Denne rapport tilhører **STATOIL**

LTEK DOK.SENTER

L. NR. 302 8532 0017

KODE Well 31/2-6 Nr - 40

RETURNERES ETTER BRUK

SPECIAL CORE AN

FOR

A/S NORSKE SHELL

Stavanger, Norway

MEASUREMENT OF RESIDUAL FLUID SATURATIONS

BLOCK 31/2

WELL: 31/2 - 6

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RETUR PETEK-ARKIV

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SINTEF

PETROLEUM ENGINEERING DIVISION
THE FOUNDATION OF SCIENTIFIC AND INDUSTRIAL
RESEARCH AT THE UNIVERSITY OF TRONDHEIM

SINTEF REPORT

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EXTRACT

The present report presents the results of measurements of residual fluid saturations after a displacement process under simulated reservoir conditions using a full size core from well 31/2-6. The core sample, saturated with gas and initial water saturation, was first flooded with reservoir oil, and then flooded with synthetic formation brine. Fluid saturations of the core sample was determined during and after the displacement process. Finally the core underwent a pressure depletion test and final fluid saturations were found. Also included in the report is a full description of the apparatus developed and the procedures used in the test.

3 INDEXING TERMS

NORWEGIAN	ENGLISH
RESERVOARTEKNIKK	RESERVOIR ENGINEERING
LABORATORIEMALING	LABORATORY MEASUREMENTS
RESTMETNINGER	RESIDUAL SATURATIONS

SINTEF SPECIAL CORE ANALYSIS

WELL : 31/2-6
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SINTEF SPECIAL CORE ANALYSIS

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1. INTRODUCTION

The hydrocarbon field discovered by Shell in Block 31/2 consists of a large gas zone underlain by an oil column. A large supporting aquifer is present under the oil.

By producing the gas, the oil will invade the gas zone probably partly driven by the aquifer water. In the present project the mechanisms determining this process are simulated on a physical model consisting of a full-size core sample taken from the actual gas zone. Actual reservoir fluids are used in the experiments which were performed on an apparatus especially designed for this project. The main purpose of the project has been the determination of residual fluid-saturations after the displacement process.

The core sample was first cleaned and then saturated with reservoir gas at initial water saturation. The core was then flooded by reservoir oil at the pressure and temperature existing in the reservoir.

The core containing the residual fluid saturations from the oilflooding was thereafter waterflooded with formation brine and new residual saturations in the core were established.

Finally supplementary to the main displacement experiment the core underwent a pressure depletion test were all fluids produced were collected in order to find final residual saturations.

Besides presenting the results from the experiments, the report also gives a full description of the apparatus developed and 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 been designed in order to perform the experiments as close as possible to the displacement mechanisms expected to take place in the reservoir.

A schematic diagram of the apparatus is shown in Figure 1. A constant rate mercury displacement pump or alternatively a constant rate HPLC displacement pump was used for transferring the fluids from the fluid containers into the core holder or via a by-pass into the high-pressure separator. Three separate high-pressure fluid containers for the gas, oil and water were used. The core sample was melted into a high-pressure steel cylinder using an alloy of bismuth-tin which formed an effective seal between the core and the core-holder. A differential pressure transducer recorded the pressure drop across the core sample during the displacement. The produced fluids were collected in a high pressure separator for gas, oil and water. The fluid volumes, which were continuously recorded, were measured at the pressure and temperature used in the experiments, thus giving more exact volumes of the three phases produced. A backpressure regulator controlled the pressure during the experiments. The fluid-containers, core-holder and separator were all placed in a temperature controlled heating cabinet. A more detailed description of the apparatus is given in Appendix I.

Prior the experiments the full size core sample was mounted in the core-holder. The core sample was not 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 brine (App.IV). 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 10%. This process was carried out at reservoir temperature (68^{o}C, 154^{o}F) and atmospheric pressure. 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.

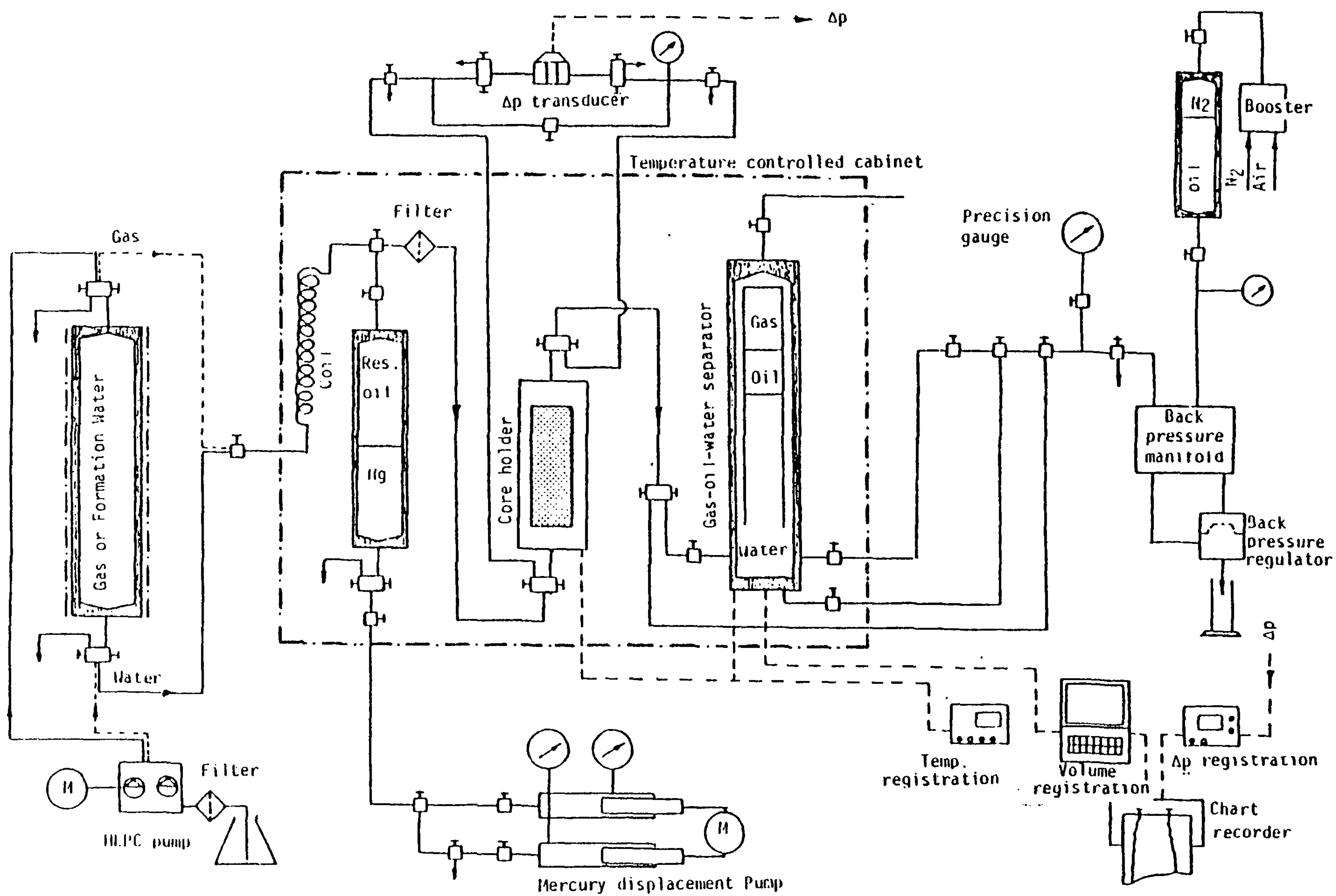

Fig. 1 Schematic diagram of apparatus

The core which had the predecided initial water and gas saturations was now ready for the main displacement experiments. The gas was first displaced at 15.9 MPa (2305 psi) and 68^{o}C (154^{o}F) by saturated reservoir oil. During the injection of oil, the displaced gas, and later also produced oil was collected in the separator and volumes were recorded. A total of one volume of oil was injected.

The core sample was then flooded with 2.1 pore volumes of formation water until no more oil and gas were produced.

In order to simulate a pressure depletion of the core sample, the pressure was decreased in steps of approximately 1.0 MPa (145 psi) until the final pressure of 7.0 MPa (1015 psi) was reached. Produced volumes of gas, oil and water were measured in each step.

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

3. RESULTS

Table 1 shows the dimensions of the core sample used and porosity and permeability as measured by helium porosimeter and as absolute water permeability respectively. Also reported in this table is the effective and relative permeabilities to oil at the end of the 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 oilflooding 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 2 and 3 as a function of injected pore volumes of oil and water, respectively.

Table 6 gives the results from the pressure depletion test. The results are presented as produced standard condition fluidvolumes for each stabilized pressure step. The final core saturation after each step are also given. Figure 4 gives a graphical presentation of these results.

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Table 1. Core Data

Sample depth 1, SINTEF	(1531.26-1531.46)m	
Core diameter	9.8 cm	0,098 m
Core length	15.0 cm	0,15 m
Porosity *)	33.8 %	0,338
Permeability **)	3.11 D	KW 3110 mD

REEGAS-O/

/TEMP = 68°C

Effective permeability to oil at the end of oilflooding (So = 69.4%) /KO (SGR)	0.380 D x	
Relative permeability to oil at the end of oilflooding x	0.122	%
Effective permeability to water at the end of waterflooding (Sw = 62.3%)	0.057 D	%
Relative permeability to water at the end of waterflooding	0.018	%

/SWI = 0,108

/SGR = 0,198

*) Measured on Helium Porosimeter and controlled by fluid saturations.

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

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Table 2. Summary of Experimental Results from Oilflooding. *). $\frac{6}{6}$

	Pore volumes injected $VnD = \frac{Ni}{Vp}$	Saturations		
		S_w(%)	S_o(%)	S_g(%)
Start	0	10.8	0	89.2
Oil breakthrough	0.689	10.8	68.9	20.3
End	1.0	10.8	69.4	19.8

Table 3. Summary of Experimental Results from Waterflooding **). $\frac{6}{6}$

	Pore volumes injected $VnD = \frac{Wi}{Vp}$	Saturations		
		S_w(%)	S_o(%)	S_g(%)
Start	0	10.8	69.4	19.8
Water breakthrough	0.447	55.5	26.0	18.5
End	2.1	62.3	19.2	18.5

*). Oil injection rate 7.53 cm^3/h.

**). Water injection rate 7.09 cm^3/h.

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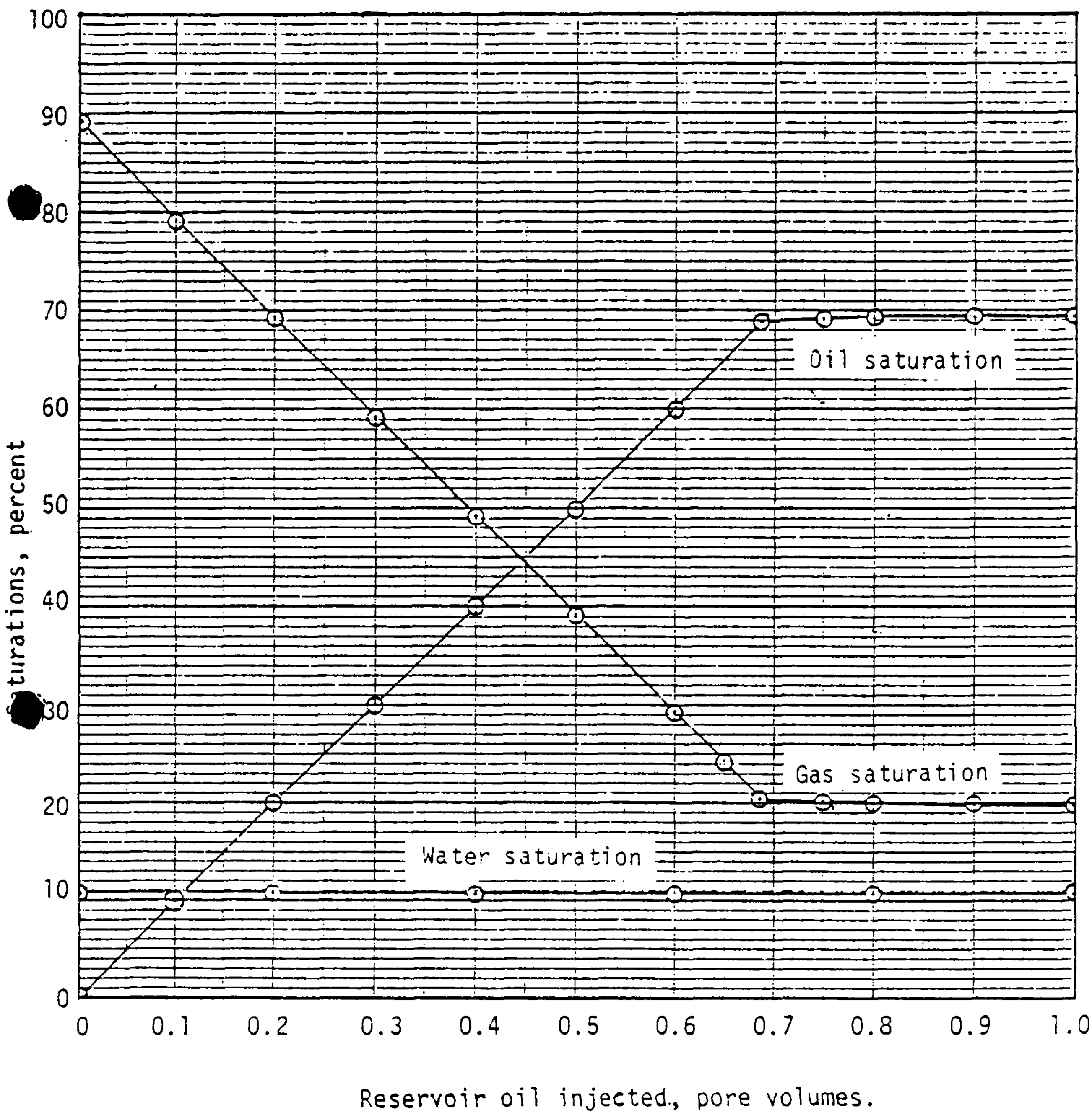

Figure 2. Experimental results from oilflooding showing fluid saturations vs. pore volumes of oil injected.

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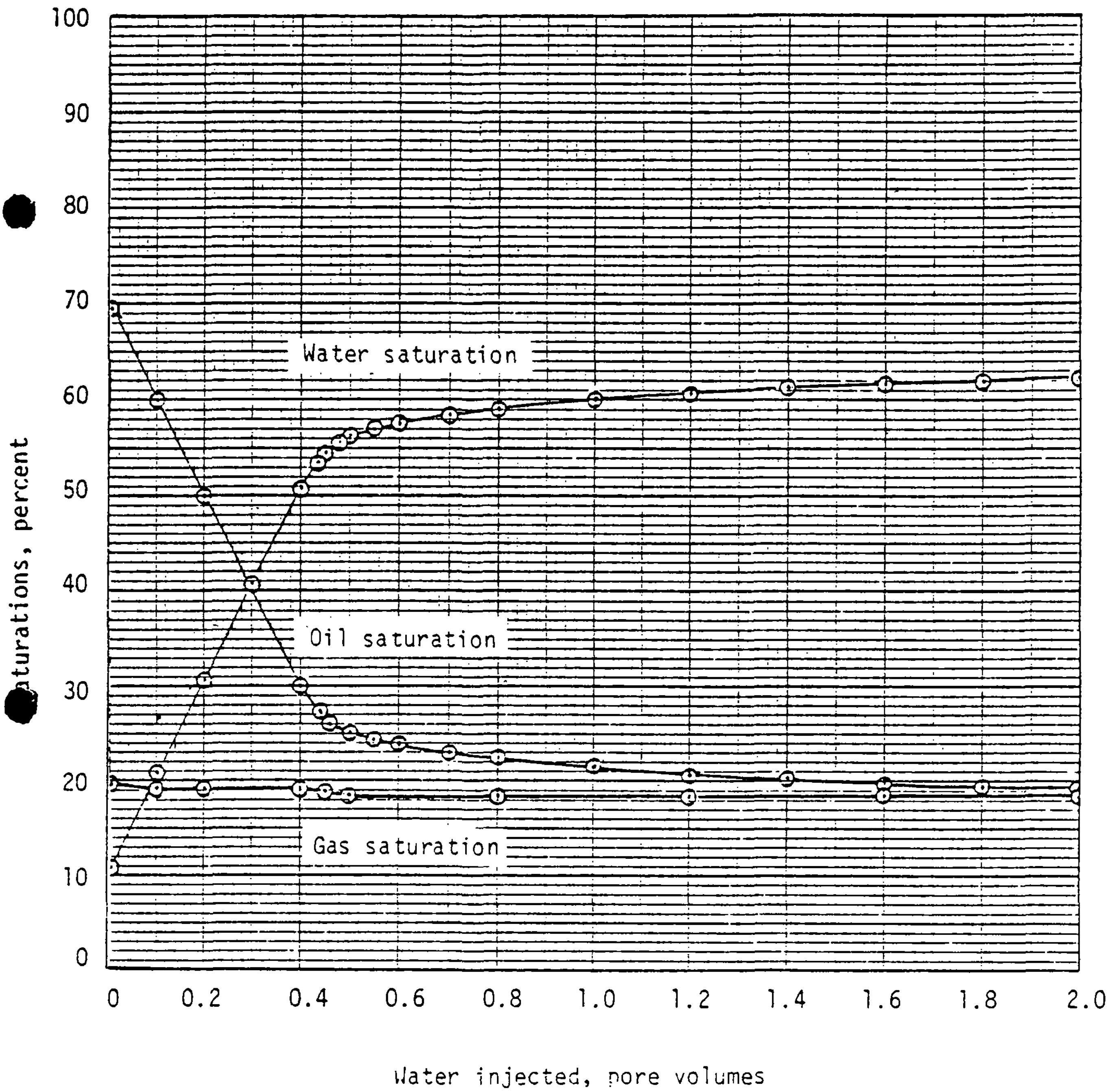

Figure 3. Experimental results from waterflooding showing fluid saturations vs. pore volumes of water injected.

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Table 4. Experimental Results from Oilflooding. 6/0

Pore volumes injected $V_{nD} = \frac{Ni}{Vp}$	Produced gas (cm^3) G_p	Water saturation S_w	Gas saturation S_g	Oil saturation S_o
0	0	10.8	89.2	0
0.10	38.5	10.8	79.2	10.0
0.20	77.0	10.8	69.2	20.0
0.30	115.5	10.8	59.2	30.0
0.40	154.5	10.8	49.2	40.0
0.50	193.0	10.8	39.2	50.0
0.60	231.8	10.8	29.1	60.0
0.65	251.3	10.8	24.1	65.0
0.689*)	265.7	10.8	20.3	68.9
0.70	266.0	10.8	20.3	68.9
0.75	266.5	10.8	20.1	69.1
0.80	267.0	10.8	20.0	69.2
0.85	267.3	10.8	19.9	69.3
0.90	267.5	10.8	19.9	69.3
0.95	267.8	10.8	19.8	69.4
1.00	267.8	10.8	19.8	69.4

*). Oil Breakthrough.

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Table 5. Experimental Results from Waterflooding.

Pore volumes injected $V_{nD} = \frac{Wi}{Vp}$	*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	10.8	19.8	69.4
0.1	1.9	36.7	20.8	19.3	59.9
0.2	2.5	74.7	30.8	19.2	50.0
0.3	2.5	113.3	40.8	19.2	40.0
0.4	2.5	151.9	50.8	19.2	30.0
0.427 *)	2.5	162.5	53.5	19.2	27.3
0.429	2.6	163.6	53.7	19.1	27.0
0.437	3.5	165.0	54.5	18.9	26.6
0.440	4.0	165.7	54.8	18.7	26.5
0.444	4.6	166.7	55.2	18.6	26.2
0.447 **)	4.8	167.3	55.5	18.5	26.0
0.460	4.8	169.0	55.9	18.5	25.6
0.50	4.8	171.5	56.4	18.5	25.0
0.55	4.8	173.4	57.0	18.5	24.5
0.60	4.8	175.5	57.6	18.5	23.9
0.70	4.8	179.2	58.5	18.5	23.0
0.80	4.8	181.5	59.1	18.5	22.4
0.90	4.8	184.5	59.7	18.5	21.8
1.00	4.8	184.8	60.0	18.5	21.5
1.20	4.8	187.5	60.7	18.5	20.8
1.40	4.8	190.0	61.3	18.5	20.2
1.60	4.8	191.5	61.8	18.5	19.7
1.80	4.8	192.5	62.0	18.5	19.5
2.00	4.8	193.8	62.3	18.5	19.2
2.10	4.8	193.8	62.3	18.5	19.2

*). Gas production starts again and oil production decreases

**). Water breakthrough.

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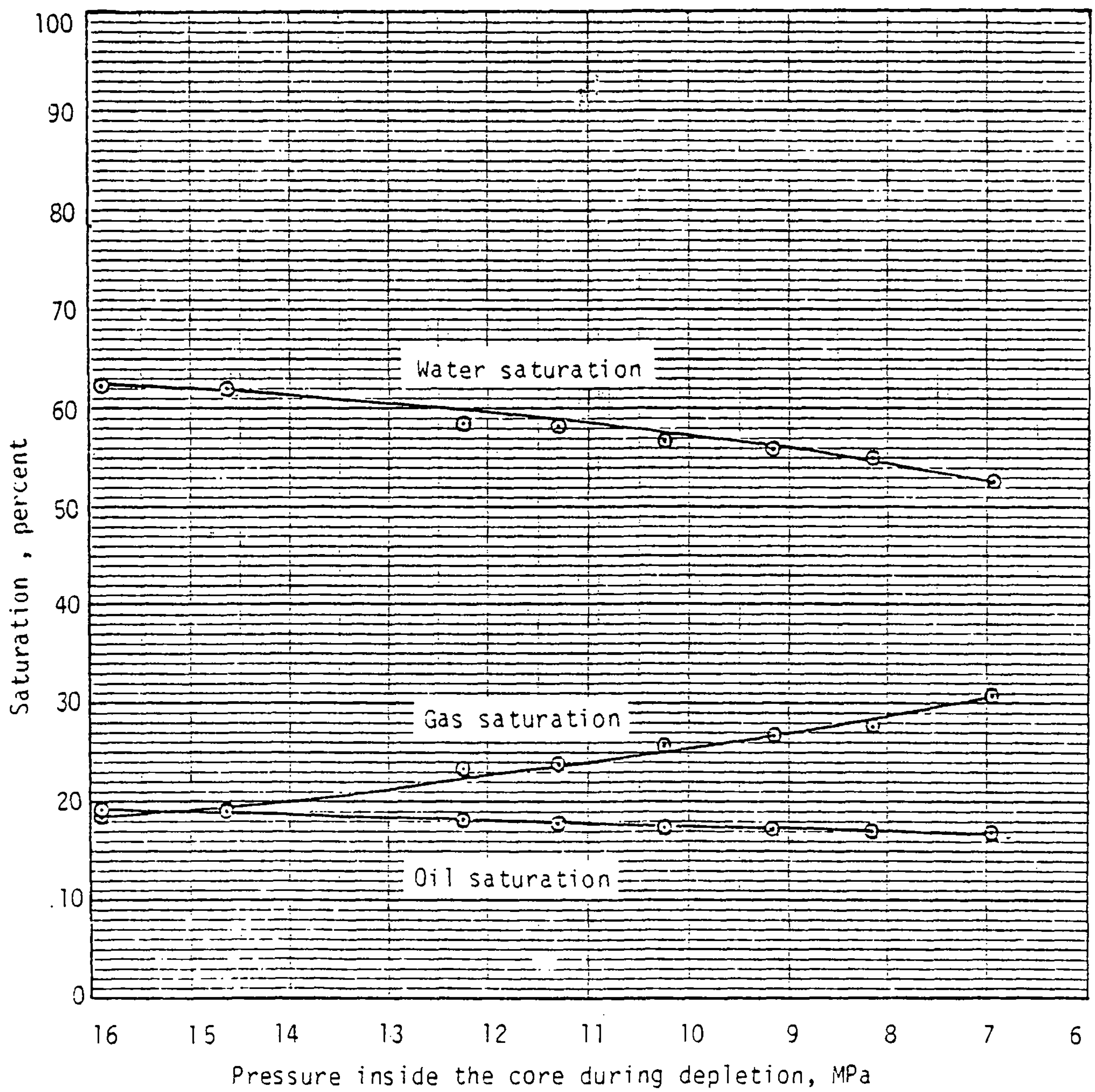

Fig. 4 Gas, oil and water saturations vs. pressure in the core during the depletion test

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Table 6. Experimental Results From Pressure Depletion Test.

Pressure (MPa)	Fluid saturations			Fluid volumes in the core (cm^3)			Produced volumes at normal conditions (cm^3)			Cumulative produced volumes at normal conditions (cm^3)		
	S_w	S_o	S_g	Water	Oil	Gas	ΔWp	ΔNp	ΔGp	Wp	Np	Gp
15.90	62.3	19.2	18.5	240.4	74.1	71.4	0	0	0	0	0	0
14.65	62.0	19.1	18.9	239.2	73.8	72.9	1.2	0.1	33*)	1.2	0.1	33
12.25	58.4	18.1	23.5	225.4	69.9	90.6	13.8	2.7	528*)	15.0	2.8	561
11.32	58.3	17.9	23.8	224.8	69.2	91.9	0.6	0.4	277*)	15.6	3.2	838
10.24	56.8	17.5	25.7	219.1	67.4	99.4	5.7	1.3	1171*)	21.3	4.5	2009
9.17	55.9	17.3	26.8	215.7	66.9	103.3	3.4	0.2	524*)	24.7	4.7	2533
8.14	55.1	17.2	27.7	212.6	66.6	106.7	3.1	0.1	1762	27.8	4.8	4295
6.95	52.5	16.7	30.8	202.6	64.4	118.9	10.0	0.6	2150	37.8	5.4	6445

*). Gas leakage on a tubing. Reported volumes may be too small.

Determination of saturations in the core is based on produced volumes of water and oil.

4. DISCUSSION

Two displacement tests and one pressure depletion test have been undertaken on a core sample from well 31/2-6.

Initially the core sample had a gas saturation of 89.2 percent and a water saturation of 10.8 percent. After an injection of one pore volume of reservoir oil, a large part of the gas was displaced giving residual saturations of 19.8 percent gas and 69.4 percent oil with the water saturation (S_{wi}) remaining constant at 10.8 percent. Most of the gas was produced before oil breakthrough; only 0.5 percent was produced after. The displacement of gas by oil seemed to be pistonlike.

The oil displacement was followed by injection of 2.1 pore volumes of formation brine. At water breakthrough at 0.447 pore volumes injected, the gas saturation was decreased to 18.5 percent and oil saturation to 26.0 percent, wheras the water saturation had increased to 55.5 percent. A gas production of 0.6 percent was observed from start of waterinjection until 0.2 pore volumes were injected, and the gas production came to a temporary stop. This indicates that an injection of oil beyond 1.0 pore volume in the first displacement test would have only produced very small quantities of gas. Trapped gas after oilflooding was mobilized by the waterfront, and a small " pillow " of gas amounting 0.7 percent was produced between 0.427 pore volumes injected and 0.447 pore volumes injected. After water breakthrough no more gas was produced, but additional 6.8 percent of oil was produced (based on total pore volume) , giving a residual oil saturation of 19.2 percent. Fig. 5 gives a summary of the recovery of gas and oil based on original hydrocarbons in place before displacement experiments.

After injection of one pore volume of reservoir oil, effective permeability to oil was measured to be 0.38 Darcy at an oil saturation of 69.4 percent, and after waterflooding effective permeability to brine was measured to be 0.058 Darcy at a water saturation of 62.3 percent. This gives relative permeabilities to oil and water of 0.122 and 0.018 , respectively.

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The displacement experiment has been conducted using low flooding rates giving very small differential pressures across the core. The differential pressure has been measured with a Validyne DP22-518 differential pressure transducer with a line pressure of 5000 psi and a range of maximum ± 1.0 psi. The transducer has a linearity of ± ½% best straight line and a hysteresis of ± ½% pressure excursion. The transducer was calibrated in our laboratory using two dead weight testers, and it showed very good linearity and reproducibility. During the displacement experiments the differential pressure across the core was in the range of 0.02-0.05 psi. Even if the transducer was correctly calibrated, the measurement of these small differential pressures across the core is very sensitive to the experimental conditions. An obstruction in the line, i.e. a bubble of oil or gas can severely influence the results. The values reported for the relative permeabilities of oil and water, therefore must be treated with care.

At these small rates of the displacement experiments capillary end effects can not be neglected. Future displacement experiments should preferably be performed at higher flooding rates, if the main objective is to evaluate relative permeabilities.

The depletion test was performed in steps of approximately 1 MPa (145 psi). The main displacement mechanism active during this experiment was gas expansion drive and to some extent solution gas drive.

Oil was produced in all steps of the test. When the gas expands in the core, some oil will be mobilized caused by the gas expansion until the gas forms continuous channels in the core. No more oil should then be produced if the volume fluxes in the core are low. The depletion steps of 1 MPa used in this test therefore seemed to be too high and should be considered reduced in an eventual later experiment.

Total decrease in the oil and water saturations in the core were measured to be 2.5 percent and 9.8 percent. The gas saturation increased correspondingly to 12.3 percent.

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A little leakege in the transfer tubing from the back pressure regulator was found during the depletion test. Produced volumes of gas are therefore reported too low, but produced oil and water volumes are correct. This leakage does not influence the saturation curves reported in fig. 4 .

A simular displacement experiment*) performed at room conditions with equal initial saturations shows 3.4 percent higher gas saturation and 7.3 percent higher oil saturation after oil- and waterflooding. Water/oil and gas/water interfacial tensions have a generally decreasing tendency when the temperature is increased, and this might be the reason to the lowering in the residual oil and gas saturations in the high pressure and temperature experiment.

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*) Ref . Lars Kyrre Olsen and Olav Selle ; " Room condition oil and waterflooding test ", SINTEF report no. STF28 F81059 , 1981

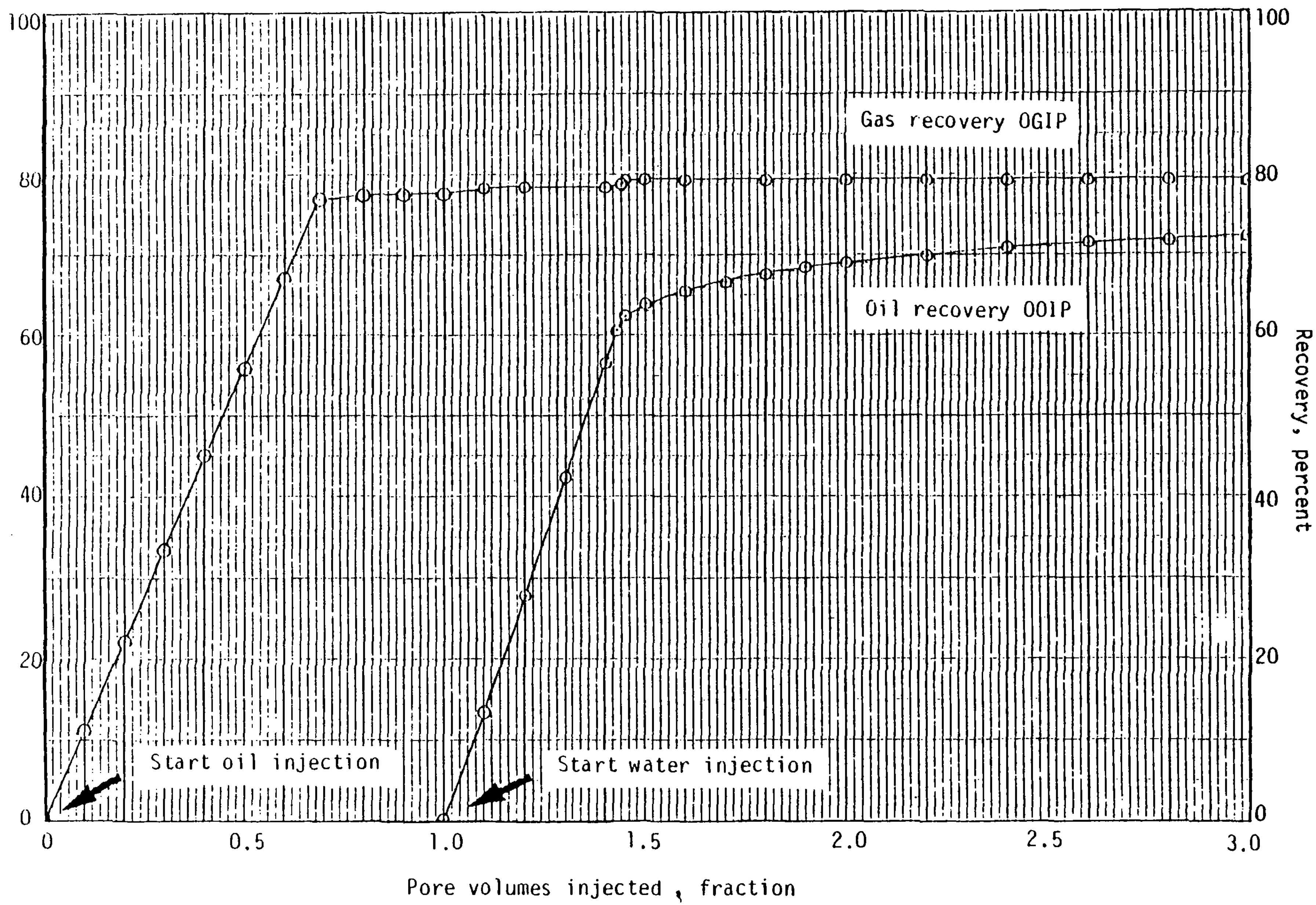

Fig. 5 Recovery of hydrocarbons based on original gas and oil in place before displacement experiment

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 volumes (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

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A P P E N D I X

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APPENDIX I

APPARATUS

The figure on next page shows the apparatus designed for the experiments. The apparatus consists of parts especially made or ordered for this project or general equipment from the SINTEF-laboratory. Below is a list of the different parts shown in the figure A1.

<u>Equipment</u>

High Pressure Mercury Displacement Pump *)
HPLC Pump *)
High pressure containers for gas, oil and
water made of Inconel 625 or SS313
Core-holder
Differential Pressure Transducer
3-phase high pressure separator**)
Back pressure regulator
Heating cabinet
Gauges
Valves, fittings
Pressure registration *)
Temperature registration
Volume registration**)
Chart recorder *)
Auxillary equipment *)

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*) Equipment for general use in the laboratory.

**) Equipment designed at SINTEF on internal project.
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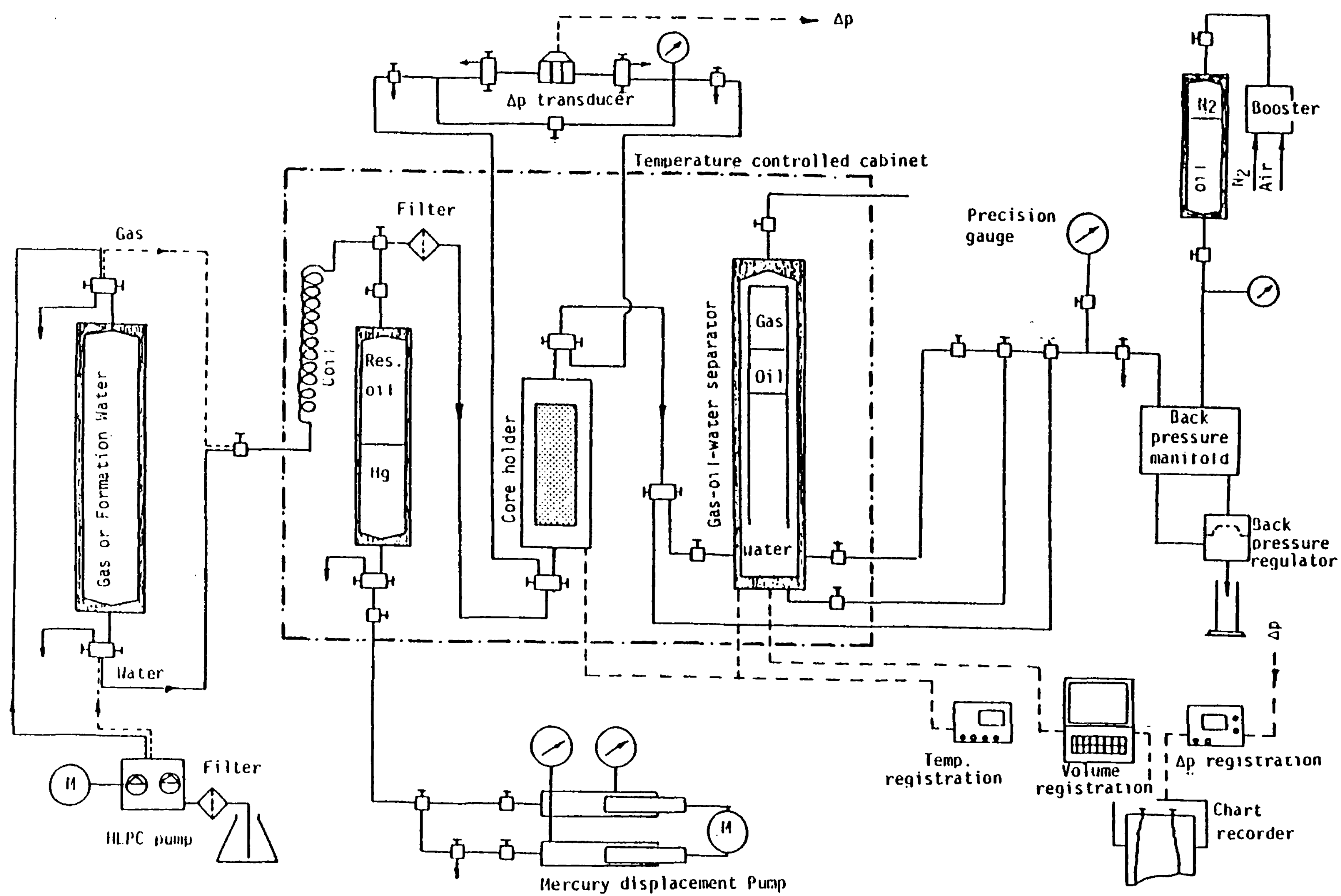

Figure A1 Schematic diagram of apparatus

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The apparatus was designed specifically to simulate desplacement processesing using a real reservoir core sample and reservoir fluids at reservoir pressure and temperature. The present version of the apparatus is limited to 35 MPa working pressure and 70°C in temperature. However, by changing the differential pressure transducer, the maximum possible pressure will be 70 MPa and by changing windows in the heating cabinet, the working temperature could increase to 150°C.

The high pressure pumps can deliver constant fluid rates varying from 0.02 cm^3/h to 1500 cm^3/h at pressures up to 90 MPa.

The different reservoir fluids to be injected into the core sample were stored in high pressure high quality steel cylinders. The formation water cylinder was manufactured from Inconel 625, which is especially resistant to corrosion, which again could influence the interfacial properties of the fluids.

The core was placed in a high pressure, steel cylinder and sealed by an alloy of tin/bismuth. The alloy having a melting point of 143°C expands 1-2% when it is cooled, thus forming an effective seal between the core sample and the steel cylinder.

The pressure differential across the core sample was measured with a Validyne ± 1 psi (7kPa) differential pressure transducer with line pressure of maximum 35 MPa. The pressure transducer was calibrated with two deadweight testers at the actual line pressure of the experiment.

A Leybold Hereaus controlled temperature cabinet was used to ensure a constant temperature on core-holder, fluid containers and separator during the experiments. Two separate temperature control systems were used to control the temperature in the heating cabinet giving a temperature accuracy of ± 0.5°C.

A 2μ high pressure filter was placed in the inlet line to the core sample to remove possible solid particles in the fluids. All tubings in contact with the brine were manufactured in Hastelloy C, which is very resistant to corrosion. All other tubings were made of 316 stainless steel.

Gas, oil and water produced from the core sample were collected in a specially designed high pressure separator*). Produced volumes were measured at the actual pressure and temperature of the experiment. This ensured a better control of produced volumes than the standard method of flashing the fluids and converting the volumes to reservoir conditions. The basic measuring principle of the separator was based on measuring the speed of sound in the oil and water phase using ultrasonic signals. Prior to the experiments the separator was calibrated with the fluids to be used in the actual experiment. The cumulative produced volumes of gas, oil and brine were monitored and continuously recorded. The excess water from the separator was produced through a ROP back pressure valve, which was regulated by a hydraulic oil with a nitrogen-cap to minimize effects of room temperature changes on the outlet pressure.

The possibility to by-pass the core sample and the separator also existed. This was necessary in the preparation process prior to the displacement tests.

*) The separator electronics and software are developed on a seperate project and all rights concerning the use of this principle and publication rights are reserved SINTEF.

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APPENDIX II

EXPERIMENTAL PROCEDURE

1. Preparation of core sample.

The core sample was carefully removed from the plastic container and sealed with the bismuth/tin alloy in the core holder. The end sections of the core were cut and the end pieces of the core holder were assembled. The cleaning of the core was done by flushing slugs of methanol and toluene through the core using a positive displacement pump. Refraction- index of the produced and injected fluids were used to check if the core was clean. The core was then dried in a controlled humidity oven at 40% relative humidity and 60°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 the experiments was made of distilled water and purified salts according to the water analysis given in Appendix IV. 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 brine 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 of 17.8 MPa. This is higher than the reservoir pressure of 15.9 MPa, but it ensures a completely gas-saturated oil at the lower pressure. The pressure was decreased and oil and gas were allowed to equilibrate at the reservoir pressure of 15.9 MPa and at reservoir temperature of 68°C. 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 a Helium porosimeter. A porosity control was obtained when the core was saturated with the synthetic formation brine.

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°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.

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 has a water saturation of 10.8 percent. This saturation constituted the initial brine saturation in the remaining part of the experiment.

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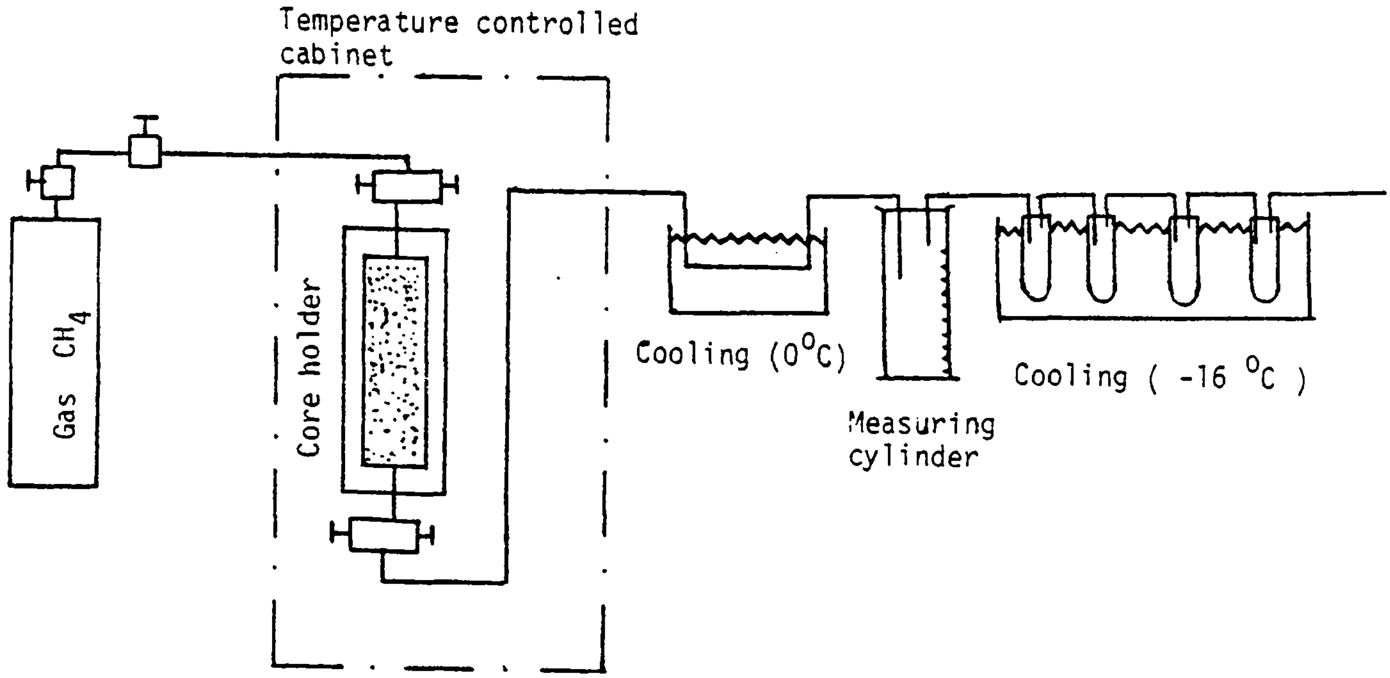

Fig. A2 Schematic diagram of apparatus for etablishing S_{wi}

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^{0}C and a preheated separator gas (68^{0}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 soundin 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 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 7.53 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.

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 7.09 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 1.8 porevolumes were injected, but the displacement process was continued until 2.1 porevolumes were injected to insure no more production.

8. Pressure depletion test

The high pressure separator system and by-pass to differential pressure transducer were closed off and upstream valve to the core was also closed. The pilot pressure on the back pressure valve was decreased to allow for a pressure decline of approximately 1 MPa (145 psi) in the core sample. The fluids thus produced due to an expansion were flashed down to standard conditions and volumes were measured. Gas, oil and water were produced through the back pressure valve until pilot pressure and the pressure inside the system had come to and equilibrium.

Based on known formation volume factors for the fluids (PVT-report from well 31/2-5, App. V) the saturations in the core sample were calculated. This was repeated 7 times until a final pressure of about 7.0 MPa reached. A schematic drawing of the apparatus used in this experiment is found on figure A3 on this page.

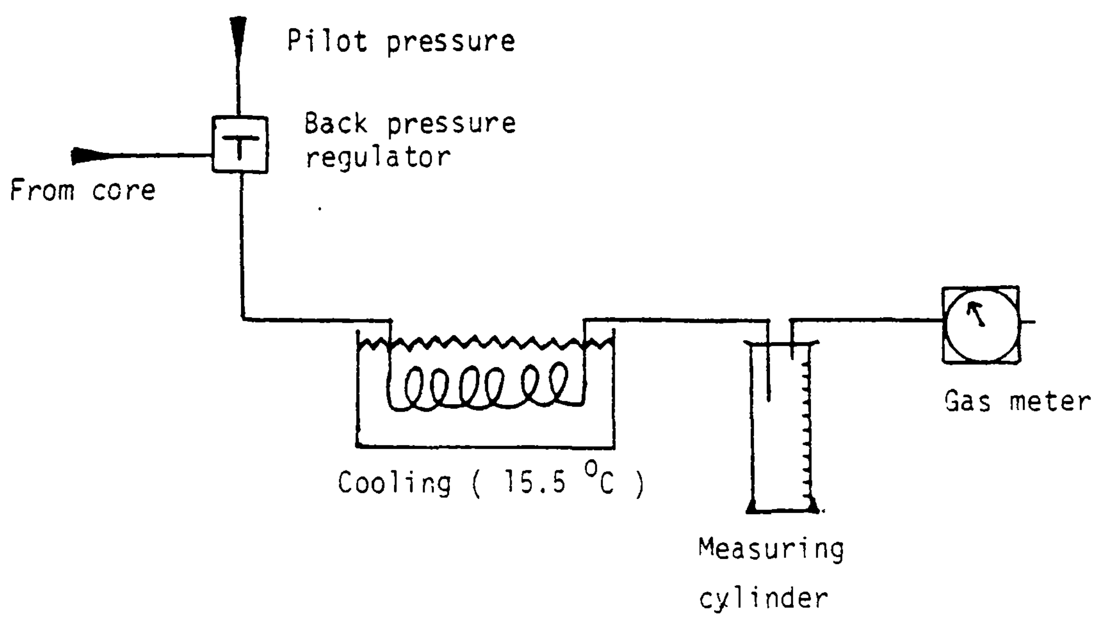

Fig . A3 Schematic diagram of apparatus used in the depletion test

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APPENDIX III

CALCULATIONS

1. Calculations of saturations in the core during displacement experiments.

The calculations of the saturations in the oil- and waterflooding experiments are based on material balance and are straight forward. Produced volumes are directly recorded by the high pressure separator unit, and all dead volumes in the end sections of the core and in the lines are corrected for.

2. Calculation of reservoir conditions oil volumes based on produced volumes in the depletion test.

Material balance is used to determine remaining oil saturations in the core. Relative volumes from the differential vaporation test (Appendix V) are used to calculate the volume at the indicated pressure and temperature. Masses of the produced oil in each step are determined and subtracted from the initial mass of the core sample. The volume of the remaining oil in the core is found in each step at the indicated pressure and temperature.

APPROXIMATIONS

1. Mass of initial oil in the core is assumed to be constant during the depletion test.

2. Produced oil flashed in a single step from the core has the same volumetric behaviour as the oil from the differential vaporation test (Appendix V).

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PROCEDURE

1. Relative oil volume and oil density (V_R and $\rho_{P.T}$ from Appendix V) are plotted versus pressure.

2. Volume of oil at indicated pressure and temperature ($V_{P.T}$) is calculated from Eq. (1).

$$V_R = \frac{V_{P.T}}{V_{STC}} \tag{1}$$

3. The mass of the produced oil volume is determined from Eq. (2).

$$\Delta M_{P.T} = \rho_{P.T} \cdot \Delta V_{P.T} \tag{2}$$

4. The mass of the initial oil volume is calculated from Eq. (3) and produced mass of oil subtracted. Remaining mass of oil is now found and volume of oil determined from Eq. (3).

$$M_{P.T} = \rho_{P.T} \cdot V_{P.T} \tag{3}$$

V_R = Volume of oil at indicated pressure and temperature divided by volume of residual oil at 15.5^{o}C (60^{o}F) and 0.1 MPa (14.5 psia).

$V_{P.T}$ = Volume of oil at indicated pressure and temperature.

V_{STC} = Volume of residual oil at 15.5^{o}C (60^{o}F) and 0.1 MPa (14.5 psia).

$\rho_{P.T}$ = Density of oil at indicated pressure and temperature.

$\Delta M_{P.T}$ = Mass of oil at indicated pressure and temperature.

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ACCURACY OF RESULTS

The volumes measured at reservoir conditions were performed in a calibrated separator. Produced volume in the separator and injected volume on the mercury displacement pump were controlled. Differencis within 0.5 percent between the injected and the produced volume were found.

The Validyne ± 7 kPa (1 psi) differential pressure transducer used was calibrated with two dead weight testers at 15.9 MPa (2305 psi). But measurement of the differential pressures in this test was difficult. The pressures measured at the end-points were in a range of 0.14 to 0.35 kPa (0.02 to 0.05 psi). At such low differential pressures, the transducer is influenced by small oscillations in the back pressure caused by the back pressure valve and good readings are difficult to make. Capillary end effects must be expected to be active at the low injection rate used.

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APPENDIX IV

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 V

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"
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