before and after the flood is crucial to evaluation of the results.

1. Introduction

This report is concerned with establishing the instrumentation required to fully monitor and analyze the progress of a CO₂ miscible displacement of reservoir crude oil. Discussions which follow pertain to CO₂ displacement, but the required instrumentation for this type flood should apply equally well to other miscible floods as well. The reason for concentrating on CO₂ flooding is that this process has the potential for recovering as much as 40 percent of all oil to be recovered by enhanced recovery methods.¹

In spite of the advances made in recent years in understanding the CO₂ displacement process, there are deficiencies in the understanding of the process that inhibit utilization of this promising recovery technique. The following quotation taken from Ref. 2 best illustrates the source of this deficiency: "It is concluded from this survey that the most significant deficiency in research on CO₂ flooding for the recovery of crude oil is the paucity of well controlled and interpreted field tests." The primary motivation for this report is to describe a system that, if implemented, would eliminate this deficiency.

Normally, and in this report, CO₂ flooding is viewed as a tertiary recovery technique following a secondary waterflood. However, CO₂ may also be used as a secondary method in low permeability reservoirs or in reservoirs containing heavy crudes. The North Cross Unit and the Lick Creek Field discussed in more detail in Section 3 are respective examples of these secondary CO₂ floods.

The primary purpose of an enhanced recovery pilot project is to determine the economic merits of extending the pilot to a field wide project. Laboratory studies using slim tubes have demonstrated that CO₂ can displace virtually all the residual oil in the swept area whenever miscibility is achieved. However, in previous field applications the extent to which this had happened was difficult to evaluate. This is not surprising in light of the incomplete understanding of the phenomenology of the CO₂ displacement process and the complexity of a real reservoir. The effects of viscous fingering, gravity segregation and permeability stratification existing in the real world are small or nonexistent in the laboratory. Real reservoirs which include these effects respond in such a way as to

reduce the sweep efficiency to a value much less than one. Whenever this happens much of the residual oil will not come into contact with the CO_2 and remains in the reservoir. Additionally, the conditions under which miscibility occurs may not be achieved in the reservoir with resultant suboptimal displacement of the crude that does come into contact with the CO_2 . It is important to clearly understand what miscible displacement means and following Ref. 3 miscible displacement will be defined as "the displacement of crude oil from pore space using a solvent action that prevents formation of interfaces between driven and driving fluids." Miscible displacement as defined above will be used in this report. An overview of the physics of CO_2 miscible displacement is given in Section 2.

Past projects have encountered difficulties in evaluating the performance of CO_2 floods. These difficulties arise not only from the complexity of the processes but also from serious problems in interpreting the data collected during the flood. A survey of the available literature suggests that this second problem is related to the following factors:

1. A lack of detailed knowledge of the composition of injected and produced fluids and a failure to obtain a continuous record of temperatures, pressures, and flow rates,
2. Inadequate knowledge of the type and the accuracy of data from a pilot flood required to provide for meaningful simulator projections of reservoir response,
3. Lack of knowledge of the composition and PVT properties of the reservoir fluids during the flood. This relates to the question of the extent to which miscible displacement is taking place within the reservoir,
4. Inaccurate determination of initial and final residual oil saturations,
5. Lack of knowledge about the extent of frontal instability due to fingering and the degree of stratification occurring in the reservoir during a flood.

Based on the above, it appears that a need exists for one or more additional pilot tests using state-of-the-art instrumentation and data acquisition systems to address and rectify these deficiencies. Such a test should also have several additional goals. First, the pilot would have, as stated earlier, the primary goal of determining the economic viability of extending the pilot to a field wide CO₂ flood. Second, the pilot should provide for improvements in the understanding of the displacement process under field conditions by making available accurate data records of the physical parameters governing the displacement. The third goal would be to establish in a systematic manner the degree and type of instrumentation required to successfully implement future commercial pilots. Finally, one wishes to provide a means of evaluating the predictive capabilities and limitations of miscible displacement simulators. Both these latter goals would be strongly influenced by the particular geological and fluid properties of the reservoir.

The remainder of this report examines the characteristics and requirements for such a fully instrumented field test. The next section begins this process with a review of the physics of CO₂ miscible displacement. Following this are sections on available instrumentation, site selection, site characterization, field operation and on-site testing, simulator evaluation, cost estimates, and finally a concluding section which identifies areas where more research is needed.

2. Physical Basis of CO₂ Miscible Displacement

The following characteristics of CO₂ originally tabulated in Ref. 4 are effective in removing oil from porous rock.

1. It promotes swelling.
2. It reduces oil viscosity.
3. It increases oil density.
4. It is highly soluble in water.
5. It exerts an acidic effect on rock.
6. It can vaporize and extract portions of crude oil.
7. It is transported chromatographically through porous rock.

Characteristic 6 above is the important attribute of CO₂ as a miscible recovery agent. Before briefly describing miscible displacement, it is important to note that the first five characteristics enhance recovery without the displacement being miscible in the sense of the previous definition of miscibility. Swelling and viscosity reduction obviously enhance recovery, and the fact that CO₂ is soluble in water causes the water density to decrease whereas characteristic 3 indicates that the oil density increases. The combination of these two makes the density of water and oil closer, reducing the chance of gravitational segregation.

CO₂ is itself not directly miscible with reservoir crudes at attainable reservoir pressures. However, it is believed that miscible displacement results when CO₂ dissolves in the reservoir oil to the point where extraction or vaporization of the lighter ends of the oil occurs, forming a hydrocarbon-enriched gas phase. At a sufficiently high pressure (the minimum miscibility pressure or MMP), the enriched phase becomes miscible in situ with the remaining liquid hydrocarbons and a miscible displacement results. The enriched phase or solvent generated in situ acts in the same manner as if the two fluids were miscible upon injection.

In reality the enriched phase does not have to be a gas phase, and there is evidence that a miscible displacement can occur between two liquid phases, one of which is a liquid CO₂ phase enriched with lighter hydrocarbons extracted from the original reservoir crude. The distinction between vapor-liquid and liquid-liquid in situ miscible displacement appears to depend strongly on the reservoir temperature and the composition of the reservoir crude. It is known that the MMP depends on CO₂ purity, oil composition, and reservoir temperature. One method for estimating the MMP contained in Ref. 1 is shown in Table 1 below.

TABLE 1. METHOD FOR ESTIMATING MISCIBILITY PRESSURE

API Gravity	Miscibility Pressure (psi)	Temperature Corrections	
		Temperature (°F)	Additional Pressure Required (psi)
< 27	4000	120	None
27-30	3000	120-150	+200
> 30	1200	150-200	+350
		200-250	+500

The above method clearly illustrates that heavier oils require larger pressures to achieve miscibility and that increasing the temperature likewise increases the miscibility pressure. Additional techniques for estimating MMP are found in Ref. 8. The effects of CO₂ purity on MMP are further discussed in Section 7 of this report. Whatever technique is used to estimate MMP, it is obvious that initial screening of candidate reservoirs must eliminate those for which MMP is unattainable. This criterion leads in general to reservoirs having light crudes at depths such that the original reservoir pressure approaches the MMP. In fact, Ref. 1 lists the depth requirements for CO₂ flooding as being between 2500 and 7200 ft.

From the instrumentation point of view the exact mechanism of in situ miscibility generation that occurs (if it occurs) in the reservoir is not important. What is important is the capability of the system to detect, monitor, analyze, and record what is taking place in the reservoir. It should be emphasized that the above discussion of the physics of miscible displacement results primarily from laboratory analysis. Reservoir behavior even when miscibility is assumed can depart radically from laboratory scale model results due to fingering, frontal instability, stratification and gravitational segregation of fluids. Thus, a carefully instrumented and operated field test should provide data for determining the magnitudes of the effects of the above "real world" conditions as well as data needed to understand the physics of miscible displacement under reservoir conditions. Therefore, as a preliminary to the discussions of Section 7, it is obvious that high resolution instruments will be required to detect the time of arrival and identify the vertical extent of breakthroughs occurring at unequal times in a vertical zone, and fluid analysis under reservoir conditions will be required to establish the PVT properties of the moving fluids.

3. Existing CO₂ Floods

A number of CO₂ pilot and field tests have been carried out or are currently in progress. The most important groups of projects are discussed below.

A. SACROC Unit^{2,7,8} - The Kelly-Snyder Field located in Scurry County, Texas, comprises the major portion of the Scurry Canyon Field. In 1953, the Kelly-Snyder portion of the field was

unitized by the Scurry Area Canyon Reef Operators Committee (SACROC) with Standard Oil Company of Texas as operator. The field discovered in 1948 was essentially developed by 1951 and water injection began in the SACROC Unit in 1954. In 1968, the decision was made to develop a CO₂ injection program and in 1972, CO₂ injection began.

This project is unusual in the sense that the entire unit was scheduled for injection in three phases with no apparent pilot testing preceding the full-scale three-phase project. Based on studies, it was decided to use CO₂-WAG (water-alternating-gas) injection where slugs of water alternating with slugs of CO₂ were injected. The slug sizes expressed as a percent of the hydrocarbon pore volume (HCPV) were determined by numerical simulator studies. Injection of CO₂ into the area included in Phase 1 began in January 1972 with CO₂ breakthrough occurring in the production wells by mid-1972, a full two years earlier than predicted by the numerical simulators. This breakthrough necessitated a curtailment of oil production in Phase 1 at the end of 1972 due to lack of CO₂ removal capacity from the produced gases. In July 1973, the Phase 1 production was returned to capacity with the completion of additional CO₂ removal plant. This underscores the necessity of evaluating simulator capabilities and limitations.

Overall, the project was rated an economic success by the operator who also offered the following conclusions pertinent to this report:⁸

1. The dominant factor controlling oil recovery by CO₂ processing at SACROC is the geology of the system; i.e., vertical and areal reservoir heterogeneity.
2. Achieving the most economical oil recovery by the CO₂-WAG process requires a level of geologic and engineering sophistication substantially higher than that traditionally applied to normal injection projects using low-cost fluids. This higher level of sophistication applies from the initial project feasibility studies through laboratory core and fluid testing to project design and execution.

It is noteworthy that apparently no determination was made of whether a miscible drive occurred. Additionally, no produced fluid compositional analysis data is available, nor is there any mention

of reservoir fluid samples being taken under reservoir conditions. Therefore, while the project was rated a commercial success, it did not greatly increase our knowledge concerning CO₂ flooding.

B. Willard Unit^{9,10,11} - The Willard Unit of the Wasson Field is the largest of the unitized operations in that completely unitized field. Operated by ARCO, this West Texas Permian Basin Unit has been successfully waterflooded since 1965. In 1972, two separate tests were begun to examine the application of CO₂ miscible displacement to recover the substantial oil left behind after the waterflood.

The first test consisted of eight adjacent CO₂ injection wells on regular waterflood spacing with the reservoir properties in the test area representative of the average for the Willard Unit. The test objectives were to determine if injection rates and pressures could be maintained to achieve miscible displacement, to investigate control measures necessary to avoid CO₂ channeling, and to estimate additional oil recovery.

The second test was designed for short-term investigation of factors affecting fluid flow behavior in this reservoir. The well configuration of Figure 1 was used for this test.

FIGURE 1. WILLARD UNIT WELL CONFIGURATION.

CO₂-WAG injection was the selected test method. This test appears to be the most comprehensive in terms of data collection and

analysis of any reported in the literature. Included among the data collection and analysis activities were measurements of injection rates and temperature at well 32A, frequent logging of well 32AO, and periodic sampling and analysis of the fluid produced in well 32AS. It will become obvious later in this report that this test is the philosophical father of the system described herein, with the major differences being greatly expanded collection, monitoring, and analysis capabilities.

The Willard Unit testing was concluded in 1976 with the decision whether or not to extend the flood field-wide unreported in the available literature. However, the following conclusions pertinent to this report included:

1. A reliable estimate of oil saturation left in the CO₂ invaded zones could not be made because of the uncertainty in the calculated CO₂ and water saturation changes.
2. Flow of water and CO₂ into the formation was dominated by permeability stratification.
3. Stratification rather than gravity segregation has a dominant effect on both waterflood and CO₂ flood behavior with most incremental oil from CO₂ flooding recovered after CO₂ breakthrough.

If there is one aspect of CO₂ flood evaluation that is dominant, it is illustrated by conclusion 1 above. Namely, determination of oil saturation before and after CO₂ flooding is extremely difficult but absolutely vital in predicting the additional incremental oil recovery. Thus, conclusion 1 above implies that estimates of incremental oil recovery due to the CO₂ flood could not be made since the estimate obviously depends on the change in oil saturation.

C. North Cross (Devonian) Unit^{12,13} - The North Cross Unit was formed when the West Texas Crossett Field was unitized by Shell in 1964. The field, originally discovered in 1944, was fully developed by the mid-1950's and pressure maintenance by gas injection was begun in 1964 when the field was unitized. Studies after unitization to determine an effective secondary technique ruled out waterflooding due to the reservoir's low permeability to water. Miscible displace-

ment by CO₂ was determined to be the most attractive technique and in 1970 a comprehensive CO₂-flood design began. CO₂ injection began in April 1972 and is presently continuing.

Two interesting features concerning this project are that this is not a WAG injection due to the low permeability to water but is a pure CO₂ injection; and secondly, like the SACROC, unit the project was instituted field-wide with no pilot or slow phase-in. The published results concerning flood performance conclude that:

1. Compositional analysis of produced fluids indicates that in situ miscibility is the displacement mechanism.
2. The Shell simulator predictions of recovery were overly optimistic, and the simulator was unable to accurately model the reservoir behavior.

Conclusion two above underscores the need for pilot floods to evaluate and calibrate simulators prior to field-wide flooding. Additionally, the conclusion underscores the necessity for continued research aimed at developing more sophisticated miscible displacement simulators than the one used by Shell and documented in Ref. 14.

D. Other Tests - There are several additional CO₂ field floods currently underway. Several of these are in West Virginia and will not be described in detail. However, Ref. 15 reports on the Granny's Creek Project in West Virginia and while short on detail concerning the reservoir behavior and analysis of the produced fluids, it concludes that "from a reservoir standpoint the major problem is that of evaluating the project. It has been calculated that only 3%-6% of the injected CO₂ entered the pattern. If this is true, then oil recovery based on the volume is reasonable. We are currently working with both DOE and two consulting firms to develop a program to evaluate the project."

The above quotation which may appear to focus attention harshly on project shortcomings is nevertheless indicative of the West Virginia project data available in the literature. These projects attempted to establish residual oil saturation through pressure coring, but there is no pre-flood evidence to indicate that a sufficient amount of modeling and flood monitoring of pressures, temperatures, compo-

sitional analysis, etc., were utilized to properly evaluate these projects.

The final CO₂ flood that is ongoing which is of some interest is the Lick Creek Field in southern Arkansas. Information on this flood was obtained from a private source and is sketchy. However, it is known that this particular project is currently active, is apparently an economic success, and is one of the few if not the only CO₂ flood directed at heavy oil. Lick Creek Field, discovered in 1957, contains 17° API gravity oil with initial reservoir pressure of 1200 psi and initial reservoir temperature of 118°F. CO₂ injection into this reservoir began in 1976 as a secondary technique to supplement the solution gas and natural water primary drives. At the time of injection, the reservoir pressure was estimated to be 1000 psi at the boundaries and dropping near 150 psi in the center. Injection pressure is approximately 1000 psi. The fascinating point about this reservoir is that for this type of oil, the miscibility pressure far exceeds the injection pressure and therefore miscible displacement is not taking place. Since the project is evidently economically successful, one somewhat surprising conclusion could be that CO₂ drives for heavy crudes are viable enhanced recovery techniques even when miscibility is not achieved. Unfortunately, no published data is available to evaluate the project, but it is probable that a contributing factor is the reduction in viscosity of the original reservoir crude from 160 cp to a value on the order of 20 cp when repressurization of the reservoir due to CO₂ injection occurred. This viscosity reduction characteristic of CO₂ was discussed earlier in Section 2 and warrants further investigation when applied to heavy crude reservoirs. It is worth noting that CO₂ enhancement at pressures below the MMP is one of the reasons Sandia National Laboratories is developing a high pressure downhole steam generator as part of project DEEP STEAM.

4. Reservoir Evaluation and Pilot Monitoring Techniques

In order to evaluate the success of a pilot project, it is necessary to have detailed information about the reservoir both before, during and after CO₂ injection. This data is used to isolate potential problems such as early gas breakthrough due to high permeability strata and to allow reasonably accurate extrapolation to field-scale operations using numerical simulators. A large number

of data points obtained from a variety of testing methods and instruments are potentially available for this task. The outline of these methods and instrumentation systems in this section will serve as background for the more detailed discussion in the next three sections. No attempt is made at completeness and for further information on a particular subject the reader is referred to the references cited.

A. Coring - Coring is a standard technique used to study formation lithology and to obtain data needed for estimates of porosity-relative permeabilities and fluid saturation. Cores intended for use in tertiary recovery projects must be obtained with special care. There are two important reasons for this. First, all coring operations are complicated by the fact that invasion of drilling fluids into the core occurs. As discussed in Ref. 16, steps to reduce this problem are possible using low invasion coring fluids. However, estimates of residual saturation from such cores are often complicated and doubt about their accuracy exists. This is a serious situation since one wishes to know the change in residual saturation as a result of CO₂ flooding. If it is assumed (for simplicity) that the residual oil saturations obtained from cores before and after flooding are independent samples with variances σ_1^2 and σ_2^2 , respectively, then the uncertainty in the change in saturation due to the CO₂ is

$$\sigma_{\Delta}^2 = \sigma_1^2 + \sigma_2^2$$

Therefore, when the sample variances are large, the uncertainty in the change in ROS will be great. This is an important consideration and applies to all methods for estimating ROS and will be examined at length later.

The second reason for exercising special care in coring operations is the necessity of retaining the core under reservoir pressure. Unless this is done, solution gas may evolve from the reservoir crude thereby distorting the saturations as well as the analysis of the entrapped fluids.

B. Pressure Testing - In general, a great deal of pressure testing will have been done before a tertiary pilot begins, and this data should be available. These tests include pressure buildup (or drawdown) in single wells as well as interference or pulse testing with multiple wells. Pressure tests can be used in conjunction with relative permeability data to estimate oil saturation. The accuracy of such estimates in a reservoir nearing the end of secondary production may not be high. However, such testing provides valuable information on wellbore damage and on injectivity efficiency of injection wells. An excellent discussion on pressure testing is given in Ref. 16 and in the well-known monographs specifically aimed at this technology.^{17,18}

C. Well Logging - As in the case of pressure testing, a great deal of well logging should have been done before the pilot begins. The available logs should include those taken when the field was brought on line and those taken during primary and secondary production. The suite of logs and associated analysis may vary considerably depending upon the age of the field. This implies also that the accuracy with which the porosities and residual saturation in the pay intervals are known could be poor.

A summary of available logs is given in Table 2. If it is assumed that sampling and observation wells are to be drilled (see Sections 5 and 6), then logging in new wells will be possible. This has several advantages. First, a complete suite of open-hole logs can be run in a well which has not been produced. This improves the chances of measuring the field-average, as opposed to near-well, residual saturations. Secondly, the log signals can be stored on digital tape to facilitate comparison with logs obtained during and after pilot operation. Finally, a series of log-inject-log tests can be run. This technique was developed during the last decade¹⁶ and allows a considerable increase in the accuracy of residual oil saturation estimates. It will be discussed in detail in Section 6.

D. Tracer Surveys - A relatively simple and straightforward way of evaluating reservoir properties is to use tracer surveys. Normally, this term refers only to the use of chemicals (ethyl acetate, ethyl formate) to measure saturation. However, in this report it is also taken to include radioactive isotopes. Chemical tracers are used

TABLE 2. OUTLINE OF WELL LOGGING TOOLS

Tool	Principle	Purpose	Run In Cased Hole	Comments
Gamma Ray	Detect decay of naturally occurring radioactive isotopes	Study lithology	Yes	Detectors can also be used in tracer studies
Sonic	Measure acoustic transit time in formation	Study lithology determine porosity	No	Used in cased wells to test cement job
Neutron	Measure thermal neutrons and capture gamma rays following high energy neutron emission from source	Determine porosity	Yes	Used in combination with other porosity logs to detect gas zones
Formation Density	Measure Compton scattered -rays from gamma source	Determine formation density, porosity	No	
Spontaneous potential	Measure potential between surface and drilling mud at depth	Determine permeable zones; determine formation water	No	Affected by mud type, shaliness
Resistivity	Measure formation fluids resistivity	Detect presence of hydrocarbons, water estimate saturations	No	Many types of electrical logs used
Pulsed Neutron	Measure thermal neutron lifetime following fast neutron pulse	Locate hydrocarbons; estimate saturations	Yes (Preferred)	Can be used to measure variations in saturations
Nuclear Magnetism	Measure oscillating voltage produced during precession of proton magnetic moment	Detect presence of fluids; estimate saturations	No	Limited field experience

generally in single well tests (inject, shutin, produce) but may also be used in two well tests. In the latter case, there appear to be complications in the interpretation. Tracer tests are particularly suitable for tertiary CO₂ recovery projects because the results are permeability weighted. That is, the tracer tends to flow into higher permeability regions and these are also the regions where CO₂ will preferentially flow. Reviews of the chemical tracer technique are given in References 16 and 19.

Radioactive tracers are used in injectivity tests to determine into which vertical zones the injected fluids are flowing. This is useful in detecting high permeability zones and fractures which lead to poor flood conformance. The possibility also exists that radioactive isotopes could be injected with the CO₂ and then detected at an observation well using gamma detectors (NaI crystals, etc.). This would yield important confirmation about CO₂ flow in the reservoir.

E. Downhole Monitoring Systems - In addition to the methods described above, measurements downhole at sampling and producing wells are desirable. A reasonable set of data includes temperature, pressure, and, in the injection well, the percentage of total flow as a function of depth in the payzone. This latter measurement is obtained from a spinner survey and allows determination of the amount of fluid injected into various layers. Additionally, downhole fluid samples taken and retained under reservoir conditions are needed. Instrumentation for all of these data requirements is currently available.

F. Other Techniques - Several instruments currently under investigation may also be of value in a CO₂ pilot. The borehole televiewer²⁰ is a device for visually examining a wellbore. With recent improvements in signal processing developed by AMOCO, high quality scans in complex reservoirs are obtainable. It appears to be promising as a tool to supplement conventional well logs. The detection of highly fractured zones with the device would be extremely valuable in designing a CO₂ injection system.

The borehole gravimeter should also be considered. References 20-23 provide documentation of this interesting tool and in fact Ref. 20 reports the case of one well, now a producer, that was considered to be dry using conventional logging techniques. Advantages

of the tool are that it can be run in open or cased holes and it has a radius of investigation from tens to hundreds of feet which is far beyond the capabilities of other logging tools. While the accuracy of the tool is unknown, it could be quite good. A field test where other logs are used would be ideal for evaluation of the tool.

5. Site Selection

Since it is widely accepted that the full potential of CO₂ flooding cannot be achieved without miscible displacement, it is necessary to consider as candidate reservoirs only those for which miscibility can be achieved. Early screening of reservoirs capable of withstanding pressurization to MMP (no induced fracturing) can be accomplished by using the estimates of MMP contained in Table 1, Section 2, and comparing this pressure estimate with the original reservoir pressure. This process will result in reservoirs for which miscibility is at least possible. Additional firstcut screening criteria are given in Table 3 below, extracted from Ref. 16. Using geological data, it should be possible to eliminate highly fractured or stratified reservoirs.

TABLE 3. BASIC SCREENING CRITERIA FOR
CO₂-ENHANCED RECOVERY PROJECTS (FROM REF. 16)

Oil Viscosity (cp)	< 10
Oil Gravity API	> 25
Depth ft	> 2300
Temperature F	< 250
Residual Oil Saturation Fraction	> 0.25
Rock Type	Sandstone or Carbonate

All reservoirs which satisfy these criteria should be considered as candidates for the pilot project. At this point, several additional factors such as cooperative agreements with the lease operator must be considered. An important assumption in this report is that the final site will be selected with little or no new testing. The

philosophy here is that for a fixed budget, money is better spent completely characterizing a suboptimally selected site rather than suboptimally characterizing and operating an optimally chosen site. Accordingly, a reasonably complete set of well logs, pressure test results and production data, including water flood operation, are needed. Further, in light of the West Virginia experiences, it would be prudent to consider only fields currently under production but approaching their economic limit. This ensures on-site equipment (pumpers, etc.) in reasonable operating condition.

It is recognized that the primary requirement is to locate an operator with a suitable field willing to participate in such a pilot project. Locating such an operator is beyond the scope of this report and is not considered further.

6. Site Characterization

Following selection of the field for the pilot, a comprehensive program should be carried out to define the properties of the reservoir and formation fluids.

A. Pilot Configuration - An idealized schematic of a CO₂ pilot is shown in Figure 2. Shown are one injection and three logging, sampling and production wells. Well spacing would be field specific and is a function of the expected project lifetime, volume to be flooded and project operating budget. Care should be taken to avoid interwell effects. These matters are beyond the scope of this report and will not be considered further.

While a total of ten wells is recommended, it would be possible to operate the project with one logging, one sampling and one production well. The decision as to how many of each would be determined by the available budget since well costs represent the single largest expenditure of money. The larger number of wells will allow for better determination of sweep efficiency and measurement of the various zones in the miscible displacement. It should be noted that a limited number of wells probably implies a small pilot; in the past, extrapolation from small pilots to full field operation has proven difficult.

FIGURE 2. RECOMMENDED WELL CONFIGURATION.

Each of the fluid sampling wells may require multiple tubing and packers to isolate layers in the reservoir. This complicated completion would allow for fluid sampling in a layer without crossflow between layers. Figure 3 illustrates this type of completion. Additional variations in sampling depth could be obtained by selective in-casing cement and perforating jobs.

B. Determination of Residual Oil Saturation - It has been noted several times earlier that the determination of ROS before and after a pilot is extremely important. There are several definitions of ROS that can be used. However, since a CO₂ flood is normally considered a tertiary process after a waterflood, the following definition of ROS is used: ROS is the oil saturation remaining in the water-swept zones.¹⁶ Many of the techniques reviewed in Section 4 are applicable to ROS determination. Table 4, originally compiled by Wymon²⁴ and here extracted from Ref. 16, lists these methods and describes briefly their history and expected accuracy. Reference should also be made to Table 2 in Section 4.

None of the techniques in Table 4 can be said to yield the "true" residual saturation. There are several reasons for this. First, several of the methods actually require two or more measurements. Consider, for example, the conventional use of a pulsed neutron log (PNL) in a cased hole. In order to obtain a good saturation estimate, the following conditions should be met:²⁵

1. water salinity $\geq 50,000$ ppm
2. porosity greater than 15%
3. reasonably shale-free formations
4. known lithology
5. known hydrocarbon type.

The last two are needed in order to obtain Σ_{ma} and Σ_h ; the total macroscopic neutron-capture cross-sections for the rock matrix and the hydrocarbon. In addition, one needs to account for neutron diffusion and wellbore effects. Finally, it should be noted that in order to obtain the oil saturation, one needs to know the porosity, say from a neutron or formation density log and that the oil saturation will actually be deduced from the water saturation. Uncertainties on the order of 10% in the ROS estimate appear typi-

FIGURE 3. POSSIBLE COMPLETION SYSTEM FOR SAMPLING WELLS.

TABLE 4. BASIC TOOLS AND TECHNIQUES TO
DETERMINE RESIDUAL OIL SATURATION¹

Basic Tool	Technique	Can Be Used When Hole is Cased	Has Been Field Tested	Expected Accuracy ²
Reservoir performance	Volumetric deter- mination	Yes	Yes	Poor
Well tests	Pressure Transients			
	Fluid Compressibility	Yes	Yes	Very Poor
	Effective Permeability	Yes	Yes	Poor
	Water-Oil Ratio	Yes	Yes	Poor
Cores				
Conventional	Saturation measure- ments from fresh cores	Core must be cut while drilling holes	Yes	
	Lab flooding tech- niques, imbibition, centrifuge, etc.	Core must be cut while drilling holes	Yes	Poor to Fair
Pressure	Core with specially designed mud	Core must be cut while drilling holes	Yes	Poor to Excellent
Single-well tracer	Backflow hydrolyzed tracers	Yes	Yes	
Logging tools				
	Resistivity	No	Yes	Poor
	Conventional Log-inject-log	No	Yes	Good to Excellent
Pulsed neu- tron capture	Conventional	Yes	Yes	Poor
	Log-inject-log with waterflood	Yes	Yes	Good to Excellent
	Log-inject-log with chemical strip	Yes	Partially	Fair to Good
Nuclear magne- tism ³	Inject-log	No	Yes	Excellent
Carbon/Oxygen	Conventional	Yes	Yes	Poor
Gamma radia- tion	Log-inject-log	Yes	No	Unknown (but could be excellent)
Dielectric constant ³	Conventional	No	Partially	Unknown

1. Adapted from Wyman²⁴

2. Expected accuracy at 2 standard deviations-percent pore volume:
Excellent 0-4; Good 4-8; Fair 8-12; Poor-greater than 12.

3. Subject to "well-bore" errors because of shallow penetration

cal.¹⁶ Further, it should be remembered that the radius of interrogation is restricted to the immediate vicinity of the wellbore.

Some of these problems can be overcome for the PNL log by using the previously mentioned log-inject-log (LIL) technique. The approach here is to log with the original brine in place, inject water of contrasting salinity, and log again. This allows one to eliminate Σ_{ma} and Σ_h ; knowledge of the capture cross-sections for water at the two different salinities is easily obtained. To calculate the saturation, a value for the porosity is still needed and a series of assumptions about the brine injection process must also be made. In addition to the PNL, variations of the LIL method exist for resistivity and NML logs as well. While the improvement over conventional logs is considerable, problems do remain. An excellent discussion of the practical problems involved in estimating ROS is given in Ref. 26.

From this discussion it is clear that a series of techniques to measure ROS is required. Table 5 (also extracted from Ref. 16) contains a set of suggested procedures. In general, pressure coring, the LIL method, and tracer tests are recommended where such techniques are applicable. Not listed in Table 5 is some method for porosity determination which is also required. It should be noted that the various estimates of ROS can differ significantly. A useful area to study is the application of statistical techniques (error analysis) to obtain a more accurate saturation estimate.

C. Sequence of Events - The sequence of events to fully characterize the site and prepare for site operation assuming the well configuration of Figure 1 is as follows:

1. Drill injection well, pressure core, and log.
2. Drill logging/observation wells, pressure core, and log.
3. Drill sampling wells, pressure core, and log.
4. Drill production wells, pressure core, and log.

Normally, a CO₂ flood follows a waterflood and the injection and production wells may be in place. Thus, drilling and pressure coring of these wells would not be applicable in this case.

Upon completion of the above four steps the next event would be well pressure testing to estimate overall average saturations and wellbore damage (skin factor).

TABLE 5. SUGGESTED PROCEDURES FOR DETERMINING RESIDUAL OIL SATURATION*

Borehole Condition	Conven.	Press.	Resist.	NML	PNC	Single- Well Tracer	Well Testing Methods
<u>Open Hole</u>							
New Hole		1		1	2	2	3
Old Hole (To Gauge)			2	1	1	2	3
Washed Out							
(No Cores)			2			1	3
"Shot"			?			1	3
<u>Cased Hole</u>							
Previously Cored	2				1	2	3
Not Cored					1	1	3
Washed Out or							
Disturbed Zone						1	3
Around Borehole							
Hydraulically Fractured - no method applicable							

Note:

- 1 First Choice
- 2 Second Choice or Additional Backup
- 3 Supplementary Measurement
- * Adapted from Wyman²⁴

Paralleling the field test activities, laboratory analysis of the cores and reservoir fluids would be ongoing. Core analysis is necessary for saturation estimation and relative permeability data which is required to determine saturation from pressure tests. Fluid analysis is required to determine the CO₂-crude oil phase behavior and the MMP.

7. Flood Operation and On-Site Testing

Proper site operation will require lifting units on each production well and gas-oil and water-oil separator units preferably on each production well to allow for determination of the water-oil-ratio (WOR) and gas-oil-ratio (GOR). The analysis of the separator outputs will determine the actual production history and most importantly the injected CO₂ would be recovered here. If the recovered CO₂ is reinjected, careful analysis to ascertain its purity is mandatory prior to reinjection, since it is known that small amounts of nitrogen or methane can greatly alter the miscibility pressure as well as the CO₂-crude oil phase behavior. Thus, reinjection requires continual analysis of the gas and the ability to alter the injection pressure to compensate for CO₂ impurities. Whether or not reinjection is used, the produced fluids should be periodically sampled and analyzed on-site. To insure complete and correct analysis of the production history, the flow rates and fluid heights in each production well will be required. If the fluid height is not closely monitored, some production could be lost due to infrequent pumping or incorrect gas cuts could be obtained by pumping when the fluid level is too low. Therefore, a monitoring device such as a sonic meter should be installed on each production well to record fluid heights and control the pumping cycle.

At each of the wells, bottomhole pressure and temperature measurements are highly desirable in order to form as complete a reservoir description as possible. In the case of the fluid sampling wells, temperature is required in order that a pressure retaining sample can be returned to its downhole thermodynamic state at the surface. Additionally, pressures, temperatures, and flow rates would be monitored at the surface for the injection well and production wells. These measurements would be taken automatically and time tagged by the field instrumentation system.

Frequent logging in the observation wells using a variety of the tools discussed earlier would be a part of site operation. Site personnel would perform the logging using on-site equipment. Among the reasons for having an on-site logging capability is to insure that the transition from brine to CO₂-crude oil mixtures is carefully monitored and recorded. Figure 4 below illustrates the time diagram for this transition.

FIGURE 4. TIME-OF-ARRIVAL DIAGRAM AT LOGGING WELL.

From an operational point of view, the most interesting data will be that available in the transition zone where the miscible displacement occurs. During the transition phase, frequent downhole samples kept at reservoir pressure would be taken and chromatographic analysis of these gas samples conducted on-site. Prior experiments have not provided phase composition information on recovered samples, and one of the main objectives of a fully instrumented project would be to rectify this deficiency. It should be emphasized that sampling under pressure from sampling wells is the only means of unambiguously obtaining this information. The production history, WOR, GOR, and compositional analysis available from production wells provide desirable data, but the phase changes resulting from blowdown in the vicinity of the production well does not allow for the same analysis available from an undisturbed sample in the reservoir.

A further consideration during this transition interval is the possibility of using radioactive or chemical tracers to monitor the CO₂ advance. Available literature does not suggest that this has been done in previous field tests but there are advantages in

doing so. First, the arrival time at the logging well after injection can be accurately established, and second in principal, the vertical distribution of arrival times in the wellbore can be accurately established with high resolution using a gamma log. Chemical tracers would be detected at the sampling wells. This technique could be used by on-site personnel without requiring that outside service contractors be available on short notice.

Measurements of pressures, temperatures, flow rates, fluid compositional analysis, fluid sampling, and logging requires a sophisticated instrumentation system and the remainder of this section describes such a system. Previous sections have described the available instrumentation and what remains is to form a system using the already described instruments as components.

The central component of the system is the instrumentation and control center trailer such as the one illustrated in Figure 5. This trailer would contain the computer and interfaces necessary to record and time-tag all measurements such as pressures, temperatures and flow rates. In Figure 5 the wirelines and slickline used for logging and fluid sampling can be seen. The boom truck illustrated in Figure 6 would be positioned over each well to lower logging, sampling, and pressure/temperature tools using a wireline or slickline from the centrally located instrumentation and control trailer where the downhole measurements would be recorded and analyzed.

Whenever downhole fluid samples are taken, the recovered samples retained under reservoir pressure would be analyzed in a field laboratory such as the one shown in Figure 7. The sample is first returned to the original reservoir temperature and then subjected to a complete compositional analysis using a gas chromatograph and other fluid analysis devices.

The system described above and mounted in trailers as illustrated would allow for continuous monitoring of all aspects of the flood and would provide as complete a data record as technology permits. System cost estimates are presented in Section 9.

At the conclusion of the injection phase of the field test, the crucial post analysis phase would begin. The primary purpose of this phase would be determination of the ROS. Without this determi-

FIGURE 5A. INSTRUMENTATION AND CONTROL TRAILER (FRONT).

FIGURE 5B. INSTRUMENTATION AND CONTROL TRAILER (SIDE).

FIGURE 5C. INSTRUMENTATION AND CONTROL TRAILER (REAR).

FIGURE 6. BOOM TRUCK.

FIGURE 7A. SAMPLING TRAILER (OUTSIDE).

FIGURE 7B. SAMPLING TRAILER (INSIDE).

nation, evaluation of the project would be extremely difficult. All of the tests described earlier for initially determining ROS would be required again. including at least one pressure core taken within the flooded area. This post-testing phase adds considerably to the project expense but correct determination of post-flood ROS cannot be overemphasized.

8. Simulator Evaluation

At various places in this report it was stated that numerical reservoir simulators are virtually the only tools available to extrapolate pilot performance to an entire reservoir. Furthermore, even when pilots are not run, simulators are used to predict the CO₂ slug sizes in WAG injections, time for CO₂ breakthrough, and the incremental field recovery. This section will present recommendations as to how a well-designed pilot test can be used to evaluate simulators and determine needed improvements in both simulators and future pilots. As a starting point, the following conclusions concerning miscible displacement simulators are extracted from Ref. 6 and presented below:

1. Simulators need to account more accurately for the displacement mechanisms,
2. Improved mathematical formulations of the physical processes are needed,
3. More research is needed to develop preferred methods for using available simulators,
4. There is a need for performance data from field trials to evaluate simulator predictions.

A field test of the type described in this report would provide data from which improved mathematical formulations could be developed. The extent to which such an improved formulation might be used in the numerical simulators to model the displacement mechanism depends on the degree of detail needed in the mathematical formulation. Therefore, an improved formulation, while desirable, by no means assures that the numerical model could incorporate the necessary refinements without requiring excessive storage and running times.

Given this possible constraint the question is what additional steps can be taken to evaluate and improve existing simulators. The answer to this question is found by relying on a history match of the simulator output to the field test results during the field test. Recall that this type of field test provides injection rates, pressures, temperatures, compositions of the fluids in the reservoir and at the production wells, and production rates. The trick to simulator evaluation is to history match the simulator to the field test and compare the future predictions after the history match to the production history for the remainder of the field test. Furthermore, the reservoir fluid analysis provides an excellent check on the accuracy of the simulator to model the displacement mechanism.

Paralleling the simulator evaluation should be consideration of the type and amount of data required from future pilots to improve simulator predictions. As noted earlier, in both the SACROC and North Cross (Devonian) Units the simulator predictions were in error, and it may be impossible to increase the predictive capabilities without providing data not normally provided from pilot floods. Therefore, included under simulator evaluation should be the determination of the minimal data requirements necessary to obtain a good history match. This establishes minimal instrumentation requirements for future pilot tests.

A final note is that if a fully instrumented field test were run, the initial planning group for such a test should include those responsible for simulator studies. Without their inputs important data requirements could be overlooked.

9. Cost Estimates

The preferred well configuration for site operation and characterization is that shown in Figure 1, Section 3. There it was also stated that a minimal configuration would consist of one production well, one logging well, one sampling well, and one injection well; whereas the preferred configuration would consist of a triplet of production, logging, and sampling wells. Cost estimates of the preferred configuration will be represented below as Case A costs and cost estimates of the minimal configuration will be represented as Case B costs. Normally, a CO₂ flood would follow a waterflood and in both Case A and Case B below the costs of drilling and com-

pleting the production and injection wells are not included since they would be present in the waterflood operation.

Prior to presenting the Case A and Case B details, the costs of the components common to both configurations will be tabulated. These costs are for the instrumentation trailer, fluid analysis trailer, logging tools, and downhole sampling and measurement tools. All cost estimates are in January 1980 dollars.

<u>Item</u>	<u>Cost</u> <u>(\$K)</u>
1. Instrumentation trailer (including computer, recording equipment, wirelines, and slickline)	500
2. Boom truck	30
3. Fluid analysis trailer (fully equipped)	200
4. Logging tools and displays*	
a. Resistivity	10
b. NML	10
c. PNC	20
d. Gamma	10
5. Downhole fluid sampler	5
6. Downhole pressure/ temperature tools	<u>25</u>
Total	\$810K

*The borehole gravimeter is not listed due to the fact that the EDCON Exploration Data Consultants appear to have the only available commercial tool and based on telephone conversations the purchase cost was given as \$250K.

Well costs including drilling and completion will be assumed to be \$250K with coring costs of \$50K per well. Thus, assuming that the production and injection wells are in place, there will be six wells required for Case A and two wells for Case B with costs of

Case A well costs - \$1800K

Case B well costs - \$ 600K.

Total equipment costs for each case are then

Total Case A costs - \$2610K

Total Case B costs - \$1510K.

The above costs for equipment do not include costs for lifting units and separators on the production wells nor costs for the injection pump at the injection well. Presumably, most of this equipment would be available from the lease operator, and availability would be conditioned on the agreement between the lease operator and the pilot flood operator.

Due to the purchase or development cost of a borehole gravimeter it is recommended that use of this tool be obtained under a service contract.

Finally, the above figures do not include the costs of CO₂ or other fluids to be injected, and do not include site operation costs. The amount of CO₂ required would be determined by the volume to be flooded and the flood lifetime. Operation costs are primarily determined by the project lifetime. Further study would be required to establish these important costs. Allocation of costs between the lease operator and the field test organization is a question beyond the scope of this report.

10. Conclusions

Several conclusions can be drawn from the results obtained in this report:

1. A review of the existing CO₂ floods reported in the literature shows that deficiencies exist in their data collection and analysis capabilities. A system can be developed that is capable of

remedying these deficiencies and is capable of monitoring in more detail the behavior of a reservoir under a CO₂ flood. The system for doing this has been defined above and we expect the quality of the data from such a system to surpass that obtained from prior floods; this is the primary conclusion of this report.

2. Such a state-of-the-art system would provide process researchers with a suitable data record for detailed analysis. Thus, new theories of displacement mechanisms and new simulators could be tested against this realworld data.

3. The third conclusion is that during a pilot-flood using the system described herein, existing simulators could be evaluated. This would present a unique opportunity to determine what modeling improvements are needed in existing simulators. In addition, it would assist in defining the minimal data requirements of future pilot-floods needed to increase simulator accuracy.

4. Throughout this report it has been emphasized that ROS determination is essential to properly evaluate a flood. Research activities aimed at developing improved methods for ROS determination are underway through the Bartlesville Energy Technology Center (BETC). Results from these efforts should greatly aid in this difficult problem. However, there is another aspect of ROS determination that should be emphasized. There is evidence that in past floods available techniques for determining ROS have not always been used to the

maximum extent possible. Therefore, it is recommended that a pilot-flood not be undertaken until the initial oil saturation is established with the greatest accuracy which is possible with the current technology. Doing so could eliminate inadequate project evaluations arising from errors in initial oil saturation that were discovered only after the flood began.

5. To the writers of this report there is one curious omission in the literature concerning ROS that is worth noting. This omission is the lack of any attempt to provide optimal estimates of ROS using what is, in effect, noisy data obtained from logs, tracer studies, and core analysis. References 12, 26 and 27 present in great detail different methods of estimating ROS but no attempt is made to include

all of these into one optimal estimate using the well-developed statistical estimation theory. It should also be mentioned that virtually nothing exists in the open literature concerning the probabilistic distribution of errors associated with a particular technique, and such distributions would be invaluable in assigning confidence intervals to the results.

References

1. Enhanced Oil Recovery Potential in the United States, Office of Technology Assessment, U.S. Congress, Washington, DC, January 1978.
2. "Carbon Dioxide for the Recovery of Crude Oil," University of Southern California Department of Petroleum Engineering, T. Doscher, Principal Investigator, June 30, 1979.
3. Holm, L. W., "Status of CO₂ and Hydrocarbon Miscible Oil Recovery Methods," J. Pet. Tech. (January 1976), 76-84.
4. Holm, L. W. and Josendal, V. A., "Mechanisms of Oil Displacement by Carbon Dioxide," J. Pet. Tech., (December 1974), 1427-1438.
5. Metcalfe, R. S., and Yarborough, L., SPE 7061, "Effect of Phase Equilibria on the CO₂ Displacement Mechanism," presented at Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.
6. Stalkup, F. I., "Carbon Dioxide Miscible Flooding: Past, Present, and Outlook for the Future," J. Pet. Tech., (August 1978), 1102-1112.
7. Dicharry, R. M., Perryman, T. L., and Ronquille, J. D., "Evaluation and Design of a CO₂ Miscible Flood Project - SACROC Unit, Kelly-Snyder Field," J. Pet. Tech., (November 1973), 1309-1318.
8. Kane, A. V., "Performance Review of a Large-Scale CO₂-WAG Enhanced Recovery Project, SACROC Unit Kelly-Snyder Field," J. Pet. Tech., (February 1979), 217-231.
9. Charlson, G. S., Bilhartz, H. L., and Stalkup, F. I., SPE 7049, "Use of Time-Lapsed Logging Techniques in Evaluating The Willard Unit CO₂ Flood Mini-Test," presented at the Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.

10. Bilhartz, H. L., Charlson, G. S., Stalkup, F. I. and Miller, C. C., SPE 7051, "A Method for Projecting Full-Scale Performance of CO₂ Flooding in the Willard Unit," presented at the Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.
11. Bilhartz, H. L., and Charlson, G. S., SPE 7050, "Coring For In-Situ Saturations in the Willard Unit CO₂ Flood Mini-Test," presented at Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.
12. Pontious, S. B. and Thom, J. J., "North Cross (Devonian) Unit CO₂ Flood - Review of Flood Performance and Numerical Simulation Model," J. Pet. Tech., (December 1978), 1706-1714.
13. Henderson, L. E., "The Use of Numerical Simulation to Design a Carbon Dioxide Miscible Displacement Project," J. Pet. Tech. (December 1974), 1327-1334.
14. Todd, M. R. and Longstaff, W. J., "The Development, Testing, and Application of a Numerical Simulator for Predicting Miscible Flood Performance," J. Pet. Tech., (July 1972), 874-882.
15. Conner, W. D., "Granny's Creek CO₂ Injection Project, Clay County, West Virginia," paper C-2 presented at Fourth Symposium of Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, OK, 1978.
16. Determination of Residual Oil Saturation, IOCC, Oklahoma City, OK, (June 1978).
17. Matthews, C. S. and Russell, D. G., Pressure Buildup and Flow Tests in Wells, Vol 1 of Monograph Series, Society of Petroleum Engineers, Dallas, TX (1967).
18. Earlougher, R. C., Jr., Advances in Well Test Analysis, Vol 5 of Monograph Series, Society of Petroleum Engineers, Dallas, TX (1977).

19. Deans, H. A., SPE 7076, "Using Chemical Tracers to Measure Fractional Flow and Saturation In-Situ," presented at the SPE Symposium on Improved Oil Recovery, Tulsa, OK, April 16-19, 1978.
20. Jageler, A. H., "New Well Logging Tools Improve Formation Evaluation," World Oil, (March 1980), 89-103.
21. McCulloh, T. H., Kandle, J. R. and Schoellhamer, J. E., "Application of Gravity Measurements in Wells to Problems of Reservoir Evaluation," paper presented at SPWLA Ninth Annual Logging Symposium, June 23-26, 1968.
22. Schmoker, J. W., "Accuracy of Borehole Gravity Data," Geophysics, Vol 43 (3), (April 1978), 538-542. 23. Jageler, A. H., "Improved Hydrocarbon Reservoir Evaluation Through Use of Borehole-Gravimeter Data," J. Pet. Tech. (June 1976), 709-718.
24. Wyman, R. E., "How Should We Measure Residual Oil Saturation?" Bul. Canadian Petroleum Geology, Vol 25 (2) (May 1977), 233-270.
25. Log Interpretation, Volume II - Applications, Schlumberger Limited, New York, NY 1974 Edition.
26. Bragg, J. R. et al, SPE 7074, "A Comparison of Several Techniques for Measuring Residual Oil Saturation," paper presented at Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.
27. Wesson, T. C., "How to Determine Residual Oil Saturation," Petroleum Engineer International, (December 1979), 25-36.
28. Grame, D. J. and Zana, E., SPE 7060, "Study of a Possible CO₂ Flood in the Rangely Field, Colorado," presented at Fifth Symposium on Improved Methods for Oil Recovery of the SPE, Tulsa, OK, April 16-19, 1978.
29. Yellig, W. F. and Metcalfe, R. S., "Determination and Prediction of CO₂ Minimum Miscibility Pressures," J. Pet. Tech., (January 1980), 160-168.

30. Orr, F. M., Jr., Yu, A. D., Lien, C. L., SPE 8813, "Phase Behavior of CO₂ and Crude Oil in Low Temperature Reservoirs," to be presented.
31. Private communications with Drs. F. M. Orr and J. Heller of New Mexico Petroleum Recovery Research Center, Socorro, NM.

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