FOSSIL ENERGY

DOE/MC/10689-5

DEVELOPMENT OF MOBILITY CONTROL METHODS TO IMPROVE OIL RECOVERY BY CO_2

First Annual Report
October 1, 1979—September 30, 1980

Work Performed for the Department of Energy
Under Contract No. DE-AC21-79MC10689

Date Published—March 1981

New Mexico Institute of Mining and Technology
Socorro, New Mexico

U. S. DEPARTMENT OF ENERGY

Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

NTIS price codes
Paper copy: $ 6.00
Microfiche copy: $ 3.50

DOE/MC/10689-5
Distribution Category UC-92a

DEVELOPMENT OF MOBILITY CONTROL METHODS TO IMPROVE OIL RECOVERY BY CO_2

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U.S. DEPARTMENT OF ENERGY

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I. Abstract

A. Objectives

The ultimate objective of this project is to improve the efficiency of carbon dioxide flooding as an enhanced oil recovery process. This aim is to be pursued by the development of techniques and/or additives for mobility control. Suggested methods will control those non-uniformities in frontal displacement which are due to or aggravated by the unfavorable mobility ratios between the carbon dioxide containing displacing fluid and the displaced oil and water.

Because many other researchers and engineers have worked on these problems, Phase 1 of this project has been to collect, study and assess information about their former and continuing efforts. Much of these investigators' work has been reported in the petroleum engineering and other technical literature. Relevant articles referred to have ranged from fundamental studies of the mechanisms of fluid displacement and frontal stability in porous media to accounts of field operations in ongoing CO_2 flooding projects.

The Phase 1 activity of this project has contributed to the planning of the laboratory work that is to be accomplished in its continuing phases, making possible more detailed decisions concerning the nature of the projected experimental tasks.

To this date, most Phase 2 activity has consisted of the planning and design of laboratory work. This effort has been directed to a dual purpose. The first of these is to prepare a series of experiments which will supply information on mobility control in CO_2 floods, that can be used to improve

their efficiency. Secondly, however, these tests must also be sufficiently convincing to the engineering staffs of operating oil companies to have an impact on the practice of future Enhanced Oil Recovery activity in the field. The first of these purposes is addressed by the plans documented below. The second purpose will be kept in view during these planning and preliminary reporting stages, and must become the primary objective of the later reporting phases of the project.

In case the outcome of the tests carried out in Phase 2 are sufficiently promising, a Phase 3 follow-up on the design of mobility-controlled CO_2 floods would be warranted. Such work would entail the presentation of specific operating and reservoir engineering design rules, based both on the laboratory measurements and comparisons performed in Phase 2, and on further analysis along lines which have been suggested in the literature.

B. Summary of Progress

Phase 1 of this project was completed in July 1980 with the publication of the report "Mobility Control for CO_2 Floods--A Literature Survey". This document[1] makes available to other engineers and researchers an overall view of the practical importance to CO_2 mobility control of many different problems treated in over 150 papers from the petroleum and related literature. The report's topics include the fundamental mechanisms of displacement and displacement instability in porous media, field tests and laboratory experiments on CO_2 flooding, and the methods which have been proposed to alleviate the low sweep efficiency caused by unfavorable mobility ratio. These suggested methods have been grouped, in our survey, into three categories of mobility control procedures. They all involve the reduction of the displacing fluid mobility. Special problems can be expected to arise of course, when that displacing fluid is predominately CO_2.

The first of the three methods is called Water Alternated with Gas, or WAG for short. It has already been utilized in several field operations for the purpose of delaying breakthrough and improving sweep efficiency, in both CO_2 floods[2,3,4], and, in miscible or high pressure gas drives.[5,6] The WAG method is based on laboratory work by Caudle and Dyes[7], and later by Blackwell et al[8], in which simultaneous injection of water with gas or solvent was used to reduce the mobility in and behind the displacement front. The change from simultaneous injection to the use of alternate "slugs" came several years later, described in a paper by Fitch and Griffith.[9]

A second method which has been proposed for mobility control is the use of "foam"--a dispersion of gas or solvent in water. Several early studies[10,11,12,13,14] demonstrated the marked increase in flow resistance when the rock contained such a surfactant-stabilized dispersion. Under certain conditions the decrease in mobility could even result in complete stoppage of flow--a phenomenon applicable in such auxiliary uses as sealing gas storage reservoirs.[15,16] Although much fundamental understanding has been gained on the surface chemistry of the films involved in such dispersions, the selection and synthesis of optimum foaming agents or foamants is still largely empirical. Thus in a recent work by Bernard, Holm and Harvey,[17] the most effective foamant for a set of CO_2 displacement experiments was chosen from a field of six on the basis of laboratory measurements of the time to foam collapse.

The third proposed mobility control method is the use of thickeners. Existing literature on this method has been concerned with the use of polymers which, when dissolved at low concentration in brine, are able to greatly increase its viscosity.[18] Use of a thickened displacing fluid can then increase recovery efficiency in polymer--or in surfactant polymer--floods. In the chapter of the Literature Survey devoted to a review of this usage, possible adaptations of this technology to CO_2 floods are also considered. The general strategy of thickener usage, including the question of how much "transition zone" must be created in the reservoir for effective mobility control, has been examined in several patents and articles.[19,20,21,22,23] These are discussed, with the objective of constructing from them a general method of design for the reservoir engineering of Mobility Control in CO_2 floods.

Activity on Phase 2--experimental design, and laboratory work--was initiated early in the life of the project and has accellerated steadily. First steps in this work consisted of the selection and ordering of several long lead-time items of research equipment, the design and construction of some supporting experiments, and the collection of information from other laboratories on applicable techniques for use with high pressure CO_2 systems. Final, detailed decisions on the nature of the major laboratory tests to be conducted were not made until after completion of Phase 1. These plans, transmitted by the April 1-July 1 Quarterly Report were approved by DOE on August 13, 1980. Since that time substantial progress has been made in carrying out those plans. A suitable dolomite rock sample* has been obtained and cut to shape, a high pressure core holder has been designed and contructed, and preliminary tests made on a foam generation method.

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* This rock was obtained from the J.E. Baker Co., 232 East Market Street, P. O. Box 1189, York, Pa 17405. It has been described in an article in the JPT by J. J. Meister.[24]

In addition to the work outlined above on Phases 1 and 2, some time has also been devoted to consideration of Phase 3--the available methods for optimum mobility control in enhanced oil recovery projects using CO_2. These include preliminary calculations of the growth rate of instability patterns as a function of the mobility ratio between the displacing and displaced fluids, and consideration of the criteria for deciding the necessary reservoir volume fraction of the mobility control slug.

II. Introduction

A. Background

The possibility that CO_2 could be used as a displacement fluid in Enhanced Oil Recovery has long been recognized.[25] The suitability of CO_2 for this purpose results from the combination of its relatively high availability with its generally favorable physical and chemical properties. These latter include high mutual solubility with crude oils, and enough compressibility to enable a density comparable to that of the crude to be attained at pressures of several thousand psi--which can be contained in many oil reservoirs. Both of these factors have recently been discussed by Foster.[26] Detailed information on the displacement of crude oil by CO_2, and on the phase behavior of mixtures of these fluids is currently being produced by research programs at New Mexico's PRRC[27] and elsewhere.[28,29,30]

These phase behavior studies have shown that CO_2 and most crude oils are not completely miscible with each other even at high pressure. Nevertheless because the lighter components of the oils are miscible in all proportions with sufficiently compressed CO_2, and because of the high extractive power of CO_2, there is great similarity to the miscible displacement processes considered earlier by the petroleum industry. As the displacement of a crude oil by high-pressure CO_2 proceeds, a transition zone, composed of CO_2 and the lighter components of the oil, is developed. This "developed miscibility zone" can displace the remaining oil at high efficiency.

Unfortunately the similarity between CO_2 floods and many of the industry's miscible displacement projects extends also to the latter's principal failure mechanism. Particularly in the horizontal liquified petroleum gas (LPG) or enriched gas floods of the fifties and sixties, overall flooding efficiencies fell short of expectations. The inefficiency manifested itself in each case by early breakthrough of the injected solvent, with a resulting drastic reduction in oil production. It is now generally agreed that a major cause of this difficulty was the frontal instability resulting from the severe viscosity contrast between crude oil and solvent.

The shape of the transition zone or front between displacing and displaced fluid in a porous rock is not fixed but develops during a displacement. Evolution of this shape is influenced not only by the distribution of permeability and porosity in the rock, but also by the properties of the fluids, if there is a contrast in density or mobility between them. When the displacing fluid's mobility is higher than that of the displaced, then the induced shape change of the displacement front will be the growth of a set of irregularities or "fingers". It is this instability which leads to inefficiencies of sweep in floods with either CO_2 or LPG as the displacing fluid. The seriousness of the instability--that is, the extent of the decrease in sweep efficiency--depends on the magnitude of M, the ratio of displacing to displaced fluid mobility. In addition, various physical characteristics of the reservoir (such as its heterogeneity and external geometry) as well as economic factors have been used to determine the degree of flooding inefficiency which could be tolerated.

B. Scope of Project

The tasks addressed by this project are all related to the CO_2 flooding situations described above, and have been classified into three phases of activity. These are

*Phase 1: Survey of Existing Literature

This survey has included fundamental work on displacement and displacement stability in porous media and reports of laboratory and field work on displacement by CO_2. Additionally, it covers literature on the means which have been proposed for alleviation of displacement instability--that is, for "mobility control". These include three more or less distinct methods of decreasing the apparent flow mobility of the displacing fluid in order to decrease the rate of growth of the instabilities.

*Phase 2: Experimental Design and Laboratory Work

This phase of project activity includes the planning and detailed design of a major experimental procedure by which various methods of mobility control might be tested for effectiveness. The test procedure is required to be repeatable, so that valid comparisons might be made between successive runs. In this procedure, a given "test core"--a sample specimen of porous and permeable rock, brought to a standard saturation of oil and brine--will be flooded with a CO_2 containing displacement fluid. Instrumentation during these core floods will be used to obtain data from which comparative displacement efficiencies can be calculated. This phase of the project will also include calculation and presentation of the results of the tests.

*Phase 3: Formulation of Field Recommendations

Phase 3 activity will at a minimum consist of the preparation and dissemination of reports about the test results and their implications, to serve as a guide to operating and reservoir engineers on the circumstances under which the various mobility control methods are most effective. In addition, if the results of Phase 2 warrant it, the final phase of this project will also include efforts directed at the integration of these results into more specific recommendations. These may include calculation procedures for the design and assessment of efficiency of CO_2 flooding projects in the oil field.

III. Phase 1: Survey of the Literature

Only the salient points and conclusions of the Literature Survey are discussed in this section, since the survey itself has been published separately.[1]

A. The Effect of Adverse Mobility Ratio

The early studies of flow and displacement in porous media which are recorded in the petroleum literature are mostly concerned with the flow of distinct and relatively non-interacting phases--oil and water, or oil and gas. The first studies[31,32,33] of the influence of mobility ratio on displacement were thus directed principally toward determing sweep efficiency during the waterflooding of heavier oils. Further impetus was given to this research, however, by the idea of miscible displacement--the possibility that oil might be displaced from the reservior with very high efficiency by the use of a miscible solvent as the displacing fluid. At that time, and up through the middle sixties, such light hydrocarbon fluids as liquified petroleum gases (LPG) were inexpensive and plentiful enough to inject as flooding liquids in many oil fields. There was consequently much industry interest in the affect of the high adverse mobility ratio which would be experienced in such uses, due to the low viscosity of LPG. Research on the subject was carried forward in many industry laboratories, both experimentally, (in model flow systems) and theoretically. Despite accumulating evidence of severe fingering[34,35,36,37] in high mobility ratio displacements, several miscible displacement projects[38] were launched and operated. Except for those vertical floods which were properly stabilized by gravity, these solvent displacement projects have generally demonstrated the early breakthrough and low sweep efficiency suggested by their unfavorable mobility ratios.

These field disappointments, coupled with the increasing price and decreasing availability of LPG, have discouraged further field testing and even research on solvent flooding processes. In particular, efforts to discover general remedies for the frontal instability induced by high mobility ratio have been reduced in scope, being carried on mostly in regard to water or surfactant flooding. These efforts have been centered on the further development of polymers[39] by which the brine or surfactant solution itself might be thickened,[18] in order to retard the growth of fingers.

B. CO_2 Floods

The high mutual solubility of CO_2 and oils has been known for more than twenty-five years,[40,41] and there were even earlier suggestions[42,43] that CO_2 could be utilized to induce the vaporization and recovery of light oils. Results of laboratory experiments in which CO_2 was used as a displacement fluid[44,45] were somewhat comparable to those partially miscible displacements which utilized natural gas enriched with intermediate hydrocarbons. These studies, and subsequent work[46,47,27] paved the way for a major and well recognized principle of CO_2 flooding technology. This is, that for a given reservoir temperature and crude oil composition, a definite CO_2 flooding pressure must be maintained or exceeded for high displacement efficiency. This pressure has been irreversibly-(but perhaps erroneously, since complete miscibility is not attained for all mixtures)-named the "minimum miscibility pressure".[48,49] It has recently been suggested that the required solvent power of the CO_2 is related to the density to which it is compressed at a given temperature.[50] Phase behavior and mutual solubility studies have supported direct measurements of the pressure and temperature conditions under which CO_2 can displace oil at high efficiency--approaching 100 percent--in "slim tube" experiments.

As noted by the same investigators, however, the oil displacement which occurs in a reservoir is less than that measured from the slim tube. The lower recovery occurs also in laboratory floods if the lateral dimensions of the flow cell--perpendicular to the average flow directions--are appreciable. The decrease in flooding efficiency is a consequence of non-uniform flow, resulting mostly from frontal instabilities quite similar to those which occur in other unfavorable mobility ratio floods.

C. The Influence of Phase Behavior on CO_2 Flooding

But similarity with hydrocarbon solvent floods is not exact, because there are some special properties of CO_2 displacements that follow from the unusual phase behavior. As a consequence of the complete or partial miscibility of most crude oils with high pressure CO_2, the displaceable fluids can include two or three distinct hydrocarbon-containing fluid phases. Even though the interfacial tensions between these phases may be small, the pressure gradient required to move them through the reservoir can be significantly greater than that which would be required in a purely miscible displacement. It has thus been suggested[51,27,52] that the decreased mobility which is induced in the frontal region by the relative permeability effects of the multiple phase flow might be helpful. The lowered mobility might serve to limit the decrease in sweep efficiency caused by the high overall mobility ratio. To sustain such partially miscible conditions at the front, and to optimize the mobility control benefits, careful pressure control would be required. A procedure for the estimation of the required pressure has been given recently by Orr[53] et al. There thus might be a possibility that the effective mobility ratio in secondary CO_2 floods can be manipulated by the pressure, and kept lower than that calculated simply from the oil and CO_2 viscosities, and relative permeabilities with immobile water.

In addition to the above possibility, there are several other "mobility control" methods which have been proposed. These all involve some means of decreasing the mobility of the injected fluid, in order to reduce the frontal instability and improve the poor sweep efficiency. The applicability of these methods to CO_2 floods has been considered in Phase 1 the project's activities and the possible procedures classified into three categories. These are also discussed in the Literature Survey[1], as well as in the Summary of Progress section of the Abstract to this report.

D. Water Alternated with Gas

The first of these methods uses Water Alternated with Gas (abbreviated WAG) in the attempt to reduce displacing fluid mobility by the injection of substantial quantities of water, along with the CO_2. Although reduction of CO_2 relative permeability does occur, the WAG procedure is not free of uncertainty. Even SACROC, the largest of the CO_2 floods, which utilizes WAG, has had early breakthrough in many patterns,[54] indicating that the decreased mobility is not well controlled. There is also the question of WAG's effect on microscopic recovery efficiency. No matter what the distribution of the injected water, its presence will probably increase the trapping of residual oil, rendering that oil more inaccessible for solution or extraction by the CO_2. Although an early study[55] indicated the existance of oil trapping, it naturally did not directly address the problem raised by it in the use of WAG in CO_2 flooding. That problem is: What is the trade-off between the increased oil recovery gained by reducing the overall mobility ratio and the decreased efficiency of oil displacement due to the induced trapping?

E. Foam

A second method of mobility control appears to offer the most promise, although it is as yet not fully understood. This method calls for the use of "foam"--a high pressure dispersion of CO_2, in water combined with a suitable foamant. The latter component is a surface active chemical which acts to stabilize the foam, preserving the water films which separate the CO_2 into bubble-cells. The flow of such a dispersion through the rock is apparently not describable by the same relatively simple linear equations appropriate for homogeneous fluids. Despite this complexity there is ample evidence that the flow rate is much reduced by the presence of the bubble films. Consequently there have been numerous attempts to utilize foam floods to increase the uniformity of oil displacement. These have included laboratory experiments,[56,14,57] a field test, [58] and a recent demonstration of increased recovery in laboratory situations by a dispersion containing CO_2 at a suitably high pressure.[17] Outstanding questions, in the use of foam for mobility control, are concerned with the influence of the dispersion's distribution perameters, (e.g. concentration and size of bubbles) on the apparent mobility. Also of interest are the characteristies of various foamants in giving stability to the dispersion in the presence of CO_2, salts and oil, and the resistance of the components to adsorption on the rock surfaces.

F. Thickeners

The third mobility control method is the use of thickeners. The method has been developed in water and surfactant floods, in connection with the use of polymers which can greatly raise the effective viscosity of water, even when present in low concentration. The possibility of finding analagous compounds that might be soluble in supercritical CO_2, and would also increase its viscosity, cannot be ignored. Presumably the solubility of such compounds, like that of hydrocarbons, would also depend markedly on the CO_2 density.

A secondary way in which the technology of thickeners might be applicable to CO_2 flooding is in the consideration of the pattern of use of the low mobility fluids. There has been, in connection with polymer flooding activity, some theoretical study to determine the most desirable profile or injection schedule for the application of thickeners. Similar considerations will be necessary both in the use of a possible CO_2-soluble polymer and for the application of foam. The design problems of sizing a slug of mobility control agent, or of shaping its concentration or mobility profile, have been described in several papers starting with an early patent on the grading of viscosity during displacement.[19,20,21,22,23] In any usage of reduced mobility materials for mobility control in CO_2 floods, it appears that this work should be taken into account and extended.

Although the Phase 1 work on this project has been officially completed, it is in a sense still open--both because new literature on these problems is constantly appearing, and because further application of insights and information from the literature to Phases 2 and 3 of the Project must yet be made.

IV. Phase 2: Laboratory Work

Much of the following description is of apparatus under construction at the time of writing. The major objectives of the CO_2 displacement test procedure, and the principal design features of the experiment, had been fixed several months before, and described in the third quarterly report dated July 15, 1980. These, along with further details which have been developed since that time, are recapitalated here. Because design work continues, however, some details of the experimental set-up may yet be altered.

A. Overall View of the Flow and Measurement System

The primary requirement of the flow experiment is that the different methods of mobility control shall be fairly and reliably compared. For this purpose, the experiment is designed so that it can be repeatedly returned to the same condition of fluid saturation. This will be done by means of a standardized procedure of cleaning, brine saturation, oil flooding and brine flooding. To reduce the number and solvency power of the solvents necessary to remove all oil components, crude oil will not be used in the tests. Instead, crude will be simulated by a synthetic oil containing a range of hydrocarbons of varying molecular weights, but with no very heavy naphthenes or asphaltenes. Such a mixture can be expected to exhibit complex phase behavior, with compressed CO_2, comparable to that shown by many crude oils, and yet be easily cleaned up by paraffinic solvents alone.

At the conclusion of the secondary waterflood, the fluid saturating the core will contain a residual oil saturation comparable to that which occurs in the watered-out sections of many oil fields where tertiary recovery by CO_2 is contemplated. In testing and comparing the effectiveness in the tertiary core flood of CO_2 alone, of CO_2 with water, of various "high pressure foams" and of possible combinations of CO_2 with other thickening agents, more than just the recovery efficiency will be measured. The additional observations will be designed to measure the actual flow mobility in the core, and will consist partly of measurements of pressure gradient, taken at four locations along the flow system. At each of these places, pairs of tubes leading to differential pressure transducers will be embedded into the side of the rock. From these readings and the known flow rate and dimensions of the flow system, dynamic values of mobilities can be calculated, so that changes can be followed as the displacement proceeds.

The differential pressure measurements will be supplemented by electrical resistivity data. The purpose of these is to provide a continuous, though qualitative, picture of the brine saturation distribution. In particular, the electrical measurement system is designed to detect differences of saturation along the core. For this purpose, current will be introduced through gold plated mesh current electrodes placed at the fluid inlet and outlet faces. Voltage measurements will then be made between adjacent potential electrodes embedded into the side of the core with a spacing of 0.260 inches (.6604 cm.) Figure 1 is a schematic representation of the flow and measurement system.

The data from the core tests will consist of measurements of cumulative fluid input and oil recovery, of front position and profile, and of flow mobility before, during, and after the passage of the front. All of this information will then be used to assess the sweep efficiency to be expected from a field operation utilizing similar mobility control procedures.

B. The Core Holder

In order to perform the above described tests at reservoir conditions, it is necessary to contain the rock sample in a core holder capable of withstanding the requisite temperatures and pressures. As in the case of the choice of oil, a compromise has been made for the purpose of making a system able to do repeatable standard tests in resonable time. A pressure limit of 17.2MPa (2500 psi) and an upper temperature of 66°C (150°F) have been chosen for the tests. These limits will enclose most of the P-T area in which interesting and economically important phase behavior occurs, but will make no excessive demands on the apparatus and materials of construction.

The coreholder consists of a steel tube 32 inches (81.3 cm) long, of 4 inches (10.2 cm.) ID and 5 inches (12.7 cm.) OD. One end is closed by a threaded-on cap pierced by a central hole for the main flow tube and by two others for introducing hydraulic oil. The other end of the coreholder is fitted with a welded-on flange 7 1/2 inches (19.1 cm.) in diameter. To this flange can be bolted a faceplate pierced by nine holes--one for the central flow tube and eight for the tubes to the four differential pressure transducers. Between the O-rings in the flange and faceplate is clamped a printed circuit board with a radial pattern of 128 conductors, by which signals from the voltage electrodes are led out of the pressure chamber. All of the flow and pressure transducer tubing connections through the pressure vessel walls are electrically insulated, so as not to interfere with the saturation measurements. Construction drawings of the coreholder are shown in Figure 2.

The core itself is coated with a non-conducting and impermeable epoxy resin compound, which also serves to hold in place the voltage electrodes pins and the pressure transducer tubes along the sides of the rock, and the current electrodes and flow distribution plates at the inlet and outlet faces. The coated rock sample is loosely held in place along the center of the core holder by the flow connections, and the annulus filled and pressured with hydraulic oil. In operation the hydraulic pressure in the coreholder will be kept above the upstream flowing pressure in the core by about 100 psi (700kPa).

C. Data Collection and Reduction

Although analog or digital readouts of most of the above measurements will be available as they are made, these indications will be used only for backup and to provide assurance of the system's operation. The principal data-recording tasks will be performed by a Terak 8510a microcomputer.* This is supplemented by peripheral data acquisition circuitry: a digital input/output card (DEC DRV-11), a 16 channel Analog to Digital Converter (ADC) card (Burr Brown MP1215) and an auxiliary multiplexor to handle voltage electrode signals. Data acquisition and reduction programming is written in UCSD Pascal.

The main program will operate continuously during each experimental run. and will periodically call subroutines or procedures designed to switch the ADC to a particular voltage source, read the voltage, perform some numerical computations with the value, and store data or the calculated results in memory. Auxiliary procedures will also keep track of time, and of the cumulative fluid flows, temperatures and various other parameters of the experiment, and occasionally print out intermediate results during each run.

Generally, the computer will not be used for control of the experiment, but only for data acquisition, calculation, and display. This means that each experimental run will be controlled during its operation by the experimenter. All pump controls and valves will all be hand-operated, but the experimenter will be relieved of most of the tasks of taking and recording data.

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* The Terak 8510a microcomputer was bought with the aid of a cost-sharing grant 20-CS-6K-0 from the State Mining and Mineral Resources and Research Institutes, of the U.S. Department of the Interior-Office of Surface Mining, Division of Technical Services and Research.

For example, the computer can be pre-programmed to take over completely the task of scheduling current pulses of alternate direction through the core, and making measurements of the voltage drops between adjacent electrodes along the side of the rock and across a standard resistance in series with it. In the same procedure the computer can then calculate the resistivity and apparent saturation of the corresponding section of the rock.

D. Auxiliary Experiments

In support of the main experimental tests described above, several other problems must be solved experimentally. These have to do with the preparation of flooding fluids.

The largest fraction of the mobility control displacement tests will be evaluations of foamant compositions, concentrations and CO_2/aqueous phase ratios. So that maximum information can be obtained from these tests, it is intended to prepare the high-pressure dispersion of CO_2 in the aqueous phase on line but outside the rock sample, in a separate foam generator. A preliminary design, based on a method used successfully for the generation of uniform air in water foams at atmospheric pressure, has been adapted to high pressure use. This method uses a thin porous plate supporting a small liquid column of water with foamant. The gas is bubbled in from below, through the porous plate, producing foam which passes off through a connection at the top of the cell. The preliminary design, utilizing fine stainless steel mesh, is shown in Figure 3. Whether the high pressure foam produced by this device, or modifications of it, will be sufficiently uniform for the displacement tests, or whether external energy will need to be supplied, is a question which can only be settled by further experiment.

A second possibility for mobility control is the direct use of a CO_2-soluble thickener. An suxiliary experiment which seeks to measure the solubility of polymers or other substances in supercritical CO_2 is shown in Figure 4. This system provides a visual mixing chamber, consisting of a sapphire tube capable of withstanding pressures up to 5000 psi (35 MPa). In this tube, a mixture of liquid or supercritical CO_2 and a sample substance may be stirred by the longitudinal motion of a teflon-covered bar magnet. After settling, the solution may then be displaced at the same pressure over into the bottom of a glass bead-filled test tube contained in a Nitrogen-pressurized stainless steel cylinder. When sufficient solution has been transferred, the inlet valve is closed and Nitrogen and CO_2 bled slowly out of the top of the chamber. As this occurs, the dissolved polymer is precipitated out of the liquid or supercritical CO_2 and condenses onto the glass beads in the lower end of the test tube, where it can be weighed. This experiment, although not yet perfected to a routine operation, may make it possible to select CO_2-soluble polymers which could be used directly as mobility control agents for CO_2 floods.

V. Phase 3 Analysis and Recommendations

At this time, only halfway through the project, it is not possible to anticipate with certainty the character of the flood design recommendations which will result from the experimental work. It seems likely, though, that some conclusions can be drawn in each of three areas. These are enumerated below.

A. Foams - Generation and Application

It is expected that several "high pressure foams" - dispersions of supercritical CO_2 in water containing a suitable foamant--will be investigated. For each of several foamants, data on the optimum concentration, the CO_2/water ratio and on the extent of adsorption on the rock matrix will be sought. Such information is regarded as the major experimental task of the project, in line with the view that high pressure foams offer the best hope for economic and timely mobility control in CO_2 floods. Thus the first task of the Phase 3 analysis will be to use the results of this work to recommend particular foamants and foam generation methods, and to estimate quantities of chemicals needed.

B. Possible Direct Thickeners

The major Phase 3 task in this category will be the analysis of experimental work in search, of CO_2-soluble polymers. Depending on the outcome of this search the analysis may be coupled with an evaluation of the effectiveness of some polymers in laboratory core floods, (including estimates of needed quantities of material in possible field usage). Recommendations for a modified experimental design for more efficient determination of solubility and viscosity may also be in order.

C. Front Design

The final Phase 3 activity will be to develop further the basic principles for the reservoir engineering design of mobility controlled floods. This will assume major importance if the laboratory tests show useful and controllable mobility reductions with either foams or thickeners.

The principles involved were referred to in Chapter 7 of the Literature Survey.[1] They have been discussed by Claridge[22] and Koval,[23] and must be developed further for the case of CO_2 floods. The basic question involves the amount of front stabilization that is needed, to sufficiently delay breakthrough of displacing fluid into the injection wells.

This design choice will be a compromise based on economic as well as technical considerations. This is not only because the application of mobility control procedures may be expensive in themselves, but because they will generally decrease injectivity. Because the only available mobility control methods involve the reduction of displacing fluid mobility, the use of any of these methods will cause some increase in the pressure drop required for a given flow rate. The resulting decrease in production rate will delay to some degree the payout time at which the cost of the procedure is made up by the sale of produced oil. Estimates must be made, during the consideration of any field project, of the extent of this delay time, and of the magnitude of the incremental oil production that will justify the actions that lead to it.

We trust that the results of the analysis to be made in Phase 3 will be of assistance to reservoir engineers and oil company managers faced with the sort of decision referred to above. The effort which can be applied to such matters in the final phase of this project will depend both on the experimental results and on the time available.

References

1 Taber, J.J. and Heller, J.P., "Mobility Control for CO_2 Floods-A Literature Survey," PRRC 80-29, Prepared for the DOE under contract DE-AC21-79MC10689 and for the New Mexico Energy and Minerals Department under contract 68R-3307.

2 Dicharry, R.M., Perryman, T.L., and Ronquille, J.D., "Evaluation and Design of a CO_2 Miscible Flood Project-SACROC Unit, Kelly-Synder Field," JPT. XXV, (November 1973), pp 1309-1318.

3 McRee, B., "West Virginia Co_2 Oil Recovery Project Interim Report," ERDA, 4th Annual DOE Symp, (Aug. 1978), pp c-4/1 to c-4/6.

4 San Filippo G.P. and Guckert L.G., "Development of a Pilot CO_2 Flood in the Rock Creek-Big Injun Field, Roane County, W.V." ERDA Enhanced Methods, C/3-1 to C/3-15, (August 1977).

5 Blanton, J.R., McCaskill, N. and Herbeck, E.F., "Performance of a Propane Slug Pilot in a Watered-Out Sand-South Ward Field," JPT, 22, (1970), pp 1209-1214.

6 Harvey, M.T., Shelton, J.L., and Kelm, C.H., "Field Injectivity Experiences with Miscible Recovery Projects Using Alternate Rich Gas and Water Injection," JPT, 29, (1977), pp 1051-1055.

7 Caudle, B.H., and Dyes, A.B., "Improving Miscible Displacement by Gas-Water Injection," Trans. AIME, 213, (1958), pp 281-284.

8 Blackwell, R.J., Terry, W.M., Rayne, J.R., Lindley, D.C. and Henderson, J.R., "Recovery of Oil by Displacement with Water-Solvent Mixtures," Trans. AIME 219, (1960), pp 293-300.

9 Fitch, R.A. and Griffith, J.D., "Experimental and Calculated Performance of Miscible Floods in Stratified Reservoirs," JPT 16, (November 1964), pp 1289-1298.

10 Bond, D.C. and Holbrook, O.C., "Gas Drive Recovery Process," U.S. Patent 2,866,507, (1958).

11 Fried, A.N., "The Foam Drive Process for Increasing the Recovery of Oil," USBM Report of Investigation 5866, (1961).

12 Bernard, G.G. and Holm, L.W., "Effect of Foam on Permeability of Porous Media to Gas", SPEJ 4, (1964), pp 267-274.

13 Bernard, G.G., Holm, L.W. and Jacobs, W.L., "Effect of Foam on Trapped Gas Saturation and on Permeability of Porous Media to Water," SPEJ, 5, (December 1965), pp 295-300.

14 Marsden, S.S., and Khan, S.A., "The Flow of Foam Through Short Porous Media and Apparent Viscosity Measurements," SPEJ 6, (Mar. 1966), pp 17-25.

15 Albrecht, R.A. and Marsden, S.S., "Foams as Blocking Agents in Porous Media," SPEJ, 10, (March 1970), pp 51-55.

16 Bernard, G.G. and Holm L.W., "Model Study of Foam as a Sealant for Leaks in Gas Storage Reservoirs," SPEJ 10, (1970), pp 9-16.

17 Bernard, G.G., Holm, L.W., and Harvey, C.P., "Use of Surfactant to Reduce CO_2 Mobility in Oil Displacement," SPE #8370, Presented at the 54th Annual Fall Meeting SPE-AIME, Las Vegas, (1979).

18 Chang, H.L., "Polymer Flooding Technology - Yesterday, Today and Tomorrow," JPT, XXX, (August 1978), pp 1113-1128.

19 Weinaug, C.F. and Ling, D., "Production of Hydrocarbon Material," U.S. Patent 2,867,277 (January 6, 1959).

20 Slobod, R.L. and Lestz, S.J., "Use of a Graded Viscosity Zone to Reduce Fingering in Miscible Phase Displacements," Producers Monthly, 24, (1960), pp 12-19.

21 Uzoigwe, A.C., Scanlon, F.C. and Jewett, R.L., "Improvements in Polymer Flooding: The Programmed Slug and the Polymer-Conserving Agent," JPT XXVI, (January 1974), pp 33-41.

22 Claridge, E.L., "A Method of Design of Graded Viscosity Banks," SPE 6848, Presented at 52nd Annual SPE-AIME Meeting (1977), Denver.

23 Koval, E.J., "A Method for Predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media," SPEJ 3, (1963), pp 145-154.

24 Meister, J.J., "A Porous, Permeable Carbonate for Use in Oil Recovery Experiments," JPT 30 (Nov. 1978), pp.1632-1634.

25 Whorton, L.P., Brownscombe, E.R. and Dyes, A.B., "Method for Producing Oil by Means of Carbon Dioxide," U.S. Patent 2,623,596 (Dec. 30, 1952).

26 Foster, R.W., "Carbon Dioxide-Sources and Use for Enhanced Oil Recovery," PRRC Report 80-4 (Prepared for New Mexico Energy and Minerals Departm) New Mexico Institute of Mining and Technology (January 1980).

27 Orr, F.M. Jr., Yu, A.D. and Lien, C.L., "Phase Behavior of CO_2 and Crude Oil in Low Temperature Reservoirs," SPE 8813, Presented at First Joint SPE-DOE Symposium on EOR, (April 1980), Tulsa.

28 Watkins, R.W., "A Technique for the Laboratory Measurement of Carbon Dioxide Unit Displacement Efficiency in Reservoir Rock," SPE 7474, Presented at 53rd Annual SPE-AIME Meeting (October 1978), Houston.

29 Metcalfe, R.S., "Effects of 'Impurities' on Minimum Miscibility Pressures and Minimum Enrichment Levels for CO_2 and Rich Gas

Displacements," SPE 9230, Presented at the 55th Annual Fall Meeting SPE-AIME, Dallas (1980).

30 Mehra, R., Heidemann,R.A., and Aziz, K., "Computation of Multiphase Equilibrium for Compositional Simulation," SPE 9232, Presented at the 55th Annual Fall Meeting SPE-AIME, Dallas (1980).

31 Aronofsky, J.S., "Mobility Ratio - Its Influence on Flood Patterns During Water Encroachment," Trans. AIME, 195, (1952), pp 15-24.

32 Dyes, A.B., Caudle, B.H. and Erickson, R.A., "Oil Production After Breakthrough - As Influenced by Mobility Ratio," Trans. AIME, 201, (1954), pp 81-86.

33 Chuoke, R.L., Van Meurs, P., and Vander Poel, C., "The Instability of Slow, Immiscble, Viscous Liquid-Liquid Displacements in Permeable Media," Trans. AIME, 216, (1959), pp 188-194.

34 Habermann, B., "The Efficiency of Miscible Displacement as a Function of Mobility Ratio," Trans. AIME 219, (1960), pp 264-272.

35 Lacey, J.W., Faris. J.E. and Brinkman, F.H., "Effect of Bank Size on Oil Recovery in the High Pressure Gas-Driven LPG Bank Process," JPT, 13, AH(Aug. 1961), pp 806-814.

36 Perrine, R.L., "The Development of Stability Theory for Miscible Liquid-Liquid Displacement," SPEJ 1, (Mar. 1961), pp 17-25.

37 Perkins, T.K., Johnstone, O.C., and Hoffman, R.N., "Mechanics of Viscous Fingering in Miscible Systems," SPEJ 5, (Dec. 1965), pp 301-317.

38 Craig, F.F., "A Current Appraisal of Field Miscible Slug Projects," JPT, XXII, (May 1970), pp 529-536.

39 Savins, J.G., "Non-Newtonian Flow Through Porous Media," Ind. and Eng. Chem., 61, (1969), pp 18-47.

40 Francis, A.W., "Solvent Extraction with Liquid Carbon Dioxide," Ind. and Eng. Chem, 47, (1955), pp 230-233.

41 Francis, A.W., "Ternary Systems of Liquid CO_2," Journ. Phys. Chem., 58, (December 1954), pp 1099:1114.

42 Pirson, S.J., "Tertiary Recovery of Oil," Paper presented before Central Appalachian Section AIME (June 26, 1941) [Cited in Menzie and Nielsen, JPT 15 (1963) p 1247].

43 Poettman, F.H., "Vaporization Characteristics of CO_2 in a Natural Gas-Crude Oil System," Trans. AIME 192, (1951), pp 141-144.

44 Beeson, D.M. and Ortloff, G.D., "Laboratory Investigation of the Water-Driven Carbon Dioxide Process for Oil Recovery," Trans. AIME, 216, (1959), pp 388-391.

45 Holm, L.W., "Carbon Dioxide Solvent Flooding for Increased Oil Recovery," Trans. AIME, 216, (1959), pp 225-231.

46 Huang, E.T., and Tracht, J.H., "The Displacement of Residual Oil by Carbon Dioxide," SPE 4735, Presented at SPE Symp. on Improved Oil Recovery, Tulsa, (1974).

47 Metcalfe, R.S., and Yarborough, L., "Effect of Phase Equilibria on the CO_2 Displacement Mechanism," SPEJ, 19, (1979), pp 242-252.

48 Yellig, W.F. and Metcalfe, R.S., "Determination and Prediction of CO_2 Minimum Miscibility Pressures," JPT, 32, (January 1980), pp 160-168.

49 Holm, L.W., and Josendal, V.A., "Mechanisms of Oil Displacement by Carbon Dioxide," JPT, 16, (1974), pp 1427-1438.

50 Holm, L. W. and Joseudal, V.A., "Effect of Oil Compositions on Miscible-Type Displacement by Carbon Dioxide," SPE 8814, Presented at the First Joint SPE/DOE symposium on EOR, Tulsa, (April 1980).

51 Pontious, S.B. and Tham, M.J., "North Cross (Devonian) Unit CO_2 Flood-Review of Flood Performance and Numerical Simulation Model, J. Pet. Tech XXX, (December 1978), pp 1706-1714.

52 Henry, R.L. and Metcalfe, R.S., "Multiple Phase Generation During CO_2 Flooding," SPE 8812, Presented at the First Joint SPE/DOE Symposium on EOR, Tulsa, (April 1980).

53 Orr, F.M.Jr., Lien, C.L., and Pelletier, M.T.; "Liquid-Liquid Phase Behavior in CO_2-Hydrocarbon Systems," to be presented at the Division of Petroleum Chemistry Symposium on Chemistry of Enhanced Oil Recovery of the American Chemical Society, Atlanta, March-April (1981).

54 Kane, A.V., "Performance Review of a Large Scale CO_2-WAG PROJECT SACROC UNIT-Kelly Snyder Field," SPE 7091, 5th Symp. on Improved Oil Recovery, Tulsa, (1978).

55 Raimondi P., and Torcaso, M.A., "Distribution of the Oil Phase Obtained Upon Imbibition of Water," SPEJ 4, (March 1964), pp 49-55.

56 Holm, L.W., "The Mechanism of Gas and Liquid Flow through Porous Media in the Presence of Foam," SPEJ, 8, (1968), pp 359-369.

57 Minssieux, L., "Oil Dispacement by Foams in Relation to Their Physical Properties in Porous Media," JPT 26, (1974), pp 100-108.

58 Holm, L.W., "Foam Injection Test in the Siggins Field, Illinois," JPT, XXII, (December 1970), pp 1499-1506.

Experimental Setup - CO_2 Mobility Control Tests

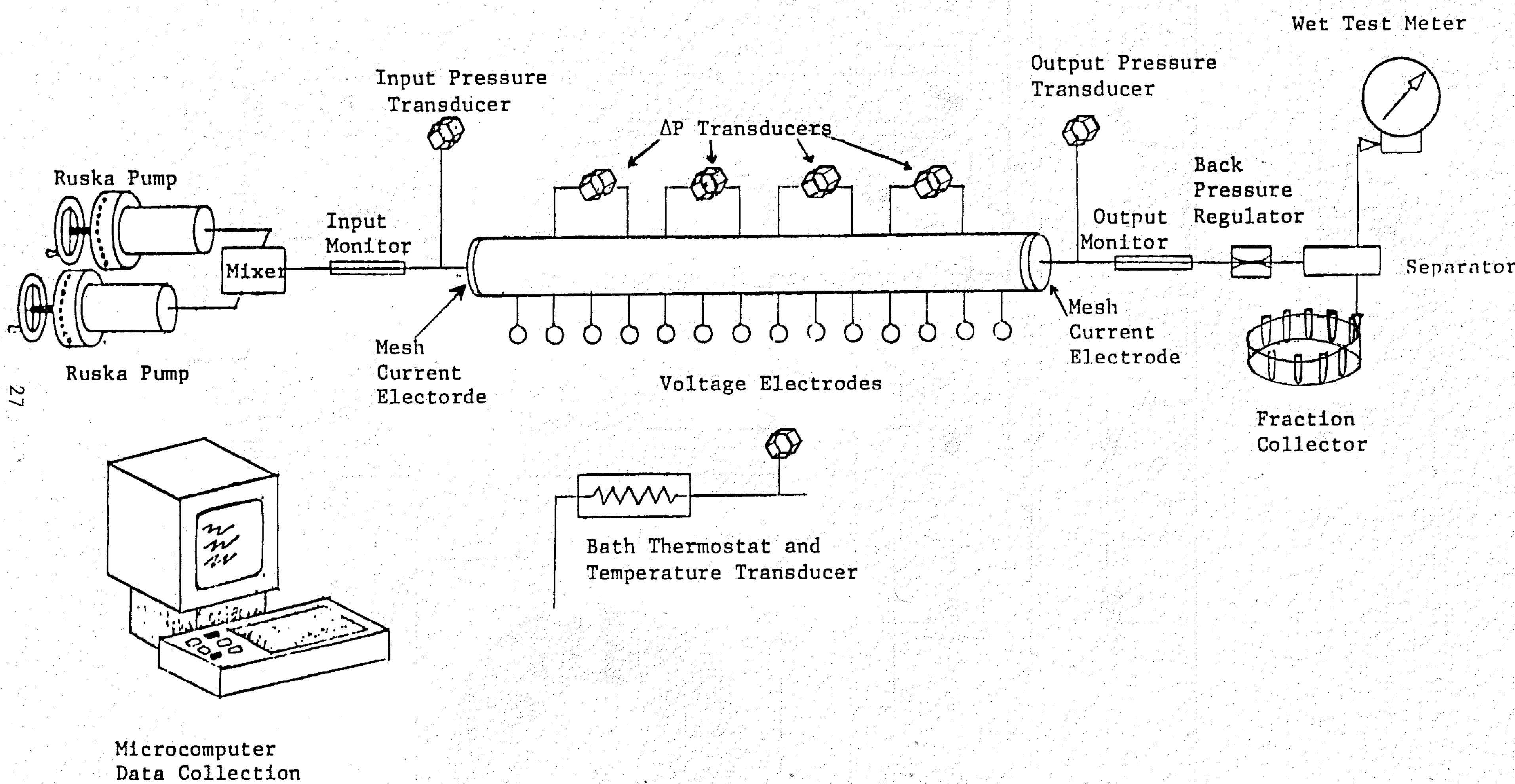
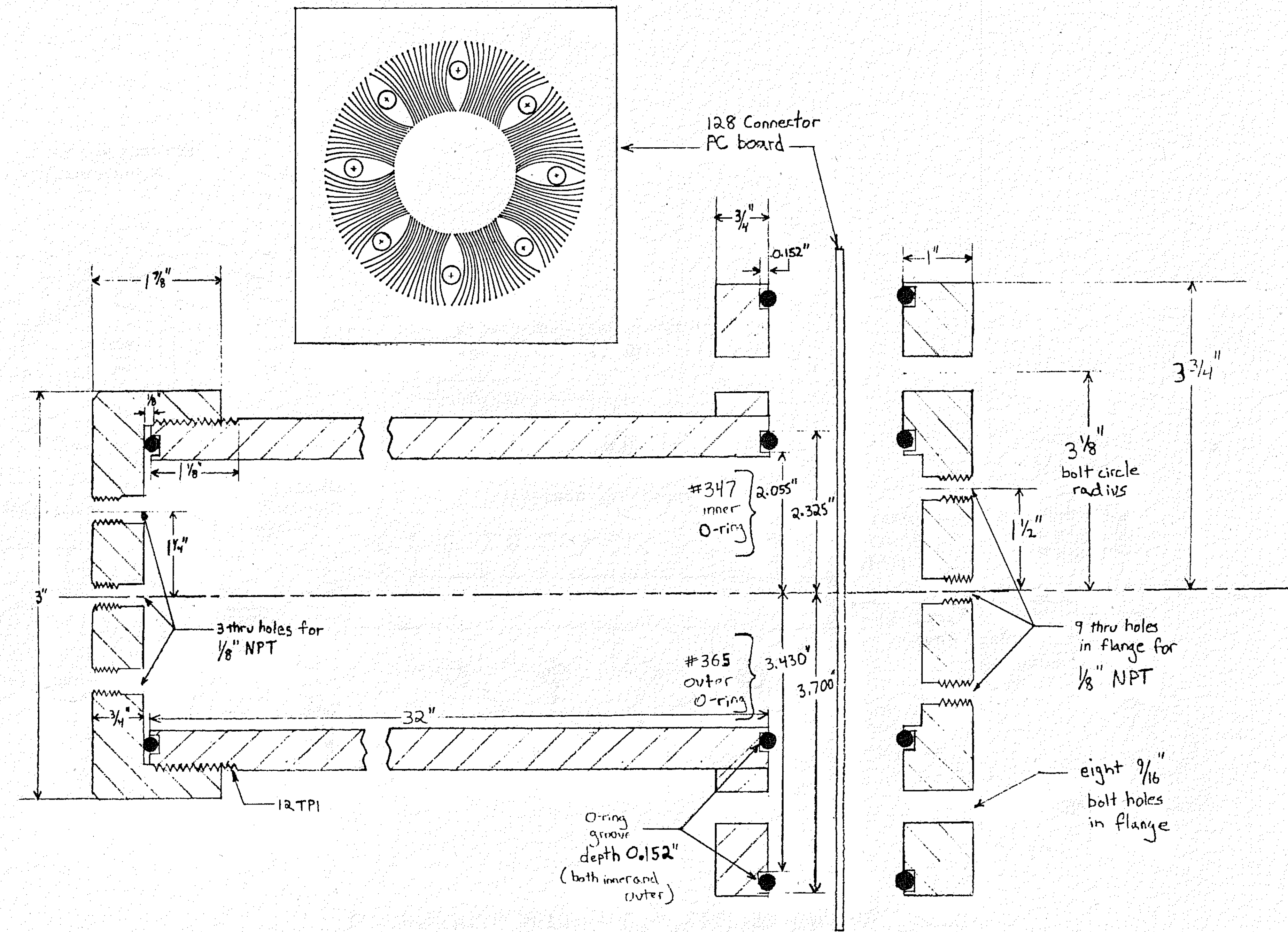
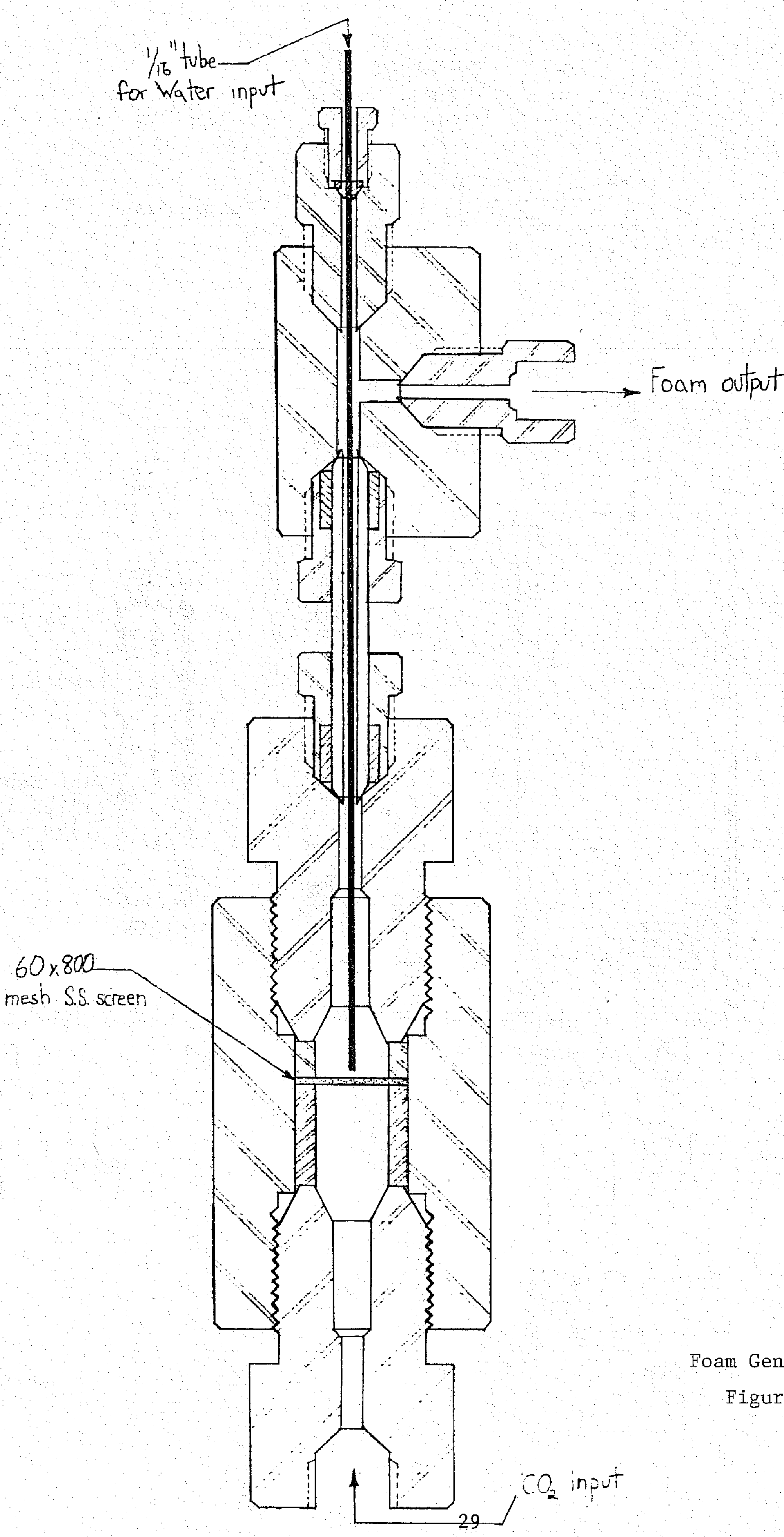


Figure 1



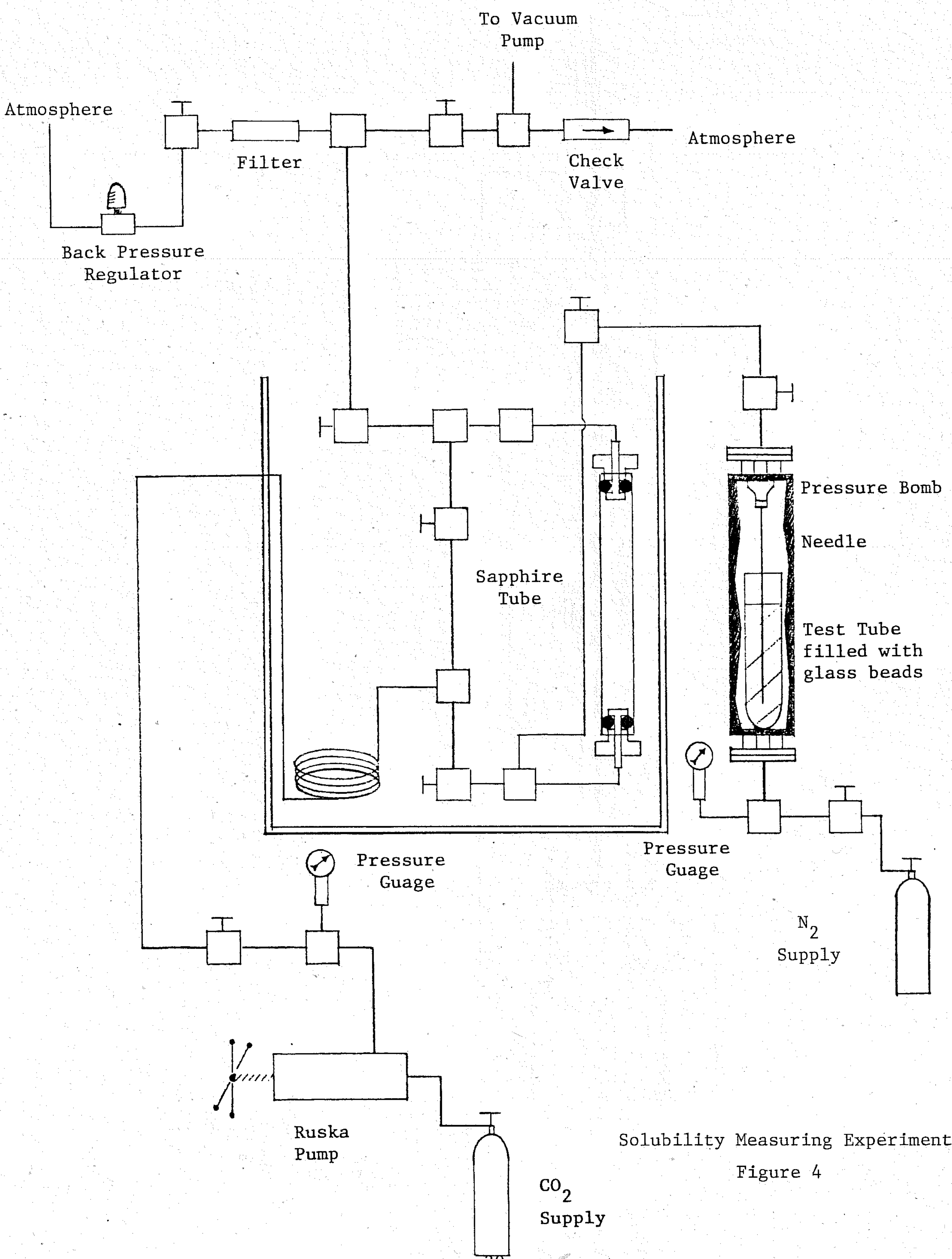
Core Holder Design

Figure 2



Foam Generator

Figure 3



Solubility Measuring Experiment

Figure 4

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