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AN INVESTIGATION OF THE EFFECTIVENESS OF NITROGEN AS A SCAVENGING GAS IN LOW-PRESSURE MISCIBLE-SLUG PROCESSES

by

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ABSTRACT

The low-pressure miscible-slug process consists of the displacement of a slug of solvent through an oil reservoir by a driving fluid, such as natural gas. Reservoir pressure is maintained high enough for miscibility of reservoir oil and solvent, but not high enough for miscibility of solvent and scavenging gas. Propane or butane is generally used as a solvent slug, and methane is generally used as a scavenging gas.

This study was conducted for the purpose of investigating the possibility of substituting nitrogen for methane as a scavenging gas in the low-pressure miscible-slug process. Subject to limitations imposed by the model used for the investigation, the following conclusions have been reached:

1. For a process in which the primary mode of dispersion is mechanical mixing, nitrogen and methane are very nearly equal in efficiency as scavenging gases.
2. The increase in oil recovery which can be obtained with a large slug of solvent may not be great enough to justify the

high cost of a large solvent slug.

3. Under the test conditions, oil recoveries were significantly higher for a scavenging gas pressure of 45 psig than for a pressure of 90 psig.

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INTRODUCTION

Because of the gradually increasing cost of finding new oil reserves in the United States, the production of oil by secondary recovery methods is increasing in importance. Although gas injection and waterflooding are the most widely used methods for secondary recovery of oil, these recovery methods usually leave a large percentage of the reservoir oil trapped in the rock capillary system. Under ideal conditions several of the more recently developed recovery processes will recover more of the reservoir oil than will either waterflooding or gas injection. However, the costs of these processes are high, and careful study is required to determine whether or not any of these processes could be used profitably in a given field.

One of the more recently developed recovery processes is miscible slug displacement. In this process a solvent is first injected into the reservoir; the solvent is then displaced through the rock with a driving fluid, such as methane or water. Frequently, butane or propane is used for the solvent slug and natural gas is used for the driving fluid. The most important advantage of the miscible-slug process is

that it will recover virtually one hundred percent of the reservoir oil from that portion of the reservoir which is swept by the injected fluids.

A conventional miscible slug drive requires miscibility of solvent and driving fluid as well as miscibility of solvent and reservoir oil. If propane is used for a solvent and natural gas is used for a driving fluid, a pressure of approximately 1200 psi is required under typical reservoir conditions to obtain miscibility between the gas and propane (Koch, Jr., and Slobod, 1957, p. 40). Since a pressure of 1200 psi would cause hydraulic fracturing of the reservoir rock in many very shallow oil fields, the miscible slug drive must be modified if it is to be used successfully in these fields.

A modified form of the miscible-slug drive is obtained when the process is operated below the pressure of miscibility of the gas-solvent mixture. With this type of recovery process, the solvent and reservoir oil are completely miscible but the interface between the solvent and driving gas is one of continuous distillation and condensation. This type of recovery process will recover almost one hundred percent of the reservoir oil from that portion of the reservoir which is swept by the injected fluids (Handy, 1963, p. 196). The process is suitable for use in very shallow oil fields, since the reservoir may be operated at a pressure less than the pressure of miscibility of the gas-solvent mixture.

Most investigations of low-pressure miscible-slug processes have been conducted with butane or propane as a solvent and methane

as a scavenging gas. Since miscibility is not obtained between the LPG and the gas in this type of system, the question may be raised whether or not it is necessary to use methane as a scavenging gas. If nitrogen could be substituted for the methane, this process could be used more economically in areas where low-cost natural gas is not available.

Although the possibility of using nitrogen as a scavenging gas in a low-pressure miscible-slug process has been discussed by L. L. Handy (1963), a search of the literature revealed only one laboratory investigation of the process (Csaszar and Holm, 1963). This experimental work concerned the use of the process in tertiary recovery, with both nitrogen and water injection following a propane slug. It was concluded by Csaszar and Holm that either nitrogen or methane could be used as a scavenging gas in this type of process.

It is the purpose of this investigation to compare the efficiencies of nitrogen and methane as scavenging gases under certain simulated reservoir conditions. A steel tube packed with an unconsolidated sand has been used to represent an oil reservoir, and normal butane has been used as a miscible slug which was displaced through the tube by a scavenging gas. The efficiencies of the two gases have been compared from the standpoints of oil recoveries, butane recoveries, and gas volume required to obtain a predetermined gas/oil ratio.

LOW-PRESSURE MISCIBLE-SLUG DRIVE PROCESSES

Two types of low-pressure miscible-slug drives have been described. Both processes involve the injection of a miscible slug, such as butane, followed by a scavenging gas which is not completely miscible with the slug. The difference between these two processes is in the degree of miscibility obtained between the miscible slug and the scavenging gas. In one recovery process the gas and slug are partially miscible. In the other process the gas is essentially insoluble in the solvent slug.

Partially Miscible Scavenging Gas

A solvent slug may be displaced through the reservoir by means of a scavenging gas which is partially miscible in the solvent (Handy, 1963). In this type of system the solvent and scavenging gas form two equilibrium phases in which the vapor phase contains a significant amount of solvent and the liquid phase contains a significant amount of scavenging gas.

The mechanism of the process may be illustrated by means of

a ternary diagram, although this type of representation is not rigorous unless each of the three components consists of a single molecular species. For purposes of comparison, two ternary diagrams are presented below.

Figure 1 represents a three-component system in which the pressure is greater than the minimum pressure of miscibility for the binary gas-solvent system at the existing temperature. Since the two-phase region does not extend to the side of the graph which represents a binary gas-solvent system, miscibility between gas and solvent is indicated. Line A-C represents a limiting tie line, tangent to the two-phase region and intersecting the gas-solvent line at point A. Point A represents the minimum concentration of solvent required for the injected gas to be miscible with an oil of composition D, as indicated on the diagram.

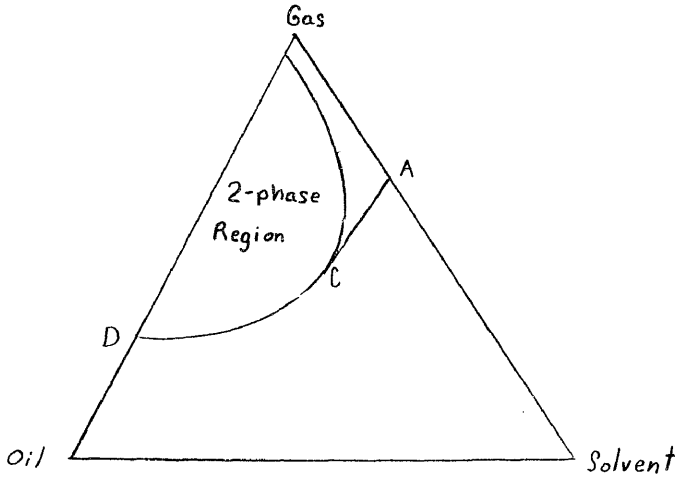


Figure 1 Ternary diagram for oil-gas-solvent system, pressure greater than critical pressure of gas-solvent system

Figure 2 represents the phase relationships in a system in which pressure is greater than the vapor pressure of the solvent but less than the minimum pressure of miscibility of the gas-solvent system. Since the two-phase region extends to the gas-solvent line, there are certain proportions of gas and solvent which will exist as a two-phase mixture. These compositions of gas-solvent mixtures lie between points A and B on the gas-solvent line. Point A represents the composition of the dew point vapor which would be present in such a mixture; point B represents the composition of the corresponding gas-saturated solvent.

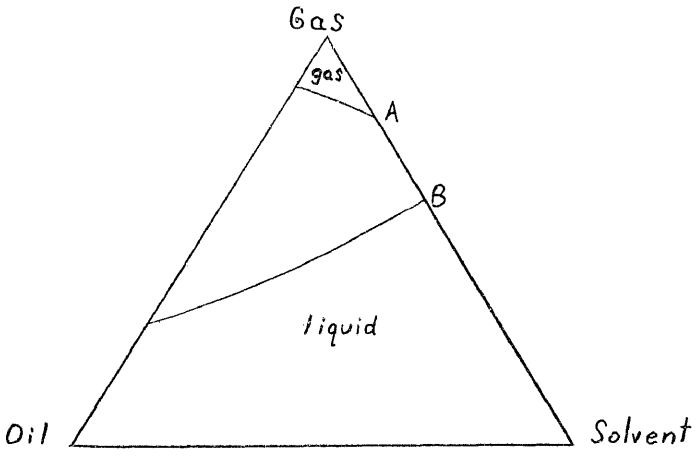


Figure 2 Ternary diagram for oil-gas-solvent system, pressure less than critical pressure of gas-solvent system; gas partially miscible

In practice the solvent may be injected into the reservoir as a slug which is followed by dry gas. Equilibrium will be established in the reservoir between gas and solvent at the area of contact between gas and solvent. In this region the fluids consist of vapor of composition A and liquid of composition B.

Although complete miscibility of solvent and scavenging gas is not obtained in this process, it is still possible to remove essentially all of the reservoir oil from the area swept by the solvent. One significant advantage of the process is that it can be used in shallow reservoirs that could not contain the pressure required for a completely miscible gas-solvent recovery process. Another advantage of the partially miscible gas-solvent drive is that the fingering of the solvent may be reduced (Handy, 1963, p. 202).

Immiscible Scavenging Gas

Another type of low-pressure miscible-displacement process is obtained when the scavenging gas is practically immiscible in the solvent slug. This type of displacement mechanism is obtained when butane or propane is displaced through the reservoir by low-pressure nitrogen. Only a limited amount of data has been published on this process, and it is the purpose of this study to investigate certain aspects of this displacement mechanism. The displacement process may be represented schematically by a ternary diagram, as in Figure 3 on the following page. Since this process is a limiting case of the process in which the scavenging gas is partially miscible with the solvent slug, the ternary diagrams representing the two processes are quite similar. The difference in the two processes, as indicated in Figure 2 and Figure 3, is in the size of the two-phase region. On both diagrams points A and B represent the compositions of the two phases present in an equilibrium mixture of gas and solvent. The

point designated A represents the composition of the dew point vapor, and the point designated B represents the composition of the corresponding gas-saturated liquid. In a low-pressure slug drive with an immiscible scavenging gas, there is little solvent vapor in the gas and little gas dissolved in the solvent of an equilibrium mixture of gas and solvent. Therefore, points A and B are far apart on the ternary diagram representing this system, and the two-phase area covers a large part of the phase diagram.

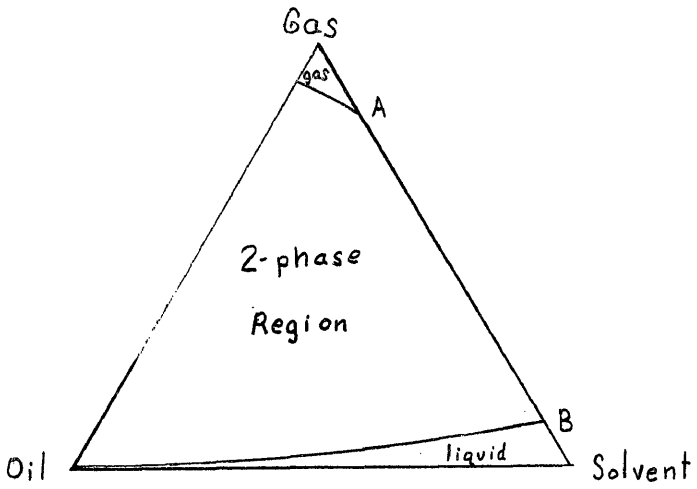


Figure 3 Ternary diagram for oil-gas-solvent system, pressure less than critical pressure of gas-solvent system; gas essentially immiscible

NITROGEN INJECTION

Various recovery processes involving nitrogen injection have been described in the literature, and several of these processes have been used in the field. A summary of processes which are relevant to the present study is presented below.

Repressuring with Nitrogen or Air

Air injection is one of the oldest methods of secondary recovery. The process is not frequently used today, but several papers have been published describing air or nitrogen repressuring projects in the United States within the past fifteen years (Clark and others, 1964; Breston, 1953; Lang, 1953; Spearow, 1954; Edinger, 1952; Tignor and others, 1950). Difficulties which are encountered with air injection projects include fire hazard, oxidation of reservoir oil, and corrosion. These problems are not met when nitrogen is injected, and several successful nitrogen injection projects have been described (Lang, 1953, and McCaslin, Jr., 1947). The injection of exhaust gas has also been suggested for the purpose of reducing oil viscosity by absorption of

carbon dioxide from the injected gas (McCaslin, Jr., 1947, and Scott, 1965).

Use of Flue Gas in Miscible Displacement Processes

The use of flue gas in miscible displacement processes has been studied by Koch and Hutchinson, Jr. (1958). The experiments were conducted at pressures high enough to obtain miscibility either between nitrogen and solvent or between nitrogen and the reservoir crude. It was concluded by the investigators that nitrogen was slightly less efficient than natural gas in displacing oil from a long core under pressures high enough to obtain miscibility between injected gas and the oil. The relative efficiency of nitrogen as compared to natural gas improved for longer flow paths, and the authors concluded that there should be little difference in efficiencies of the two gases for typical reservoir path lengths.

Use of Nitrogen in Tertiary Recovery

Csaszar and Holm (1963) conducted laboratory experiments on cores which had been saturated with oil and then flooded with water until a high water-oil ratio had been reached. Tertiary recovery of oil from the core was obtained by injecting propane driven by gas which was followed by water. Both nitrogen and methane were investigated for use as the gas phase in this recovery process. The experiments were conducted at pressures which were too low for miscibility to be obtained between the gas and propane phases. It was concluded that an

oil volume of two to three times the volume of the propane slug could be recovered under the test conditions, regardless of whether the driving gas was nitrogen or methane.

NITROGEN AS A SCAVENGING GAS

The decision whether or not to use nitrogen as a scavenging gas in a low-pressure miscible-slug displacement process will depend on economic factors and reservoir conditions, which will differ from one reservoir to another. It is possible to list some significant advantages and disadvantages of using nitrogen as a low-pressure scavenging gas, but the importance of each of these factors will depend on local conditions. Significant advantages and disadvantages of the use of nitrogen for this purpose are listed below.

Advantages

In the following respects, nitrogen is superior to methane as a scavenging gas in a low-pressure miscible-slug displacement process in which neither gas is completely miscible in the solvent:

1. The cost of nitrogen is usually less than the cost of natural gas. Engine exhaust and combustion gases generally contain 10 percent to 12 percent carbon dioxide, but removal of carbon dioxide is not required. (Koch, Jr. and Hutchinson, Jr., 1958).

2. The viscosity of nitrogen is approximately 60 percent higher than the viscosity of methane at low pressures (Hodgman, 1950, p. 1837-1838). This higher viscosity should be beneficial to oil recovery because of the more favorable mobility rate.
3. The gas volume factor is larger for nitrogen than for methane under typical field conditions. Because of the larger Z factor, fewer standard cubic feet of nitrogen are required to fill a given pore volume in the reservoir than would be required if methane were used. This effect is believed to be large enough to more than compensate for the shrinkage of injected flue gas due to the dissolving of carbon dioxide in the reservoir fluids. However, the volumetric advantage of nitrogen over methane becomes insignificant when very low operating pressures are considered (Koch, Jr. and Hutchinson, Jr., 1958).

Disadvantages

In the following respects, nitrogen is inferior to methane in a low-pressure miscible-slug displacement process in which neither gas is completely miscible in the solvent:

1. The degree of miscibility of gas in the solvent is higher for methane than for nitrogen.
2. Injection of nitrogen into the reservoir will destroy the fuel value of produced gas.

3. If methane is injected, some gas will dissolve in reservoir oil, causing it to swell and become less viscous. These effects will be of much smaller magnitude if nitrogen is used as a scavenging gas. However, the effects are probably of little significance for either nitrogen or methane in recovery processes which are operated at very low pressures.
4. Nitrogen obtained from engine exhaust gases contains nitric acid as well as a large amount of water vapor. Processing is required before the gas can be injected. This processing may cost 6 cents to 12 cents per MCF (Breston, 1953). Nitrogen obtained by burning natural gas or crude oil also contains corrosive substances if the natural gas or crude oil contains hydrogen sulfide.
5. The data available on the nitrogen injection processes are rather limited.

SCOPE OF INVESTIGATION

The investigation consisted of twenty miscible-slug displacement tests which were conducted in a steel tube packed with an unconsolidated sand. Normal butane was used as a miscible slug, and solvent volumes equal to 2 percent, 6 percent, and 12 percent of hydrocarbon pore volume were used. For each of the three slug volumes, tests were made with nitrogen and with methane as a scavenging gas. The tests were conducted at pressures of 45 psig and 90 psig. Sixteen of the tests were conducted to a limiting gas/oil ratio of 1,820 cubic feet per barrel, and four tests were conducted to a limiting gas/oil ratio of 21,800 cubic feet per barrel. A constant injection rate of 89 standard cubic centimeters per minute was used for all tests.

EQUIPMENT AND MATERIALS

The sand used for the tests was 50 percent 20/40 mesh and 50 percent 100/180 mesh Ottawa sand. Porosity was calculated to be 33.3 percent and water saturation was calculated to be 23 percent. Length of the steel tube was 31.3 cm and internal diameter was 5.33 cm. The gases used were pure grade nitrogen and pure grade methane. Technical grade normal butane was used for injected solvent slugs, and the oil used was Phillips Soltrol 160.

Measurements of injected butane were made under pressure in a Lucite tube, and produced liquids were measured under pressure in another Lucite tube. Produced gases were measured through a flow meter which was calibrated by displacement of water from a graduated cylinder. A schematic diagram of the apparatus used for the tests has been included in the appendix.

EXPERIMENTAL PROCEDURE

The steel tube was packed with moist sand and then sealed by screwing on the end bushing. The sand was dried by passing warm air through the tube, and it was cooled and weighed. The tube was then connected to a vacuum pump so that air was removed from the pore spaces. After air had been removed, tap water was allowed to enter the tube so that one hundred percent water saturation was obtained. The tube was weighed once more, and porosity was calculated to be 33.3 percent.

After porosity had been determined, water saturation was reduced to "irreducible minimum." This reduction in water saturation was accomplished by pumping oil through the tube until the produced liquid was water-free. Oil in the tube was then displaced by a small slug of butane which was followed by nitrogen. This procedure was repeated several times so that water saturation was reduced to a level which would not vary during the tests. Final water saturation was determined to be 23 percent.

Oil recovery tests were made by injecting a small slug of butane into the test cylinder and following the butane with a scavenging gas. Injection rates were controlled by means of a needle valve located downstream from the test cylinder and a pressure regulator located upstream from the test cylinder. A constant injection rate of 89 standard cubic centimeters per minute was used for all tests. Gas breakthrough was detected visually in the Lucite cylinder, and injection was continued until a predetermined gas/liquid ratio was reached. The injected fluids displaced oil from the core into a Lucite cylinder, where the oil and butane were measured under pressure. The produced liquids were then removed from the Lucite cylinder, warmed, cooled to 60°F, and were measured again at atmospheric pressure. Butane content was determined by difference from the two volumetric measurements.

After each test it was necessary to re-saturate the sand so that another test could be made. Re-saturation was accomplished by turning the tube in a vertical position and flushing it with kerosene which was introduced at the bottom of the tube. Gas remaining in the tube was exhausted by means of a vacuum pump connected to the top of the tube. Soltrol was then introduced into the bottom of the tube, and the kerosene was flushed from the sand with Soltrol.

RESULTS OF EXPERIMENTS

The relative efficiencies of nitrogen and methane as scavenging gases in a low-pressure miscible-slug process have been compared on the following bases: (1) oil recovery at a limiting gas/oil ratio; (2) oil recovery at gas breakthrough; (3) injected gas volumes (at standard temperature and pressure) required to reach limiting gas/oil ratio; (4) injected gas pore volumes (at reservoir temperature and pressure) required to reach limiting gas/oil ratio; and (5) recovery of butane slug.

Oil Recovery

Oil recoveries to a limiting gas/oil ratio of 1,820 standard cubic feet per barrel ranged from 43.1 percent to 66.8 percent of oil initially in place. Recoveries were higher for larger butane slugs, and recoveries were higher in tests made at 45 psig than in tests made at 90 psig. In all tests the recoveries obtained with nitrogen were within two percent of the recoveries obtained in comparable tests made with methane.

Four tests were carried out to a limiting gas/oil ratio of 21,800 standard cubic feet per barrel. All of these tests were conducted with a six percent butane slug, and recoveries ranged from 56.4 percent to 61.5 percent of oil initially in place. Average oil recoveries were 4.5 percent higher for tests conducted at 45 psig than for tests conducted at 90 psig. Average oil recoveries obtained with methane were one-half of one percent higher than average oil recoveries obtained with nitrogen.

Oil Recovery at Gas Breakthrough

Oil recovery at gas breakthrough ranged from 25.1 percent to 41.2 percent of oil initially in place. Recoveries were higher for larger slug sizes, but no significant difference was noted between recoveries at 45 psig and at 90 psig. Most of the tests indicated a recovery at gas breakthrough which was slightly higher for methane than for nitrogen. However, the greatest difference observed in recoveries for the two gases was equal to only four percent of initial oil in place.

Injected Gas Volume

Injected gas volumes, to a limiting gas/oil ratio of 1,820 standard cubic feet per barrel, ranged from 3,110 standard cubic centimeters to 5,070 standard cubic centimeters. No trend is evident when gas volume is compared to slug size. The gas volumes required were slightly higher when nitrogen was used as a scavenging gas than when methane was used as a scavenging gas, and gas volumes required

were slightly higher at 90 psig than at 45 psig.

Pore Volumes of Gas Injected

The number of pore volumes of gas required to obtain a limiting gas/oil ratio of 1,820 standard cubic feet per barrel ranged from 2.20 to 2.94 for tests made at 90 psig. In tests made at 45 psig the number of pore volumes ranged from 3.64 to 4.52. No definite correlation could be established between pore volumes of gas and slug size. In most tests the number of pore volumes of gas injected was slightly higher for nitrogen than for methane.

Recovery of Butane Slug

Since produced gases were not analyzed, no data are available on the recovery of butane as a vapor. Recoveries of liquid butane were found to range from 19 percent to 55 percent of the butane slug. Recoveries in tests conducted at 45 psig were generally higher than the recoveries obtained in tests conducted at 90 psig. No definite correlation could be established between percent liquid butane recovery and either slug size or scavenging gas composition.

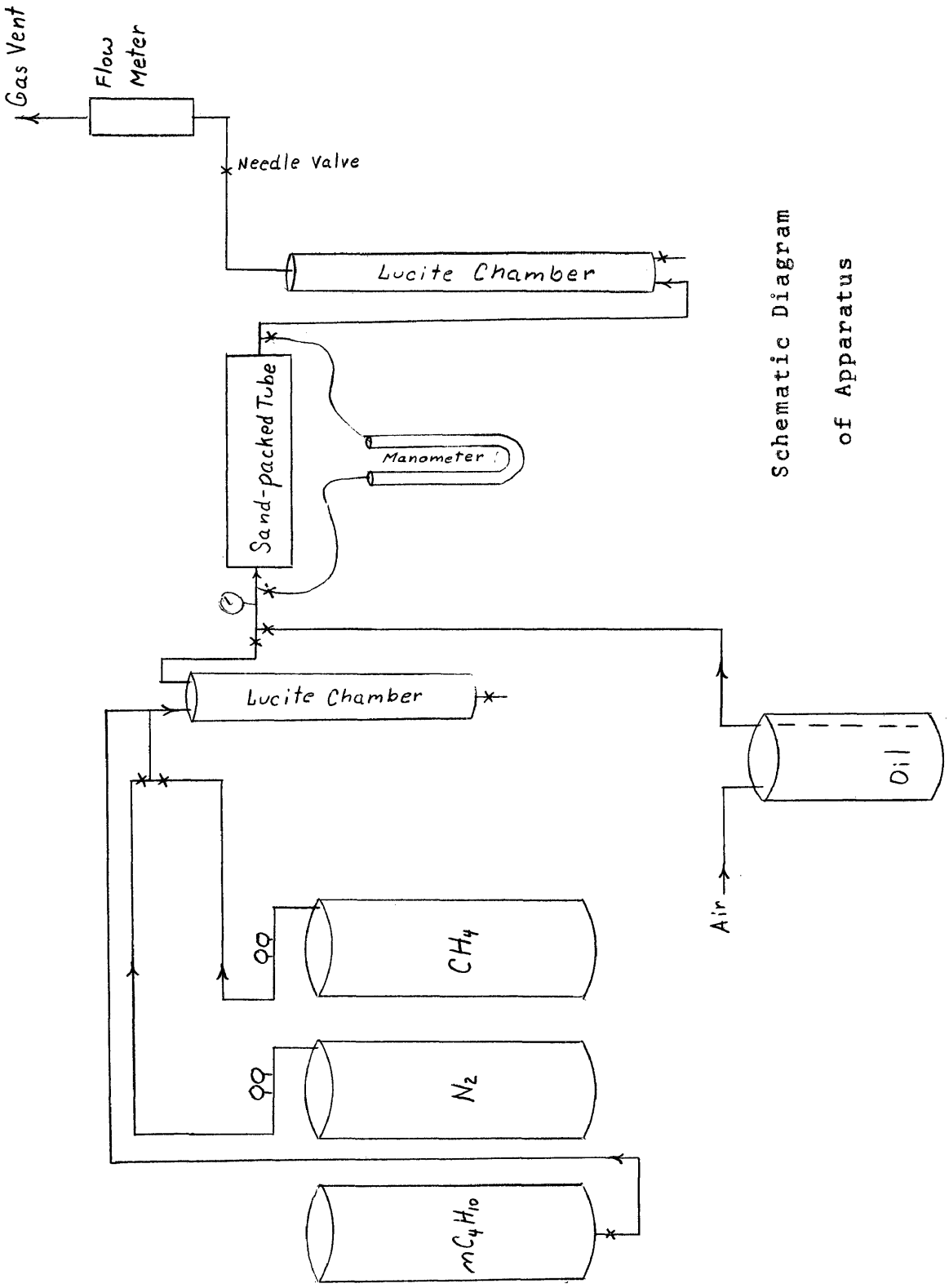
CONCLUSIONS

The model used for this study was not scaled, and it cannot be assumed that all results obtained with the sand-packed tube could be duplicated in an oil field. Subject to limitations imposed by the model used for the study, the following conclusions have been reached:

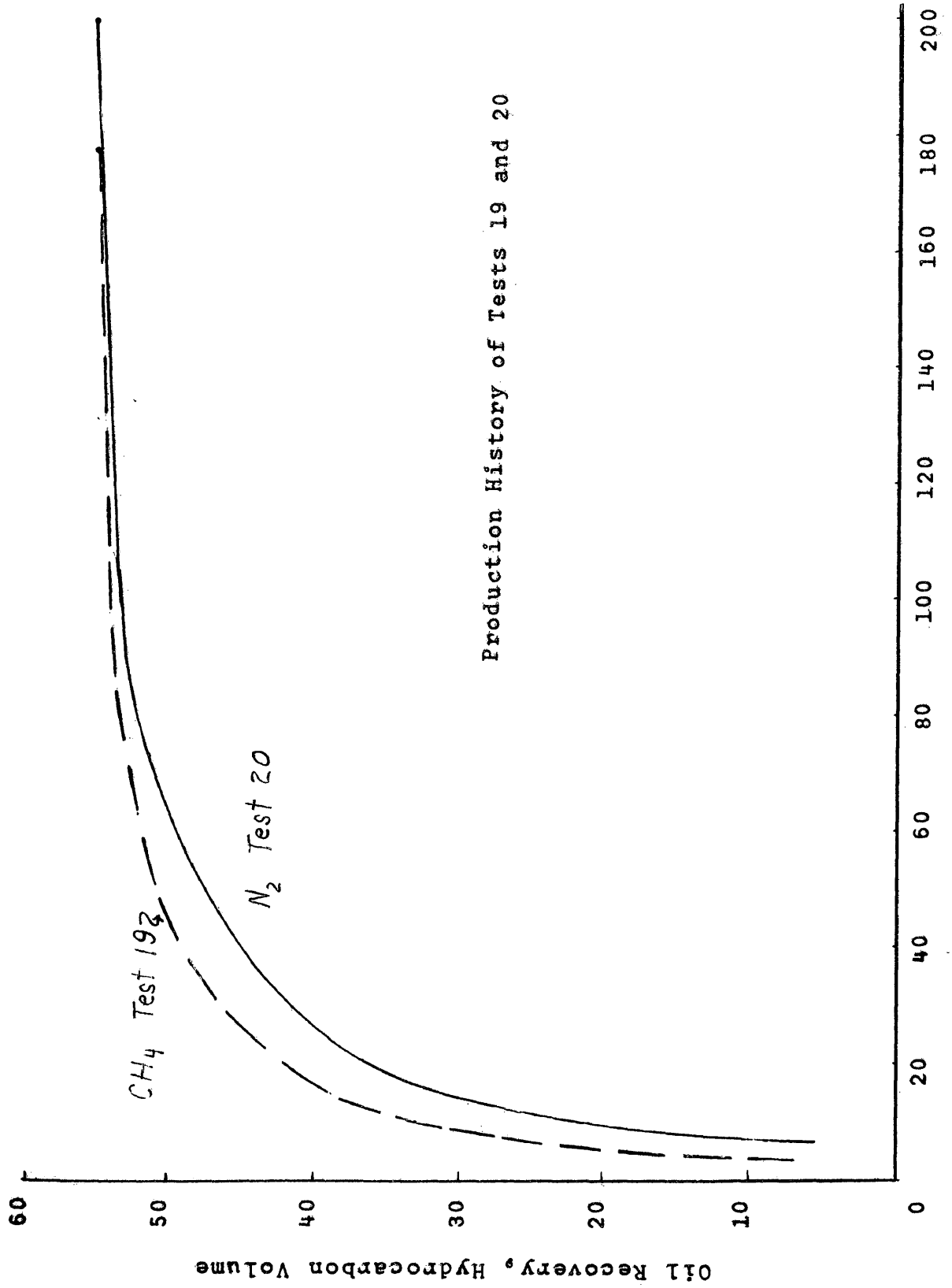
1. For a process in which the primary mode of dispersion is mechanical mixing rather than diffusion, nitrogen and methane are very nearly equal in efficiency as scavenging gases. The total volume of gas required will probably be slightly greater if nitrogen is used, but little difference in oil recovery is to be expected.
2. Oil recoveries obtained with 6 percent slugs of butane will be higher than with 2 percent slugs, and recoveries obtained with 12 percent slugs will be higher than were obtained with 6 percent slugs. However, it is doubtful that the increased recovery obtained for the larger slug sizes would justify the greater cost of the larger slug.

3. Oil recoveries obtained at 45 psig were significantly higher than were obtained at 90 psig. The primary reason for higher recovery at the lower pressure is believed to be the greater reservoir volume occupied by injected gas at the lower pressure. Higher velocity of gas moving through the sand may also have contributed to the improved performance which was noted at the lower pressure.

APPENDIX



Schematic Diagram of Apparatus


Production History of Tests 19 and 20
Oil Recovery, Hydrocarbon Volume
0
10
20
30
40
50
60
20
40
60
80
100
120
140
160
180
200
CH_4 Test 19
N_2 Test 20

OIL RECOVERIES

Scavenging Gas	Pressure psig	Slug Size % HCV	GOR Cu.Ft./Bbl.	Run No.	Recovery % Oil	Average Recovery % Oil
Nitrogen	90	2	1,820	9	43.6	--
	90	2	1,820	--	--	43.6
Methane	90	2	1,820	10	43.1	--
	90	2	1,820	--	--	43.1
Nitrogen	90	6	1,820	20	50.8	--
	90	6	1,820	13	52.5	--
	90	6	1,820	--	--	51.7
	90	6	21,800	20	56.4	--
Methane	90	6	1,820	19	51.4	--
	90	6	1,820	12	52.5	--
	90	6	1,820	4	52.5	--
	90	6	1,820	--	--	52.1
	90	6	21,800	19	55.8	--
Nitrogen	90	12	1,820	6	61.5	--
	90	12	1,820	2	63.7	--
	90	12	1,820	--	--	62.6
Methane	90	12	1,820	11	60.3	--
	90	12	1,820	3	63.7	--
	90	12	1,820	--	--	62.0

OIL RECOVERIES
(Continued)

Scavenging Gas	Pressure psig	Slug Size % HCV	GOR Cu.Ft./Bbl.	Run No.	Recovery % Oil	Average Recovery % Oil
Nitrogen	45	2	1,820	16	53.1	--
	45	2	1,820	--	--	53.1
Methane	45	2	1,820	8	50.3	--
	45	2	1,820	5	52.5	--
	45	2	1,820	--	--	51.4
Nitrogen	45	6	1,820	14	57.0	--
	45	6	1,820	--	--	57.0
	45	6	21,800	14	59.8	--
Methane	45	6	1,820	15	58.7	--
	45	6	1,820	7	59.2	--
	45	6	1,820	--	--	59.0
	45	6	21,800	15	61.5	--
Nitrogen	45	12	1,820	18	65.4	--
	45	12	1,820	1	68.2	--
	45	12	1,820	--	--	66.8
Methane	45	12	1,820	17	64.8	--
	45	12	1,820	--	--	64.8

SUMMARY OF AVERAGE OIL RECOVERIES

Pressure psig	Slug Size % HCV	GOR Cu.Ft./Bbl.	% Recovery Scavenging Gas Nitrogen	% Recovery Scavenging Gas Methane
90	2	1,820	43.6	43.1
90	6	1,820	51.7	52.1
90	12	1,820	62.6	62.0
45	2	1,820	53.1	51.4
45	6	1,820	57.0	59.0
45	12	1,820	66.8	64.8
90	6	21,800	56.4	55.8
45	6	21,800	59.8	61.5

OIL RECOVERIES AT GAS BREAKTHROUGH

Scavenging Gas	Pressure psig	Slug Size % HCV	Run No.	Recovery* % Oil	Recovery** % (Oil Plus Butane)
Nitrogen	90	2	9	26.2	25.7
Methane	90	2	10	25.9	25.4
Nitrogen	90	6	20	26.9	25.4
	90	6	13	30.7	29.0
Methane	90	6	19	30.0	28.4
	90	6	12	32.1	30.3
	90	6	4	27.9	26.4
Nitrogen	90	12	6	37.0	33.0
	90	12	2	35.5	31.6
Methane	90	12	11	41.2	36.7
			3	39.8	35.5
Nitrogen	45	2	16	25.1	24.7
Methane	45	2	8	26.5	26.0
			5	26.5	26.0
Nitrogen	45	6	14	28.3	26.7
Methane	45	6	15	31.8	30.0
			7	32.8	30.9

OIL RECOVERIES AT GAS BREAKTHROUGH

(continued)

Scavenging Gas	Pressure psig	Slug Size % HCV	Run No.	Recovery* % Oil	Recovery** % (Oil Plus Butane)
Nitrogen	45	12	18	38.1	34.0
			1	32.1	28.7
Methane	45	12	17	37.7	33.7

*Recovery has been expressed as percentage of oil initially in place which was recovered prior to gas breakthrough.

**Recovery has been expressed as percentage of liquid hydrocarbons (oil plus butane slug) recovered prior to gas breakthrough.

SUMMARY OF AVERAGE OIL RECOVERIES

AT GAS BREAKTHROUGH

Pressure psig	Slug Size % HCV	% Oil Recovered Scavenging Gas Nitrogen	% Oil Recovered Scavenging Gas Methane
90	2	26.2	25.9
90	6	28.8	30.0
90	12	36.3	40.5
45	2	25.1	26.5
45	6	28.3	32.3
45	12	35.1	37.7

INJECTED GAS VOLUMES AT LIMITING GAS/OIL RATIO

Scavenging Gas	Pressure psig	Slug Size % HCV	Limiting GOR Cubic ft/bbl	Run No.	Pore Volumes Gas Injected at Reservoir Pressure	Standard Cubic Centimeters Gas Injected
Nitrogen	90	2	1,820	9	2.20	3,560
Methane	90	2	1,820	10	2.25	3,650
Nitrogen	90	6	1,820	20	3.19	5,160
	90	6	1,820	13	2.58	4,180
	90	6	21,800	20	10.6	17,150
Methane	90	6	1,820	19	2.25	3,650
	90	6	1,820	12	2.59	4,180
	90	6	1,820	4	3.02	4,890
	90	6	21,800	19	9.67	15,650
Nitrogen	90	12	1,820	6	3.13	5,070
	90	12	1,820	2	2.75	4,450
Methane	90	12	1,820	11	3.13	5,070
	90	12	1,820	3	2.52	4,090
Nitrogen	45	2	1,820	16	4.52	4,090

INJECTED GAS VOLUMES AT LIMITING GAS/OIL RATIO
(continued)

Scavenging Gas	Pressure psig	Slug Size % HCV	Limiting GOR Cubic ft/bbl	Run No.	Pore Volumes Gas Injected at Reservoir Pressure	Standard Cubic Centimeters Gas Injected
Methane	45	2	1,820	8	4.32	3,920
	45	2	1,820	5	4.22	3,820
Nitrogen	45	6	1,820	14	4.72	4,270
	45	6	21,800	14	11.6	10,500
Methane	45	6	1,820	15	3.64	3,290
	45	6	1,820	7	3.64	3,290
	45	6	21,800	15	10.5	9,520
Nitrogen	45	12	1,820	18	3.44	3,110
	45	12	1,820	1	5.51	4,980
Methane	45	12	1,820	17	4.03	3,650

SUMMARY OF AVERAGE INJECTED GAS VOLUMES

AT LIMITING GAS/OIL RATIO

Pressure psig	Slug Size % HCV	GOR ft^3/bbl	Standard Cm^3 Gas Injected, Scavenging Gas - Nitrogen	Standard Cm^3 Gas Injected, Scavenging Gas - Methane
90	2	1,820	3,560	3,650
90	6	1,820	4,670	4,240
90	12	1,820	4,760	4,580
45	2	1,820	4,090	3,870
45	6	1,820	4,270	3,290
45	12	1,820	4,045	3,650
90	6	21,800	17,150	15,650
45	6	21,800	10,500	9,520

SUMMARY OF AVERAGE PORE VOLUMES OF INJECTED GAS

AT LIMITING GAS/OIL RATIO

Pressure psig	Slug Size % HCV	GOR ft^3/bbl	PV Injected Gas, Scavenging Gas Nitrogen	PV Injected Gas, Scavenging Gas Methane
90	2	1,820	2.20	2.25
90	6	1,820	2.89	2.62
90	12	1,820	2.94	2.83
45	2	1,820	4.52	4.27
45	6	1,820	4.72	3.64
45	12	1,820	4.48	4.03
90	6	21,800	10.6	9.67
45	6	21,800	10.5	11.6

LIQUID BUTANE RECOVERIES

Scavenging Gas	Pressure psig	Slug Size % HCV	GOR ft^3/bbl	Run No.	% Butane Slug Recovered as Liquid
Nitrogen	90	2	1,820	9	25
Methane	90	2	1,820	10	38
Nitrogen	90	6	1,820	13	27
	90	6	21,800	20	36
Methane	90	6	1,820	12	27
	90	6	1,820	4	38
	90	6	21,800	19	20
Nitrogen	90	12	1,820	6	36
	90	12	1,820	2	25
Methane	90	12	1,820	11	19
	90	12	1,820	3	25
Nitrogen	45	2	1,820	16	50
Methane	45	2	1,820	8	55
	45	2	1,820	5	55

LIQUID BUTANE RECOVERIES

(continued)

Scavenging Gas	Pressure psig	Slug Size % HCV	GOR ft^3/bbl	Run No.	% Butane Slug Recovered as Liquid
Nitrogen	45	6	21,800	14	47
Methane	45	6	1,820	7	55
	45	6	21,800	15	27
Nitrogen	45	12	1,820	18	25
	45	12	1,820	1	55
Methane	45	12	1,820	17	25

SUMMARY OF AVERAGE LIQUID BUTANE RECOVERIES

Pressure psig	Slug Size % HCV	GOR ft3/bbl	% Butane Recovered as Liquid Scavenging Gas Nitrogen	% Butane Recovered as Liquid Scavenging Gas Methane
90	2	1,820	25	38
90	6	1,820	27	33
90	12	1,820	31	22
45	2	1,820	50	55
45	6	1,820	--	55
45	12	1,820	40	25
90	6	21,800	36	20
45	6	21,800	47	27

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