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SINTEF

SPECIAL CORE ANALYSIS

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GRADERINGEN GJELDER TIL

FOR

A/S NORSKE SHELL

Stavanger, Norway

Waterflood Test at Reservoir Conditions

Block 31/2-6

PETEK

PETROLEUM TECHNOLOGY RESEARCH INSTITUTE
TRONDHEIM NORWAY
AFFILIATED WITH SINTEF

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EXTRACT

The present report presents the results of a waterflooding test under simulated reservoir conditions using a full size core sample from well 31/2-6. The core sample, which was saturated with oil and initial water saturations was flooded with formation brine at a low injection rate. Brine endpoint permeability and fluid saturations were determined and are presented in this report. Finally a rate increase test was performed in order to find the rate sensitivity of the fluid saturations and experimentally determined brine permeabilities.

3 INDEXING TERMS

NORWEGIAN	ENGLISH
Laboratoriemålinger	Laboratory Measurements
Vannfortrengning	Waterflooding
Relativ Permeabilitet	Relative Permeability

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CONTENT

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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. A previous report /1/ gave results from three-phase displacement experiments performed at reservoir conditions on a core sample from well 31/2-6.

The present report presents results from a two-phase water-oil displacement test performed at reservoir conditions, using the same core sample as described in the previous report /1/. The same apparatus as developed for the three-phase experiments has been used, and therefore the reader is referred to this report for a detailed 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 then saturated with a mineral oil at a predecided initial water saturation. The mineral oil was then displaced with live reservoir oil and the core was aged for one week at reservoir pressure and temperature.

The core was waterflooded with a synthetic formation brine at an injection rate of 7.23 cm^3/h. Residual oil saturation and endpoint brine relative permeability were determined. Finally, injection rates were increased in steps and some additional oil was produced. Final residual oil saturation after each rate increase was determined and the corresponding brine relative permability was calculated.

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

2. EXPERIMENTAL

A complete 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/.

The core sample which was initially saturated with residual fluids from the three-phase experiment was cleaned by flushing toluene and methanol through it, and then it was dried and saturated with a synthetic formation brine (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 in the range of 5 to 10%. This process was carried out at reservoir temperature, 68°C (154°F), and atmosperic pressure.

The gas was displaced at high pressure, 18.0 MPa (2600 psi), with a mineral oil freed from surface active materials by running it through a column of silica gel. This mineral oil was then displaced at 18.0 MPa (2600 psi) and 68°C (154°F) by reservoir oil. The core sample, now having an initial water saturation of 5.5 percent and an oil saturation of 94.5 percent, was aged for one week at reservoir conditions in order to achieve physico-chemical equilibrium between the fluids and the rock.

The core sample was now flooded with 1.14 pore volumes of synthetic formation brine at a low injection rate. The differential pressure across the core and produced oil volume were continuously recorded during the test.

Thereafter the injection rate was increased in steps, injecting one pore volume of synthetic formation brine in each step. Again pressure differential across the core and residual oil saturation was measured.

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

3. RESULTS

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

Table 2 gives a summary of the experimental results from the waterflooding test. Results are presented as fluid saturations as a function of injected pore volumes of fluid. These results are also presented graphically in Figures 1 and 2.

After the main waterflooding test, the injection rates were increased in steps as previously described. Table 3 presents the results from these tests. Reported in this table is the final oil- and water saturations after the injection of one pore volumes of brine at the indicated rate. Also reported are the effective and relative permeabilities of brine. Figure 3 is a graphical presentation of the results from Table 3; the brine injection rate is plotted versus residual oil saturation on a log-normal scale.

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Table 1. Core Data.

Sample depth	(1531.26 - 1531.46) m
Core diameter	9.8 cm
Core length	15.0 cm
Porosity *)	33.8%
Permeability **)	3.5 D

Effective permeability to oil at initial water saturation (S_{wi} = 5.5%, S_o = 94.5%)	3.3 D
Effective permeability to water at the end of waterflooding (S_w = 70.5%)	0.077 D
Relative permeability to water at the end of waterflooding	0.022

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*) Measured during fluid saturation

**) Measured as absolute permeability of formation water at 100% water saturation. Previous measured to be 3.11 D.

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Table 2. Summary of Experimental Results from Waterflooding Test

	Pore Volumes Injected $V_{nD} = \frac{Wi}{Vp}$	Saturations S_w (%)	S_o (%)
Start	0	5.5	94.5
Water breakthrough	0.588	64.3	35.7
End	1.14	70.5	29.5

Table 3. Experimental Results from Rate Increase Test

Injection Rate (cm^3/hour)	Saturation S_w (%)	S_o (%)	Effective and Relative Brine Permeabilities k_{eff} (mD)	k_{rel}
7.23	70.5	29.5	77	0.022
24.1	72.0	28.0	200	0.057
49.0	72.3	27.7	250	0.071
107.6	72.6	27.4	640	0.183
213.0	73.2	26.8	1140	0.326
464.0	73.5	26.5	1300	0.371

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Table 4. Experimental Results from Waterflooding Test

Pore volumes injected	*Produced oil* (cm^3)	*Water saturation*	*Oil saturation*
$V_{nD} = \frac{Wi}{Vp}$	N_p	S_w	S_o
0.0 *)	0	5.5	94.5
0.026	10.0	9.1	90.9
0.052	20.0	10.7	89.3
0.078	30.0	13.3	86.7
0.130	50.0	18.5	81.5
0.181	70.0	23.6	76.4
0.233 **)	90.0	28.8	71.2
0.264	102.0	31.9	68.1
0.390	150.3	44.4	55.6
0.514	198.5	56.9	43.1
0.577	222.6	63.2	36.8
0.588 +)	226.8	64.3	35.7
0.608	230.0	65.1	34.9
0.639	232.9	65.9	34.1
0.702	238.0	67.2	32.8
0.764	241.6	68.1	31.9
0.827	244.4	68.8	31.2
0.920	246.4	69.4	30.6
1.014	249.1	70.1	29.9
1.108	250.6	70.4	29.6
1.14	251.0	70.5	29.5

*) Injection rate: 6.00 cc/h
**) Injection rate: 7.23 cc/h
+) Water Breakthrough

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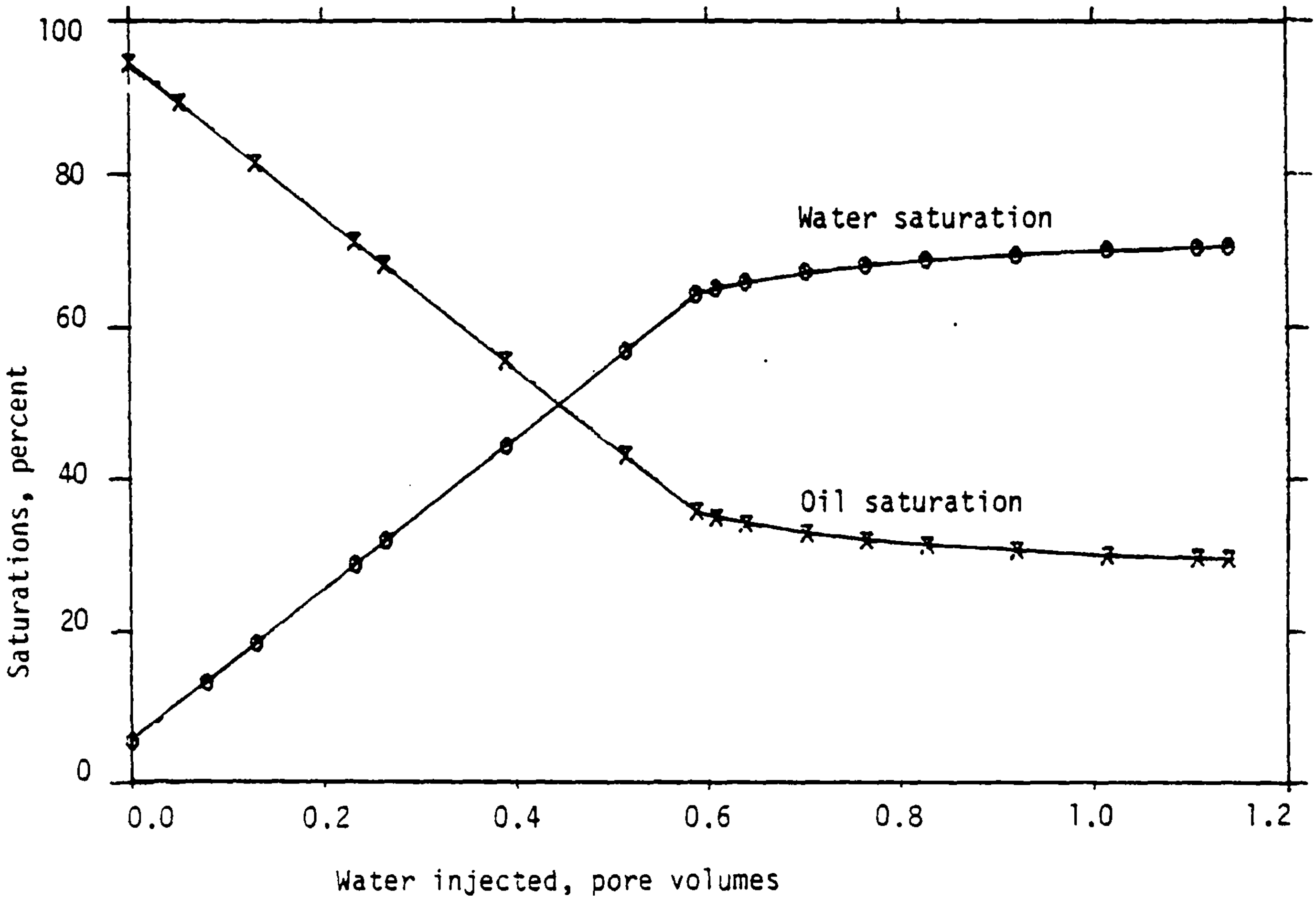

Figure 1. Experimental results from waterflooding test showing fluid saturations vs. pore volumes of water injected

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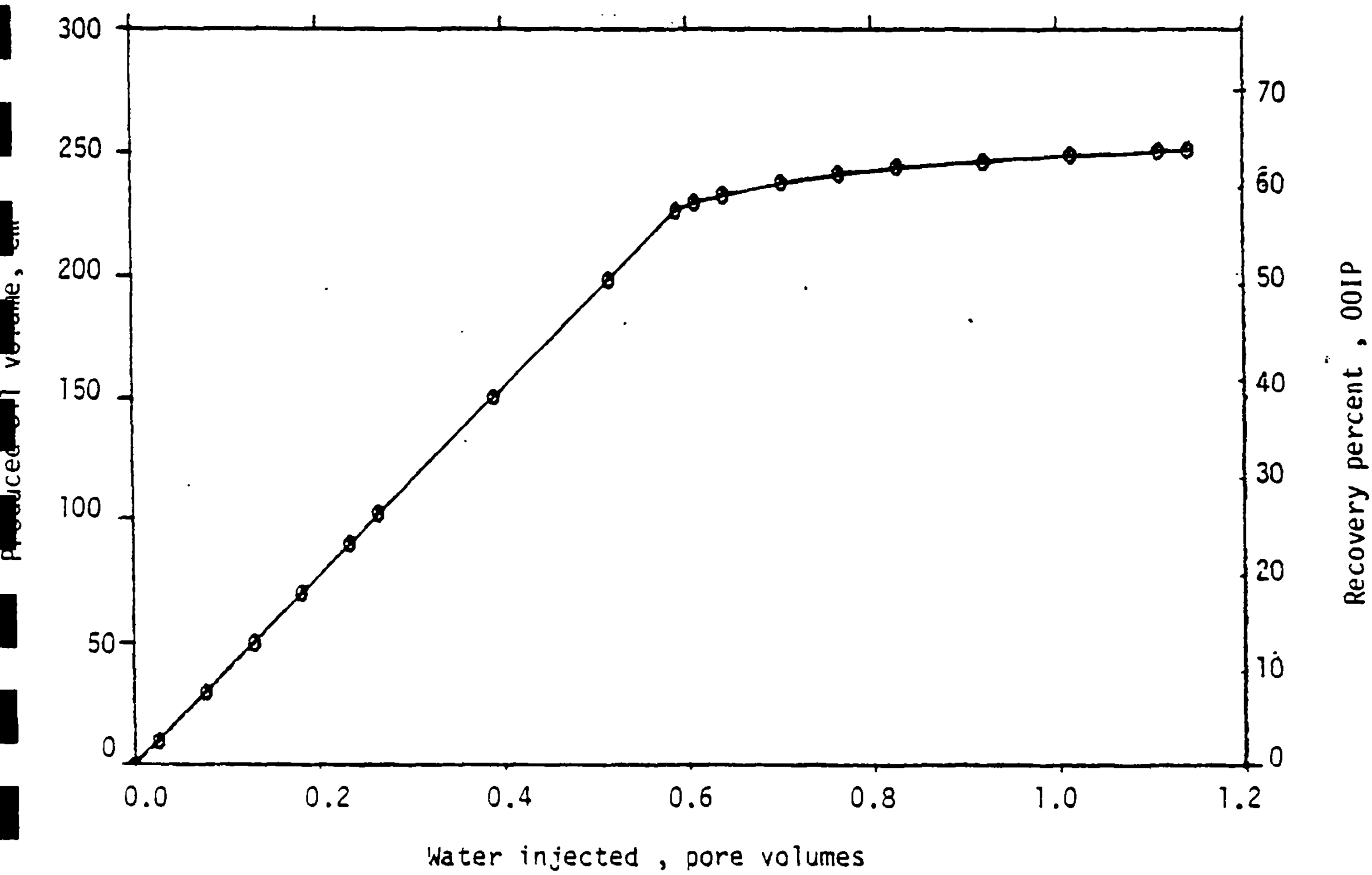

Figure 2 . Produced oil volume and oil recovery, percent of oil in place, vs. water injected.

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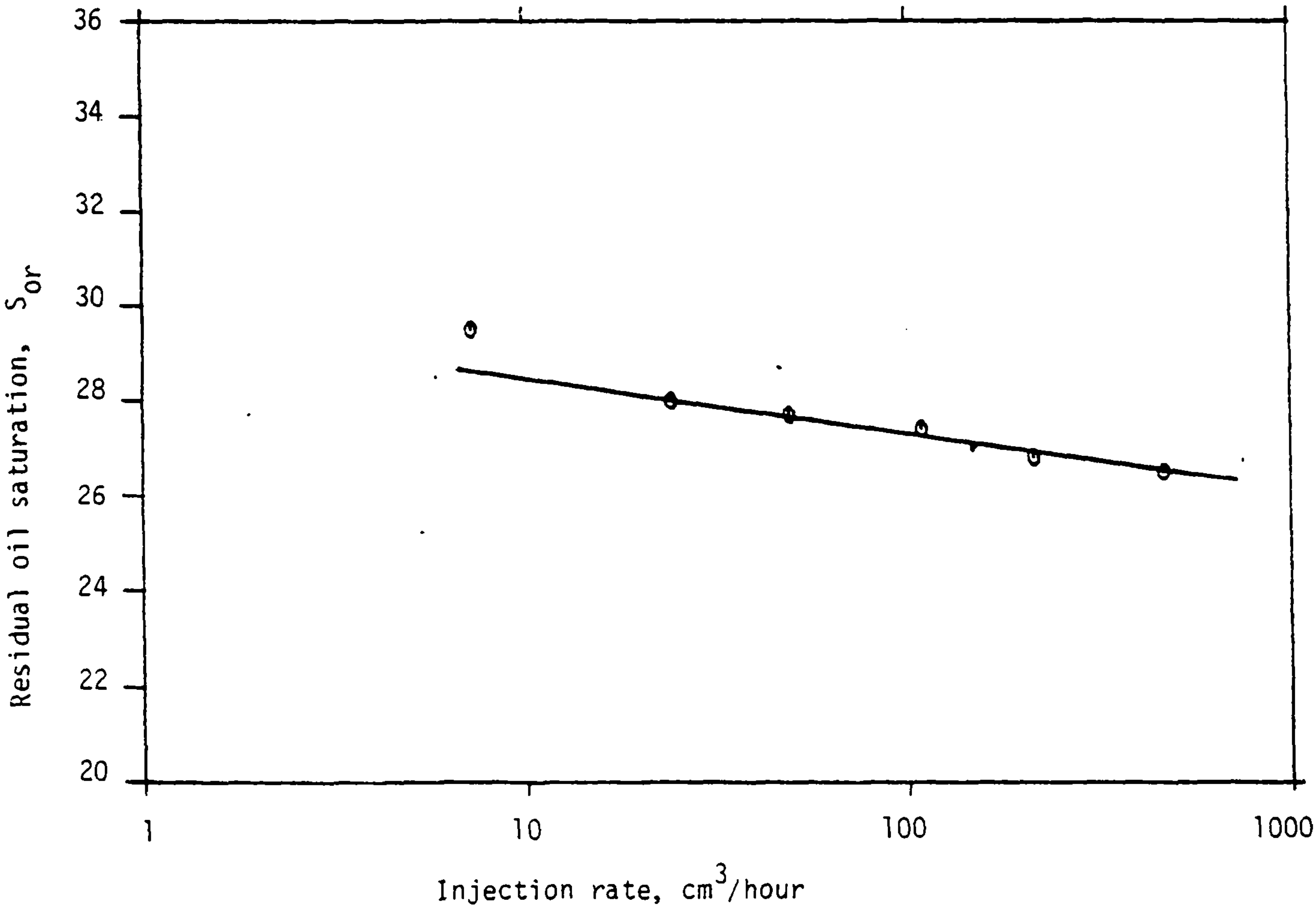

Figure 3. Residual oil saturation vs. injection rate

4. DISCUSSION

One waterflood test has been undertaken on a core sample from well 31/2-6

Initially the core sample had a water saturation of 5.5 percent and an oil saturation of 94.5 percent. After injection of 0.588 pore volumes of brine, water breakthrough occured at at a water saturation of 64.3 percent. After water breakthrough , the water saturation increased with 6.2 percent after having injected 1.14 pore volumes of synthetic formation brine.

During injection of water at a rate of 6.00 cm^3/hour, a small leakage was found on a process line downstream to the core sample. This leakage was stopped and injection of brine continued with a rate of 7.23 cm^3/hour. This small leakage will not influence the flooding behavior as it occured before water breakthrough and it did not cause the pressure in the system to drop.

After consultations with A/S Norske Shell, water injection was stopped after 1.14 pore volumes injected. At this time, oil was still being produced and therefore, this volume of brine injected was not sufficient to reach equilibrium residual oil saturation for this specific flooding rate. This was confirmed when injection rate was increased and the flow was allowed to stabilize at each rate. Injection rate vs. residual oil saturation were plotted on a semilog paper (Figure 3). Each stabilized point was found on a straight line except for the first one which indicated a lower residual oil saturation after the waterflooding test.

This capillary number displacement test is described by Chatzis and Morrow /2/ and it correlates the residual oil and capillary number curves for various sandstone samples. Figure 3 shows that the first point on the curve is not an equilibrium one, indicating that more oil could be produced at the specific injection rate.

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The use of scaling factors has been decsribed in several papers. It has long been recognized that capillary forces can influence the results of relative permeability and oil recovery measurements Scaling factors for linear displacement tests has been proposed in order to remove the dependence on oil recovery on displacement rate and system length / 3 - 5 /. One of the most used scaling factors can be expressed as /3/;

$$S_f = L \mu \frac{Q}{A} \qquad (1)$$

The respective units are ; L (cm) , μ (cp) and $\frac{Q}{A}$ (cm/min)

In order to perform a flooding where capillary effects can be neglected, this scaling factor should be in the range of ;

$$S_f \geq 1 - 5 \qquad (2)$$

The scaling factors for this experiment are given in Table 5 and show that the flow rate used in this waterflooding experiment does not satisfy equation (2). However , it should be noted that this scaling criterion is developed for specific rock samples and can not be directly used for other types of rocks. It is also assumed to be valid for a water-wet system.

Table 5. Scaling factors at different injection rates

Injection rate Q cm^3/hour	Scaling factor $L \mu \frac{Q}{A}$
7.23	0.0119
24.06	0.0395
49.0	0.0805
108.0	0.179
212.0	0.350
464.0	0.763

After injection of 1.14 pore volumes of synthetic formation brine, effective permeability to brine was measured to be 0.077 D at a water saturation of 70.5 percent. This gives a relative permeability to water of 0.022.

The main waterflooding displacement experiment was conducted using a low flooding rate giving very small differential pressures across the core. The differential pressure has been measured using a Validyne DP 22-518 differential pressure transduser with a maximum of ± 1 psi differential pressure. The transduser was calibrated in our laboratory using two dead weight testers, and it showed very good linearity and reproducibility. The low relative permeability to brine found is therefore not the result of an inaccurate differential pressure reading.

During the rate increase test,for each consequtive increase in injection rate, initially a lower pressure drop than during the stabilized flow in the previous step was observed. After some time the pressure drop increased to one higher than the previous step. This phenomena might be explained by a different dynamic and static distribution equilibrium of the fluids in the core.

The increase in the relative permeability during the rate increase test, may partly be explained by a higher water saturation giving a naturally higher relative permeability. However , the rapid increase over a short saturation range , suggests that the increase is mainly due to high viscous forces compared to capillary forces. The "correct" endpoint relative permeability to brine should therefore lay somewhere above the lowest values reported in Table 3.

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NOMENCLATURE LIST

N_p = Cummulative oil volume produced (cm^3)

Q = Injection rate (cm^3/hour)

S_o = Oil saturation

S_w = Water saturation

S_{wi} = Initial water saturation

S_f = Scaling factor

V_{nD} = Pore volumes injected, fraction

V_p = Pore volumes (cm^3)

W_i = Water volume injected (cm^3)

μ = Viscosity (cp)

OOIP = Original oil in place

R E F E R E N C E S

/1/ Olsen, L.K., Hjelmeland, O. and Selle, O.
"Measurement of Residual Fluid Saturations"
SINTEF report STF28 F82022 , 1982.

/2/ Chatzis,J., Morrow , N.R. , "Correlations of
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/3/ Leas , W.J., "Properties of Linear Waterfloods"
Trans AIME vol. 198 , 1953

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in Water-Wet Media", Trans.AIME vol.213 , 1958

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placement Measurements" SPE paper 9403, 1980

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A P P E N D I X E S

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APPENDIX 1

EXPERIMENTAL PROCEDURE

1. Preparation of core sample

The same core sample as used in the 3-phase experiment was used in in this experiment. The core containing gas, oil and water was cleaned by flushing slugs of toluene and methanol through it using a positive displacement pump. Refraction index of the produced and injected fluids were used to check if the core was clean. After cleaning,the core was dried in a controlled humidity oven at 40 % relative humidity and 60 ^{o}C for 10 days: The relative humidity was used in order to avoid dehydration of clay particles in the core sample.

2. Preparation of fluids

2.1. Formation water

The brine used in this experiment 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 18.0 MPa (2600 psi) in order to avoid extraction of gas from the hydrocarbon fluids during the experiment.

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2.1 Reservoir oil

The reservoir oil was recombined from separator oil to a bubble point of 17.8 MPa (2570 psi). This is higher than the reservoir pressure of 15.9 MPa (2305 psi) in order to ensure a completely gas- saturated oil at the lower pressure. The pressure was decreased and the oil and gas were allowed to equilibrate at the at reservoir pressure and temperature of 15.9 MPa (2305 psi) and 68 °C (154 °F), respectively. The gas was circulated out of the fluid container until it contained only a gas saturated oil. The pressure in the system was increased to 18.0 MPa which was the pressure used in the experiment.

3. Porosity and brine permeability.

The pore volume of the core sample was measured and then the core was saturated with synthetic formation brine. The value found was in agreement with the one found on the Helium porosimeter.

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 speed up the process, the injected gas was heated to 60°C . The produced water from the core was cooled in series of cooling traps according to Figure A1. 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 the prodeced water. This was done by a direct reading of the volume in the measuring burette and weight of the glass tubes in the cooling traps. The process was stopped when the core had a water saturation of 5.5 percent. This saturation constituted the initial brine saturation in the remaining part of the experiment.

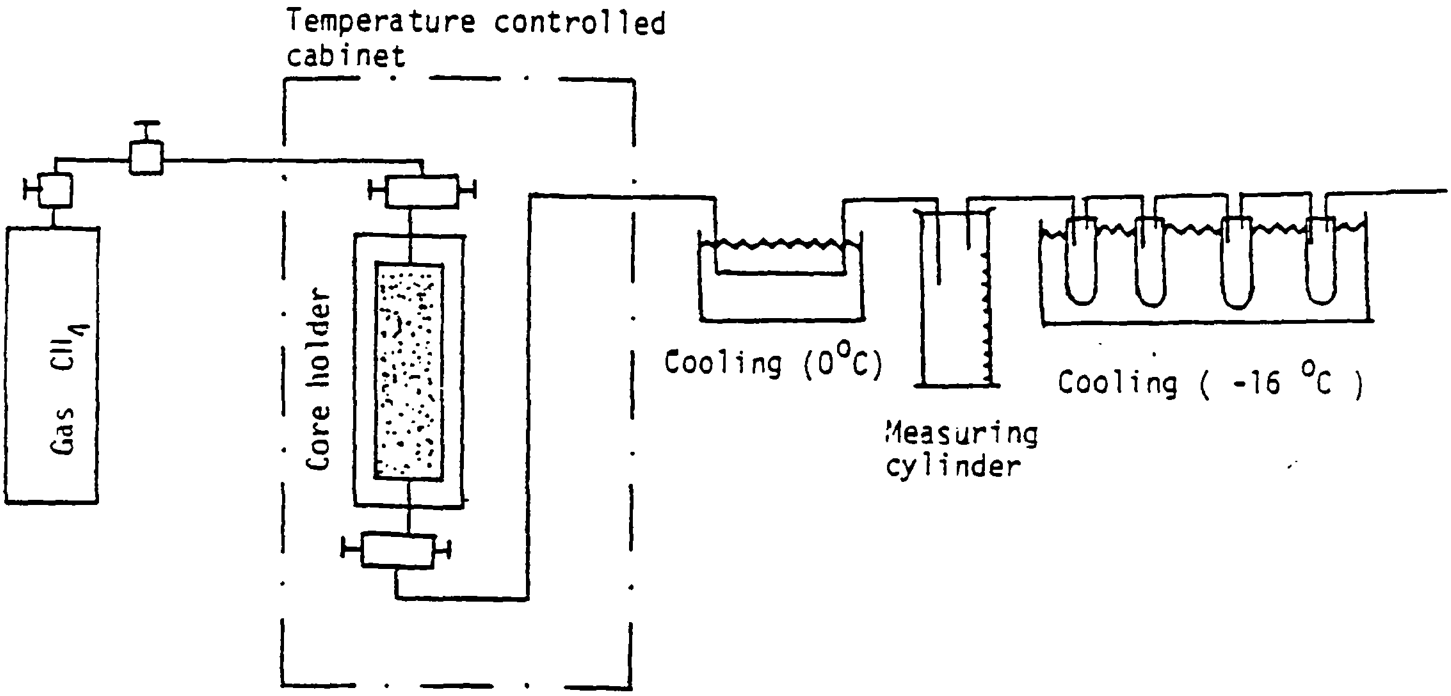

Fig. A1 Schematic diagram of apparatus for etablishing S_{wi}

The gas was displaced at high pressure, 18.0 MPa (2600 psi), with a mineral oil freed from surface active materials by running it through a column of silica gel. During this process no water was produced from the core and the gas saturation was thus replaced witn oil. Mineral oil was then displaced at 18.0 MPa (2600 psi) and 68 ^oC (154^oF) by reservoir oil.

The core sample now having an initial water saturation of 5.5 percent and an oil saturation of 94.5 percent, was aged for one week at reservoir conditions in order to achieve physico-chemical equilibrium between the fluids and the rock.

5. Preparation for displacement test.

After assembling the coreholder in the heating cabinet, the process lines, the coreholder and the separator were tested for leakages at 18.0 MPa (2600 psi) and 68^{o}C (154^{o}F) for two days.

The separator was calibrated using oil and formation water, and control of volumes of oil and 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 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 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.

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6. Displacement of oil with brine

6.1 Displacement experiment

As mentioned above the complete apparatus was checked for leakages and the separator system calibrated. Inlet and outlet valves on the coreholder were closed and the process lines filled with the synthetic formation brine. The inlet and the outlet valves on the coreholder were then opened and the by-pass lines closed.

The injection of the synthetic formation brine started at a constant injection rate of 6.00 cm^3/hour. A little leakage was found and the injection rate was increased to 7.23 cm^3/hour after the leakage was stopped. During the whole experiment a continuous recording of the brine injection rate, produced oil volume and differential pressure across the core was done. Water breakthrough was determined from pressure and production data.

6.2 Rate increase test

To achieve better relative permeability results and a controll of the residual oil saturations, injection rates were increased in steps. Brine relative permeability and residual oil saturation were measured in each step. About one pore volume of synthetic formation brine was injected in each step.

APPENDIX II

FORMATION WATER ANALYSIS

	mg/l	meq/l
Na^{+}	15700	683
Ca^{++}	12000	590
Mg^{++}	370	30
Sr^{++}	520	12
Ba^{++}	35	0.2
Fe^{++}	60	2
Cl^{-}	47000	1326

Total dissolved salts: 75685 mg/l
pH : 3.9

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

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APPENDIX III

DIFFERENTIAL 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