SPECIAL CORE A

FOR

A/S NORSKE SHELL

Stavanger, Norway

MEASUREMENT OF RESIDUAL FLUID SATURATIONS

WELL NO. 31/2-9

PETEK
PETROLEUM TECHNOLOGY RESEARCH INSTITUTE
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EXTRACT

The present report presents the results from measurements of residual fluid saturations after a displacement process under simulated reservoir conditions using a full size core sample from well 31/2-9. The core sample, saturated with gas and initial water saturation, was first flooded with reservoir oil, and then flooded with synthetic formation water. Fluid saturations of the core sample was determined during and after the displacement process.

3 INDEXING TERMS: NORWEGIAN / ENGLISH

NORWEGIAN	ENGLISH
Fortrengningsforsøk	Displacement Experiment
Laboratoriemåling	Laboratory Measurement
Restmetning	Residual Saturation

Page

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1. INTRODUCTION

The hydrocarbon field in Block 31/2 consists of a large gas zone underlain by an oil column which again is supported by a large aquifer. Two previous reports, /1/ and /2/, gave results from three-phase and two phase displacement experiments performed at reservoir conditions on a core sample from well 31/2-6.

The present report presents the results from a three phase displacement experiment performed at reservoir conditions, using a core sample from well 31/2-9. The same apparatus as developed for the earlier experiments has been used, and therefore the reader is referred to a previous report /1/ for a description of the apparatus.

After receiving the core sample, it was first mounted in a stainless steel core holder, and then it was cleaned and dried. The core was first saturated with a synthetic formation water and a predecided initial water saturation was established. The core was then flooded with saturated reservoir oil at the pressure and temperature existing in the reservoir.

The core, now saturated with reservoir oil and reservoir gas at initial watersaturation, was then waterflooded with synthetic formation water until final stabilized fluid saturations in the core were established.

Besides presenting the results from the experiments, the report also gives a description of the experimental procedures used and also included is an analysis of the synthetic formation water, and differential vaporation data for reservoir oil from well 31/2-5.

2. EXPERIMENTAL

An apparatus has previously been designed in order to perform the experiments as close as possible to the displacement mechanisms expected to take place in the reservoir. This apparatus is described in an earlier report /1/.

Prior to the experiments the full size core sample was mounted in the coreholder. The core sample was poorly consolidated, and special care in handling the core had to be taken. The core was cleaned by flushing toluene and methanol through it, and then it was dried and saturated with a synthetic formation water (App II). The brine permeability was measured and then a slow methane injection was started in order to establish the initial water saturation previously decided to be between 10% and 20%. This process was carried out at reservoir temperature of 68°C (154°F) and atmospheric pressure. The pressure was then increased to the reservoir pressure of 15.9 MPa (2305 psi) by displacing the methane in the core sample by a separator gas.

The core which now had a water saturation of 16.6 percent was now ready for the main displacement experiment. The gas was first displaced at 15.9 MPa (2305 psi) and 68°C (154°F) by saturated reservoir oil at a rate of 9.78 cm^3/hour. During the injection of oil, the displaced gas, and later also produced oil was collected in the high pressure separator and the volumes were recorded. A total at 0.76 pore volume of oil was injected into the core sample.

The core was then flooded with 2.50 pore volumes of formation water until no more oil and gas were produced.

For a complete description of the preparation of the core sample and fluids, and a detailed procedure, please refer to Appendix I.

3. RESULTS

Table 1 shows the dimensions of the core sample used and porosity and permeability as measured by saturation and as absolute water permeability, respectively. Also reported in this table is the effective and relative permeabilities to oil at the end of oilflooding and effective and relative permeabilities to brine at the end of the waterflooding.

Table 2 and 3 give a summary of the experimental results from the oil-flooding and the waterflooding tests. The results are presented as fluid saturations as a function of injected porevolumes of fluid.

Tables 4 and 5 give a more detailed production history of the two displacement tests. In these tables the produced volumes of gas and oil and the remaining fluid saturation are given as a function of pore volumes injected. The fluid saturations are also shown graphically in Figures 1 and 2 as a function of injected pore volumes of oil and water, respectively.

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Table 1. Core Data.

Sample depth *)	(1589.85 - 1590.13)m	
Core diameter	9.9 cm	D
Core length	22.1 cm	L
Porosity **)	34.4%	POR
Permeability ***)	1.45 D	KW

Effective permeability to oil at the end of oilflooding (S_o = 59.2 %)	37.2 mD
Relative permeability to oil at the end of oilflooding	0.025
Effective permeability to water at the end of waterflooding (S_w = 61.7 %)	10 mD
Relative permeability to water at the end of waterflooding	0.0066

?

*) Depth reference on core protection tube: 3.20

**) Measured by fluid saturation

***) Measured as absolute permeability to formation water at 100 % water saturation

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Table 2. Summary of Experimental Results from Oilflooding. ok.

	Pore volumes injected $V_{nD} = \frac{N_i}{V_p}$	*Saturations (%)* S_w	S_o	S_g
Start	0	16.6	0	83.4
Oil breakthrough	0.590	16.6	59.0	24.4
End	0.764	16.6	59.2	24.2

Table 3. Summary of Experimental Results from Waterflooding **) ok

	Pore Volumes injected $V_{nD} = \frac{W_i}{V_p}$	*Saturations (%)* S_w	S_o	S_g
Start	0	16.6	59.2	24.2
Water breaktrhough	0.384	55.1	21.8	23.1
End	2.500	61.7	15.3	23.0

*) Oil injection rate : 9.78 cc/h

**) Water injection rate: 9.61 cc/h

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Table 4. Experimental Results from Oilflooding.

Pore volumes injected $V_{nD} = \frac{N_i}{V_p}$	*Produced gas* (cm^3) G_p	*Water saturation* S_w	*Gas saturation* S_g	*Oil saturation* S_o
0	0	16.6	83.4	0
0.10	58.0	16.6	73.4	10.0
0.20	117.8	16.6	63.4	20.0
0.30	176.7	16.6	53.4	30.0
0.40	235.6	16.6	43.4	40.0
0.50	294.5	16.6	33.4	30.0
0.59 *)	347.6	16.6	24.4	59.0
0.60	347.7	16.6	24.4	59.0
0.65	347.9	16.6	24.4	59.0
0.70	348.2	16.6	24.3	59.1
0.75	348.5	16.6	24.2	52.2
0.76	348.5	16.6	24.2	59.2

*) Oil Breakthrough

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Table 5. Experimental Results from Waterflooding.

Pore volumes injected $V_{nD} = \frac{W_i}{V_p}$	Produced gas (cm^3) G_p	Produced oil (cm^3) N_p	Water saturation S_w	Gas saturation S_g	Oil saturation S_o
0	0	0	16.6	24.2	59.2
0.10	2.4	56.5	26.6	23.8	49.6
0.20	2.8	115.0	36.6	23.7	39.7
0.30	4.7	172.0	46.6	23.4	30.0
0.35	5.7	200.4	51.6	23.2	25.2
0.384*)	6.3	220.0	55.1	23.1	21.8
0.39	6.4	223.0	55.6	23.1	21.3
0.40	6.5	227.0	56.2	23.1	20.7
0.41	6.6	229.0	56.6	23.1	20.3
0.42	6.7	231.0	56.9	23.1	20.0
0.44	6.8	233.3	57.4	23.0	19.6
0.46	7.0	235.3	57.7	23.0	19.3
0.50	7.2	238.7	58.3	23.0	18.7
0.55	7.2	241.4	58.8	23.0	18.2
0.60	7.2	243.4	59.1	23.0	17.9
0.70	7.2	246.6	59.7	23.0	17.3
0.80	7.2	249.1	60.1	23.0	16.9
1.00	7.2	252.8	60.7	23.0	16.3
1.20	7.2	254.0	60.9	23.0	16.1
1.40	7.2	255.0	61.1	23.0	15.9
1.60	7.2	256.4	61.3	23.0	15.7
1.90	7.2	258.0	61.7	23.0	15.3
2.20	7.2	258.0	61.7	23.0	15.3
2.50	7.2	258.0	61.7	23.0	15.3

*) Water Breakthrough.

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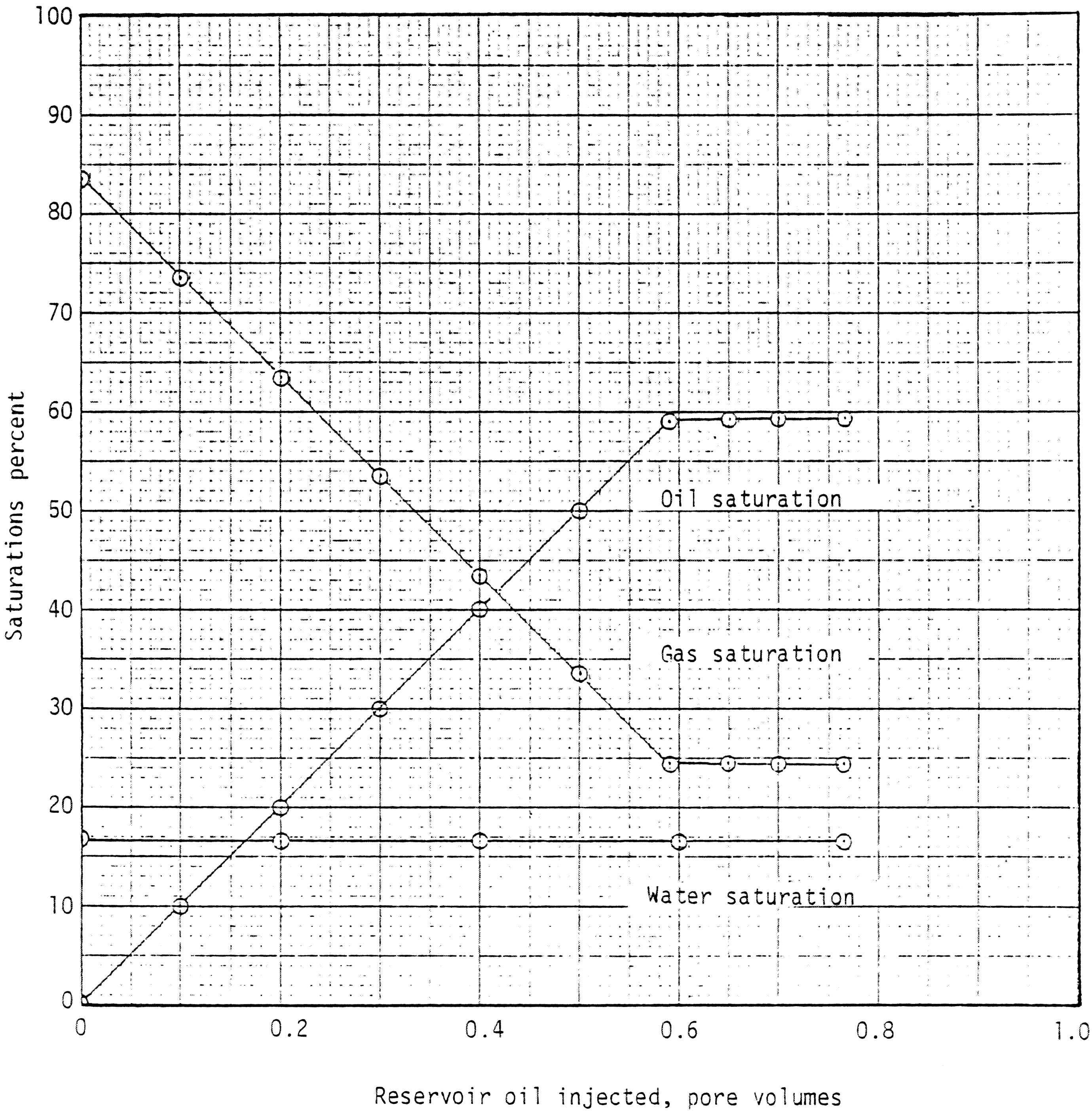

Figure 1 . Experimental results from oilflooding showing fluid saturations vs. pore volumes injected.

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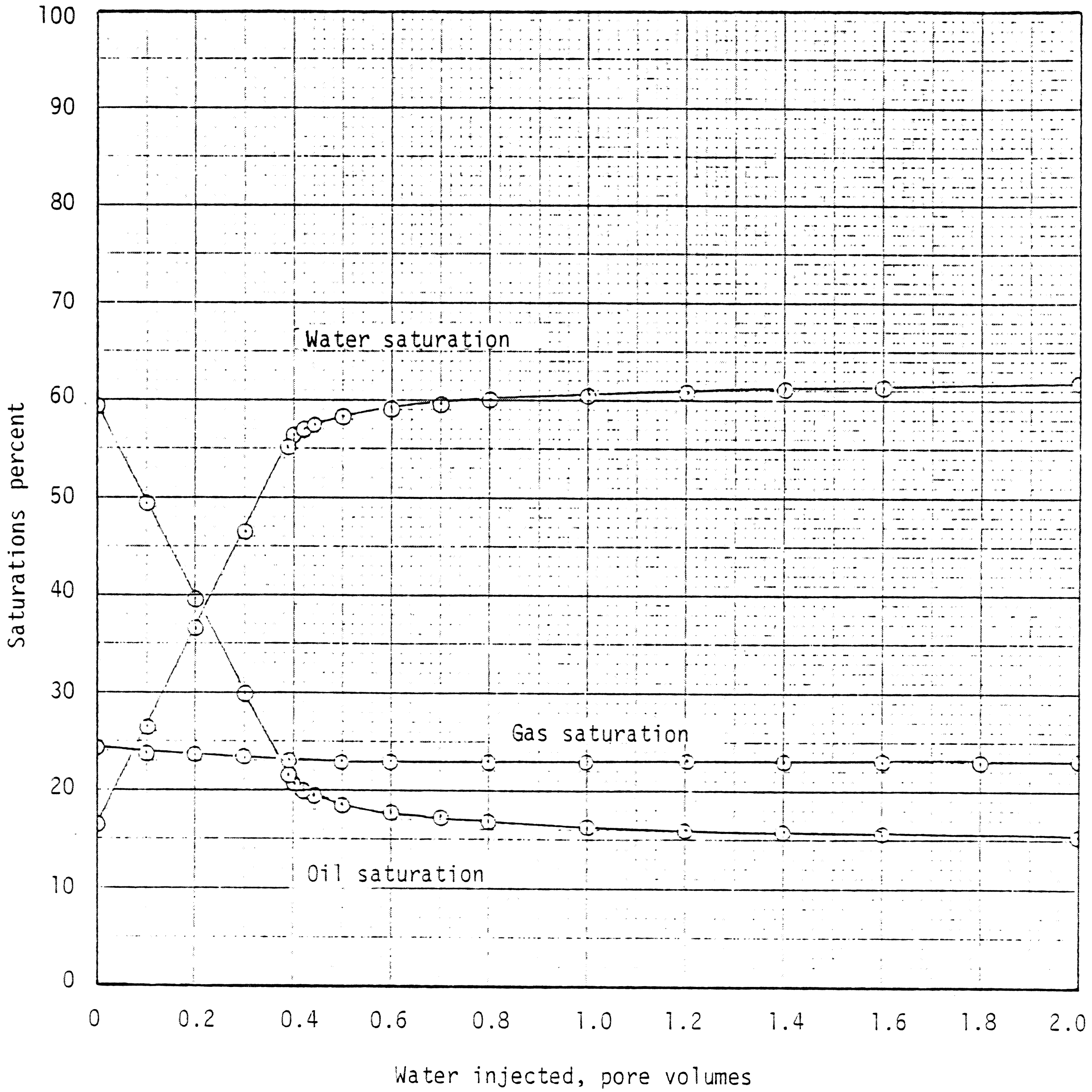

Figure 2. Experimental results from waterflooding showing fluid saturations vs. pore volumes of water injected.

4. SUMMARY.

Two displacement tests have been performed on a core sample from well 31/2-9.

Initially the core sample had a gas saturation of 83.4 percent and a water saturation of 16.6 percent. After an injection of 0.76 pore volumes of saturated reservoir oil, 71.0 percent of the initial gas in place was displaced giving the following residual fluid saturations; S_g = 24.2 percent, S_o = 59.2 percent and water saturation remaining constant at 16.6 percent. Nearly all the gas was produced before oil breakthrough; only a reduction in gas saturation at 0.2 percent was obtained after oil breakthrough. The displacement front between oil and gas therefore was acting like a piston.

The oil displacement was followed by injection of 2.5 pore volumes of formation brine. Water breakthrough occured after 0.384 pore volumes injected. The residual gas saturation decreased from 24.2 percent to 23.1 percent and residual oil saturation from 59.2 percent to 21.8 percent. The water saturation increased from 16.6 percent to 55.1 percent during the injection. After water breakthrough, gas saturation decreased 0.1 percent to 23.0 percent and oil saturation decreased 6.5 percent to 15.3 percent. Figure 3 gives a summary of recovery of oil and gas produced based on original hydrocarbons in place.

After injection of 0.76 pore volume of reservoir oil, effective permeability to oil was measured to be 37.2 mD at an oil saturation of 59.2 percent. After waterflooding the effective permeability to brine was measured to be 10 mD at a water saturation of 61.7 percent. This gives relative permeability to oil and water of 0.025 and 0.0066, respectively.

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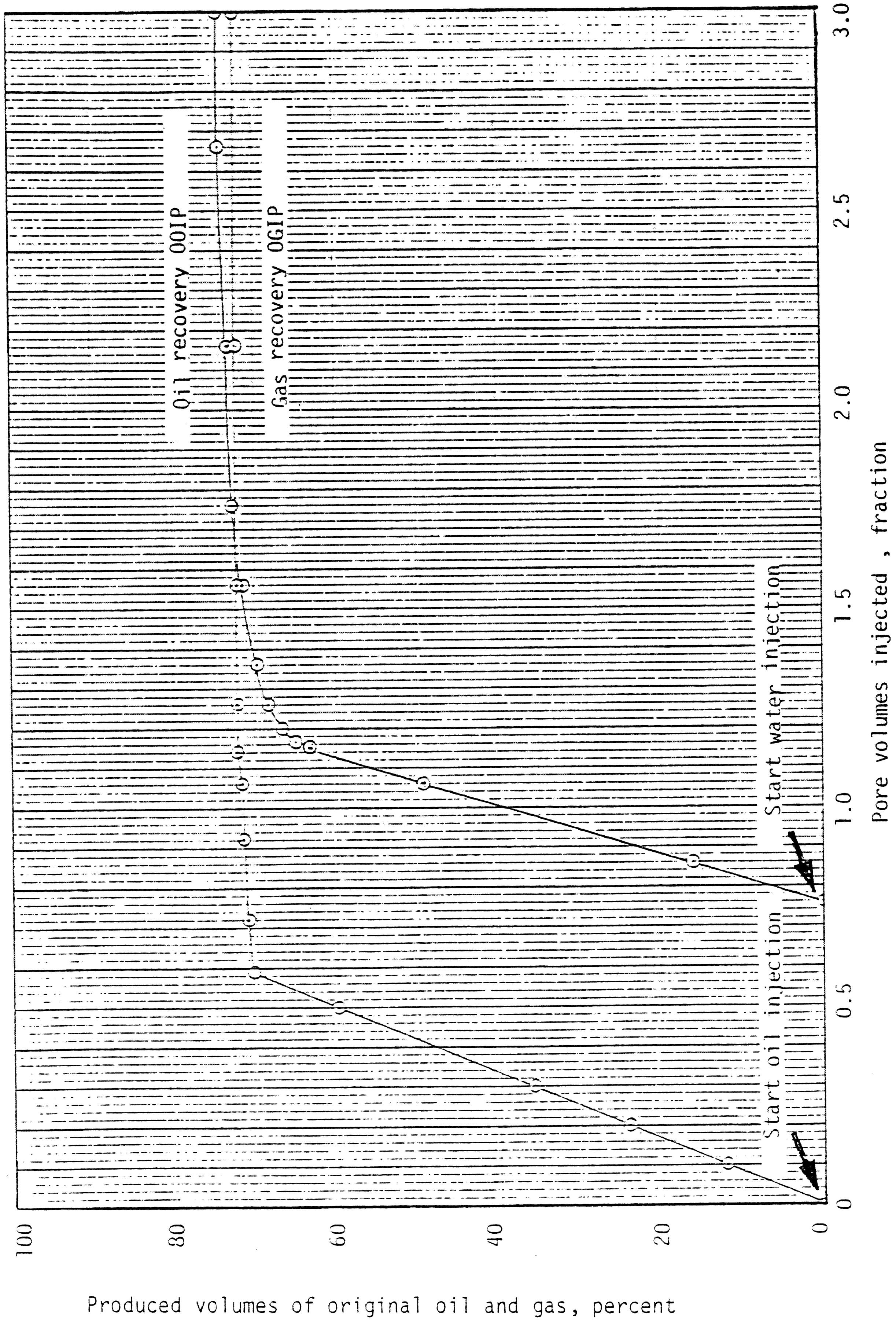

Fig. 3 Recovery of hydrocarbons based on original gas and oil in place.

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NOMENCLATURE LIST

ΔG_p = Gas volume produced (cm^3)

G_p = Cummulative gas volume produced (cm^3)

N_p = Cummulative oil volume produced (cm^3)

ΔN_p = Oil volume produced (cm^3)

N_i = Oil volume injected (cm^3)

Q = Injection rate (cm^3/hour)

S_o = Oil saturation

S_w = Water saturation

S_{wi} = Initial water saturation

S_g = Gas saturation

V_{nD} = Pore volumes injected, fraction

V_p = Pore volume (cm^3)

W_i = Water volume injected (cm^3)

W_p = Cummulative water volume produced (cm^3)

ΔW_p = Water volume produced (cm^3)

OOIP = Original oil in place

OGIP = Original gas in place

REFERENCES

/1/ Olsen, L.K., Hjelmeland, O. and Selle, O., "Measurements of Residual Fluid Saturations". SINTEF report STF 28 F 82022, 1982.

/2/ Olsen, L.K., "Waterflooding Test at Reservoir Conditions", SINTEF report STF 28 F 82039, 1982.

A P P E N D I X E S

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APPENDIX I

EXPERIMENTAL PROCEDURE

1. Preparation of core sample.

The core sample (depth reference on core protection tube : 3.20) was carefully removed from the plastic container and sealed with a tin - bismuth - lead alloy in the core holder. The end sections of the core were cut and the end pieces of the coreholder were assembled. The cleaning of the coreholder was done by flushing slugs of methanol and toluene through the core at a temperature of 68 ^{o}C using a positive displacement pump. The core was then dried in a humidity controlled heating cabinet at 40 percent relative humidity and 60^{o}C for 10 days. The control of humidity was used in order to avoid dehydration of possible clay minerals in the core sample.

2. Preparation of fluids.

2.1. Formation water.

The brine used in the experiments was made of distilled water and purified salts according to the water analysis given in Appendix II. Oxygen was removed by circulating nitrogen through the brine, and solids were removed by filtering the brine through a 0.45μ filter. The brine was then saturated with methane gas at a pressure of 15.9 MPa in order to avoid extraction of gas from the hydrocarbon fluids during the experiment.

2.2. Reservoir gas.

The gas was separator gas from a 20 liter gas bottle at a pressure of about 1.4 MPa. The gas was compressed with formation water and transferred to a one liter high pressure container. Dead reservoir oil (about 50 cm^3)

was then injected into the gas in order to saturate it with higher hydrocarbon components. The temperature of the gas was increased to reservoir temperature before the experiments were started.

2.3. Reservoir oil.

The reservoir oil was recombined from separator oil and separator gas to a bubble point slightly higher than the reservoir pressure of 15.9 MPa. The pressure was decreased and oil and gas were allowed to equilibrate at the actual reservoir pressure and temperature of 15.9 MPa and 68^{o}C, respectively. Before the experiments started, the gas was circulated out of the fluid container until it only contained saturated reservoir oil.

3. Porosity and brine permeability measurements.

The porosity was measured by saturating the core sample and accuratly measuring fluid volumes.

Brine permeability was measured using different injection rates of brine. Injection rate vs. pressure drop over the core could then be plotted on a straight line and brine permeability calculated from Darcy's law.

4. Establishment of initial water saturation (S_{wi}).

In order to establish initial water saturation in the core sample, methane was injected into the watersaturated core sample. In this way the brine was produced from the core by a combined displacement and diffusion process. In order to increase the speed of the process, the injected gas and the core sample was heated to 60^{o}C. The produced water from the core was cooled in a series of cooling traps according to the figure on the next page. During the process no water was accumulated in the last trap, ensuring an efficient cooling of the system.

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The water saturation in the core sample was controlled by measuring the volume of produced water. This was done by a direct reading of the volume in the measuring burette and weighing of the glass tubes in the cooling trap. The process was stopped when the core had a water saturation of 16.6 percent. This saturation constituted the initial brine saturation in the remaining part of the experiment.

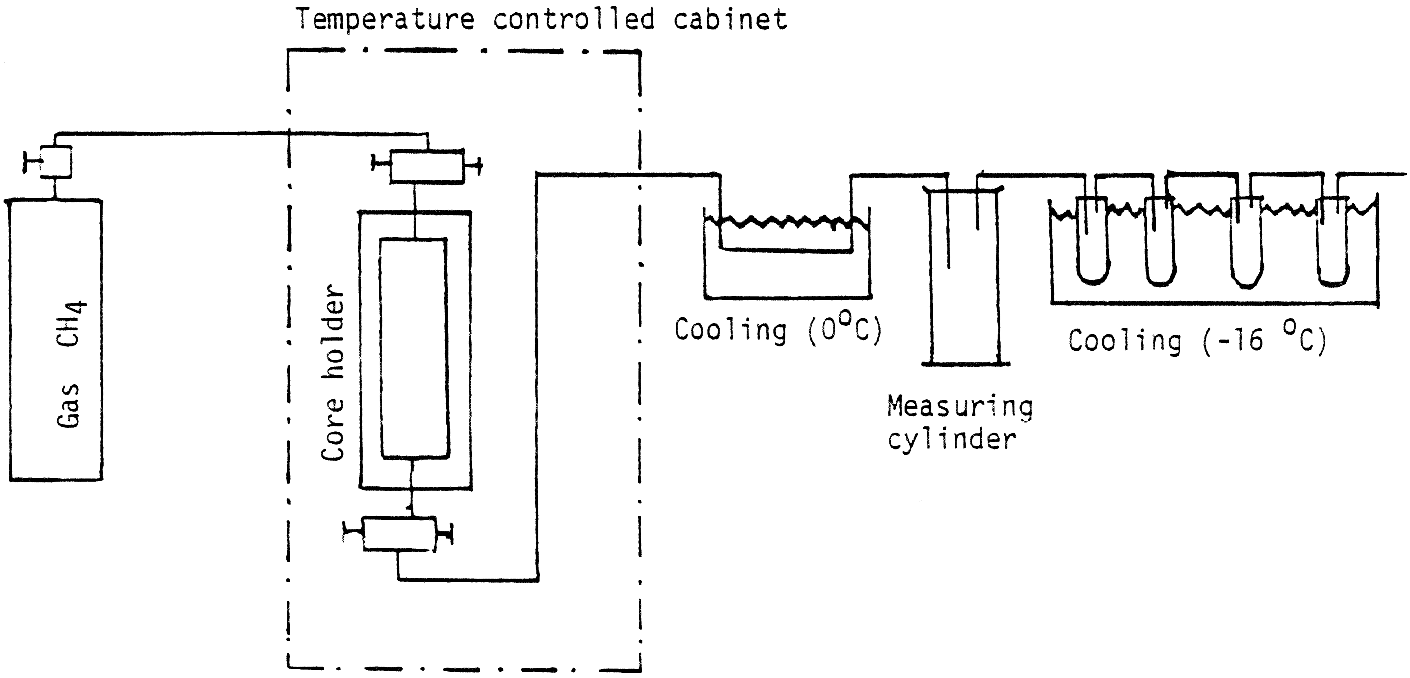

Fig. A.1. Schematic diagram of apparatus for etablishing S_{wi}.

5. Preparation for displacement tests.

After assembling the coreholder in the heating cabinet, the process lines were tested for leakages and evacuated with the coreholder closed. The coreholder and the separator were tested for leakages separately. The temperature was now increased to 68°C and a preheated separator gas (68°C) was injected into the system including the core sample until the pressure reached 15.9 MPa. No gas was circulated through the core at this stage. The whole system was pressure and temperature stabilized for 2 days before any experiment started.

The separator was calibrated using reservoir oil and formation water. Calibration and control of the speed of sound in oil and formation water could be achieved in 4 ways:

a) Volume of oil injected into the system was determined by the mercury displacement pump.
b) Volume of oil was measured by the separator system itself when only two phases were present in the system.
c) A window in the separator showed the water/oil surface when it reached a precalibrated line.
d) Produced water volume from the system was measured.

During the calibration phase point a) and c) was considered to be the most accurate way to find the speed of sound in oil and water. During the displacement test itself only point a) and b) were used to find correct produced fluid volumes. Produced gas was found by a material balance in the calibrated separator.

6. Displacement of gas with oil.

As already mentioned pressure and temperature in the apparatus were stabilized for 2 days before the experiment started. The inlet and outlet valves on the coreholder were opened and the by-pass line closed. The injection of oil at a constant rate of 9.78 cm^3/h started using the high pressure mercury injection pump to displace the oil in the oil-container with mercury. During the whole experiment a continuous recording of oil injection rate, produced fluid volumes, and differential pressure across the core sample was done. Oil breakthrough was determined from pressure and production data. A total of 0.76 pore volumes of oil was injected into the core before oil injection was stopped.

7. Displacement of oil and gas with brine.

The end section valves on the core were closed and reservoir oil in lines was displaced with formation water. The valves were then opened and injection of brine into the core sample at an injection rate of 9.61 cm^3/h started. Gas, oil and water volumes produced, differential pressure across the core and injection rate were continuously recorded.

Production of oil or gas come to an end when about 1.5 porevolumes were injected, but the displacement process was continued until 2.50 porevolumes were injected to insure no more production.

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APPENDIX II

FORMATION WATER ANALYSIS

	mg/l	meq/l
Na^{+}	16600	722.1
Ca^{++}	1870	93.3
Mg^{++}	320	26.3
Sr^{++}	295	6.7
Ba^{++}	320	4.7
Fe^{++}	20	0.7
Cl^{-}	29780	840.1
HCO_3^{-}	615	10.1

Total dissolved salts: 49820 mg/l

pH : 7.0

μ_w (68°C) : 0.47 cp

Fe^{++} was excluded due to precipitation, but an equal molar amount of Na^{+} was added to the formation water.

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APPENDIX III

DI:FERENTIAL VAPORATION DATA, WELL 31/2-5

DIFFERENTIAL VAPORATION AT 160 °F *)

Pressure PSIG	Solution Gas/Oil Ratio(1)	Relative Oil Volume(2)	Relative Total Volume(3)	Oil Density gm/cc	Deviation Factor Z	Gas Formation Volume Factor(4)	Incremental Gas Gravity
2280	405	1.198	1.198	0.7887			
2200	392	1.193	1.209	0.7907	0.861	0.00683	0.612
1900	342	1.178	1.267	0.7962	0.862	0.00791	0.612
1600	292	1.161	1.351	0.8021	0.872	0.00948	0.615
1300	241	1.142	1.488	0.8082	0.887	0.01185	0.619
1000	190	1.125	1.726	0.8144	0.907	0.01569	0.625
700	139	1.107	2.189	0.8209	0.930	0.02284	0.636
400	88	1.090	3.377	0.8270	0.957	0.04050	0.664
250	62	1.080	5.011	0.8313	0.971	0.06435	0.701
110	33	1.068	10.256	0.8357	0.987	0.13868	0.806
0	0	1.043		0.8461			1.294

At 60°F = 1.000

Gravity of Residual Oil = 28.6 API at 60°F.

(1) Cubic feet of gas at 14.73 psia and 60°F. per barrel of residual oil at 60°F.
(2) Barrels of oil at indicated pressure and temperature per barrel of residual oil at 60°F.
(3) Barrels of oil plus liberated gas at indicated pressure and temperature per barrel of residual oil at 60°F.
(4) Cubic feet of gas at indicated pressure and temperature per cubic foot at 14.73 psia and 60°F.

*) PVT-report from "Core Laboratories UK LTD"
Well 31/2-5, page 5 of 14, file RFLA 81028