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RELATIVE PERMEABILITY MEASUREMENTS ON CORE SAMPLES FROM WELL 31/2-6, NORWAY

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Investigation 9.25.234

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CONTENTS

KEYWORDS
Well 31/2-6, Norway, relative permeability, imbibition, drainage.

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Ref.: Telex for 230222, dated 23-2-'82, from Shell Forus Norway to KSEPL, Rijswijk.

1. INTRODUCTION

At the request of Shell Forus, the following relative permeability measurements were carried out on core samples from well 31/2-6.

- Measurement of (imbibition) oil/water relative permeability curves by the Welge displacement method as described in Appendix A.
- Measurement of effective oil/water end-point permeabilities, including determination of oil and water saturations.
- Measurement of (drainage) gas/oil relative permeability curves by the so-called "modified" Welge displacement method as described in Appendix B.
- Measurement of effective gas/water end-point permeabilities, including determination of residual gas and water saturation (see Appendix C).

2. RESULTS AND CONCLUSIONS

All relative permeability measurements were carried out on cylindrical one-inch diameter plugs approx. 3 cm long. These plugs were drilled from the frozen core material (submitted by Shell Forus) using liquid nitrogen as a coolant. After mounting in the core holder, in which a radial stress of 50 bar was applied to the sample, the plugs were allowed to thaw and subsequently cleaned by flooding with toluene and chlorothene. Finally, the samples were dried by purging with nitrogen, after which the samples were saturated with brine. For all measurements the brine contained 60 g NaCl/l.

2.1 Oil/water-imbibition curves (Welge)

Welge oil/water relative permeability measurements were carried out on six samples (1R-6R). To obtain a sufficient part of the relative permeability curves oil/water viscosity ratios ranging from 14 to 109 were used in the experiments.

Owing to production of fines during water imbibition, the measurements on sample 4R had to be terminated at an early stage. The results are summarised in Table I. The irreducible water saturation, S_{cw}, ranged from 11-26% PV, averaging 19% PV. The residual oil saturation, S_{or}, varied from 24 to 35% PV, averaging 31% PV. Hence, the movable oil volume (MOV) amounts to 50% PV.

The curves are presented in Figs. 1-5.

2.2 Oil/water end-point permeabilities

Directly following the oil/water-Welge measurements, i.e. without intermediate cleaning, on four samples (1R, 2R, 3R, 6R) residual oil saturation and effective water permeability measurements were also carried out applying an oil/water viscosity ratio related to reservoir conditions (oil/water viscosity ratio = 3). In order to achieve this, the samples were first flooded with the same viscous oil[1)] as used in the Welge measurements. After connate water was achieved again and the effective oil permeability measured, the viscous oil was miscibly displaced by hexadecane.

Subsequently the samples were flooded with water until residual oil saturation was established and the effective water permeability measured. The results are presented in Table II. The average value of S_{or} (29% PV) differs only slightly from the average S_{or} (31% PV) achieved under section 2.1.

2.3 Gas/oil-drainage curves

Although five plug samples were available for gas/oil relative permeability measurements, only on three samples (g1, g2

1) see Table I

and g6) were gas/oil drainage curves measured. Experimental limitations did not allow these measurements to be carried out on samples g3 and g4 because of their extremely high permeability (7.4 and 6.0 Darcy, respectively). On these samples only end-point measurements were performed.

The results are given in Table III and Figs. 6-8.

2.4 Gas/water end-point permeabilities

On the same five samples mentioned in section 2.3, after cleaning, gas/water end-point relative permeability measurements were also carried out. The results are summarised in Table IV. The measured S_{gr}-values (residual gas saturation) varied from 3 to 10% PV, averaging 6% PV, which is very low and probably not realistic. The low S_{gr}-results could possibly be explained by the also low values of the initial gas saturation, averaging 52% PV, which, in turn, resulted from the fact that, during the inital gas-drive cycle, the water saturation could not be reduced further than to about 48% PV. (Water displacement by oil in the "oil/gas" experiments resulted in an average S_{cw} of 20%). Obviously, under the conditions of the experiment, the displacing gas could not enter into the smaller pores of the samples. The poorer "gas trapping ability" of the wider pores subsequently resulted in the low S_{gr}-results.

2.5 Permeability correlations

Figures 9-11 show the correlation between air permeability and water permeability, water permeability and effective oil permeability, water permeability and effective water permeability, respectively.

TABLE I

REVIEW OF DATA OBTAINED FROM OIL/WATER RELATIVE PERMEABILITY MEASUREMENTS BY WELGE-DISPLACEMENT METHOD ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-6

Sample no.	1R	2R	3R	4R	5R	6R
Depth, m	1526.8	1538.0	1552.1	1570.0	1580.1	1585.0
Porosity, % of bulk volume	29	27	30	31	33	31
Air permeability, k_a, mD	4200	38	7000	6000	3000	920
Grain density, g/ml	2.65	2.67	2.66	2.66	2.66	2.67
Absolute water permeability k_w, mD	4200	25	7100	5800	3000	800
Irreducible water saturation, S_{cw}, % of pore volume	14	26	17	11	22	25
Effective oil permeability at S_{cw}, k_{ocw}, mD	4100	31	7100	4000	2900	910
Residual oil saturation, S_{or}, % of pore volume	29	24	33	32	34	35
Effective water permeability at S_{or}, k_{wor}, mD	740	11	960	NM	250	58
Oil/water-viscosity ratio	40	14	40	109	40	40

TABLE II

RESULTS OF OIL/WATER END-POINT RELATIVE PERMEABILITY MEASUREMENTS ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-6

Sample no.	1R	2R	3R	6R
Depth, m	1526.8	1538.0	1552.1	1585.0
Oil/water-viscosity ratio	40	14	40	40
Effective oil permeability at S_{cw}, k_{ocw}, mD	4100	29	6000	800
Irreducible water saturation, S_{cw}, % of pore volume	15	25	16	24
Oil[1)]/water-viscosity ratio	3	3	3	3
Effective oil permeability at S_{cw}, k_{ocw}, mD	4000	29	5800	750
Residual oil saturation, S_{or}, % of pore volume	27	21	30	37
Effective water permeability at S_{or}, k_{wor}, mD	900	14	1400	85

1) *Oil = Hexadecane*

TABLE III

REVIEW OF DATA OBTAINED FROM GAS/OIL RELATIVE PERMEABILITY MEASUREMENTS BY WELGE-DISPLACEMENT METHOD ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-6

Sample no.	G1	G2	G3 1)	G4 1)	G6
Depth, m	1526.8	1538.0	1552.1	1570.0	1585.0
Porosity, % of bulk volume	33.5	29.3	31.2	33.2	25.9
Grain density, g/ml	2.68	2.68	2.66	2.66	2.65
Air permeability, k_a, mD	4800	33	7400	6000	2000 2)
Irreducible water saturation, S_{cw}, % of pore volume	19	25	17	22	17
Effective oil permeability at S_{cw}, k_{ocw}, mD	4700	27	7800	5000	1500
"Residual oil"3) saturation at the end of the experiment, S_{or}, % of pore volume	29	31	38	23	50
Effective gas permeability at the end of the experiment, k_{giw}, mD	—	—	4000	4400	—

Note: water salinity 60 g NaCl/l

1) End-point only
2) Initially k_a was 1100 mD, however, due to production of some fines during measurement of k_{ocw}, k_a appeared to be 2000 mD when measured after determination of the curve.
3) "Residual oil" saturation results from hold-up by capillary forces in combination with the limited duration of the experiment. In gas drive drainage experiments at connate water the entire oil phase has to be considered mobile. This means that the curve ends at S_{cw} with an effective gas permeability k_{gcw} theoretically equalling k_{ocw}.

TABLE IV

RESULTS OF GAS/WATER END-POINT RELATIVE PERMEABILITY MEASUREMENTS ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-6

Sample no.	G1	G2	G3	G4	G6
Depth, m	1526.8	1538.0	1552.1	1570.0	1585.0
Porosity, % of bulk volume	33.5	29.3	31.2	33.2	25.9
Air permeability, mD	4800	33	7400	6000	2000 1)
Grain density, g/ml	2.68	2.68	2.66	2.66	2.65
Absolute water permeability, mD	3400	23	4500	5900	1600
Irreducible water saturation, S_{wi} % of pore volume	58 2)	50 2)	36 2)	46 2)	52 2)
Effective gas permeability at S_{wi}, k_{giw}, mD	2000	22	4400	4400	1300
Effective water permeability at "residual gas" saturation, k_{wgr}, mD	1500 3)	15 3)	3300 3)	2100 3)	1100 3)
Residual gas saturation, S_{gr}, % of pore volume	3 4)	10 4)	4 4)	4 4)	9 4)

1) See remark under 2) in Table III
2) High S_{wi} values probably resulting from capillary forces in combination with experimental limitations.
3) The values of k_{wgr} as presented in this table are probably to be considered being too high because of the very low S_{gr}-values achieved.
4) The measured S_{gr}-values are very low and probably not realistic.

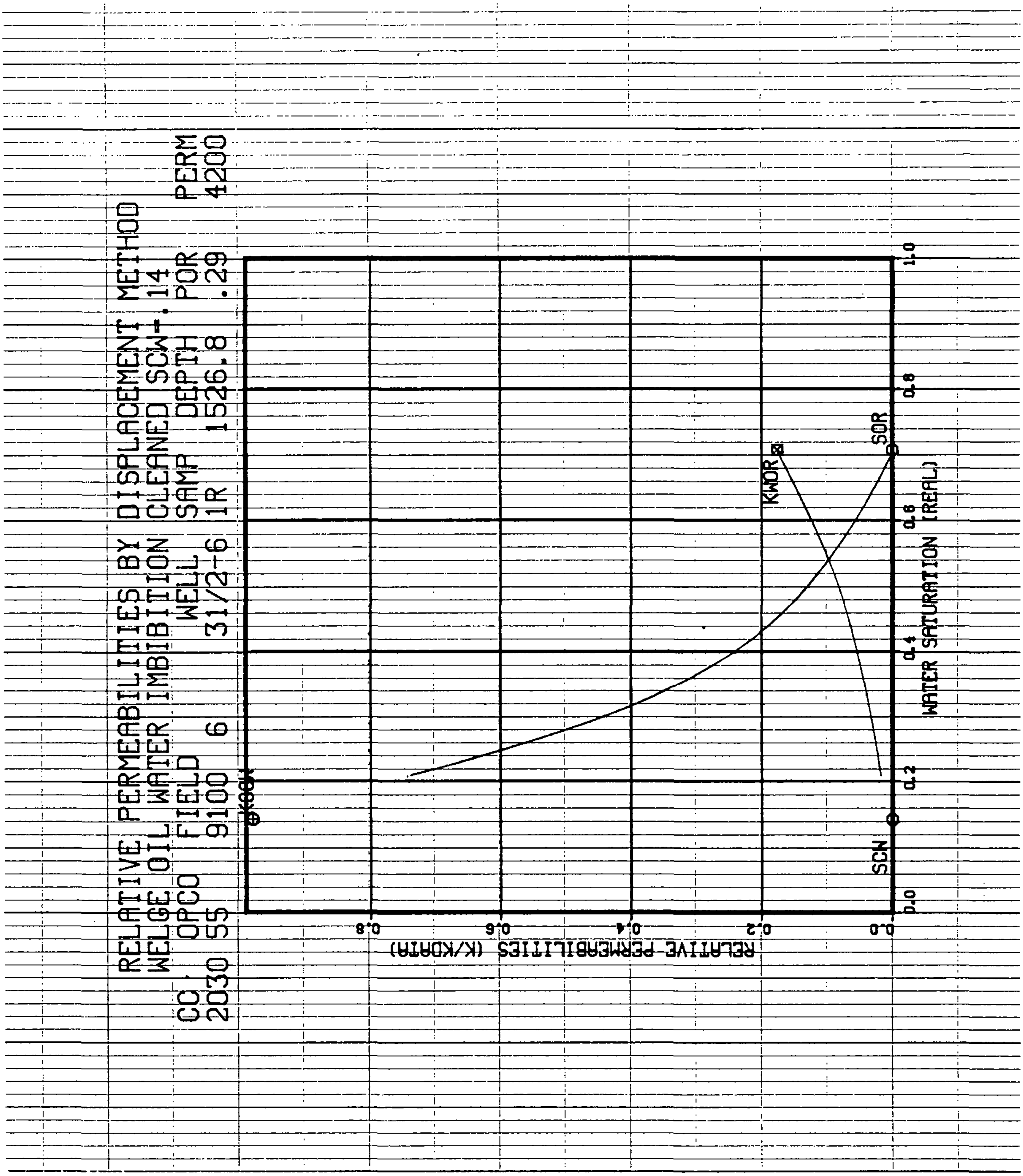

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL WATER IMBIBITION CLEANED SCW= .14
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 6 31/2-6 1R 1526.8 .29 4200
KWOR
SOR
SCW
WATER SATURATION (REAL)
RELATIVE PERMEABILITIES (K/KDATA)
0.0
0.2
0.4
0.6
0.8
1.0

Figure 1

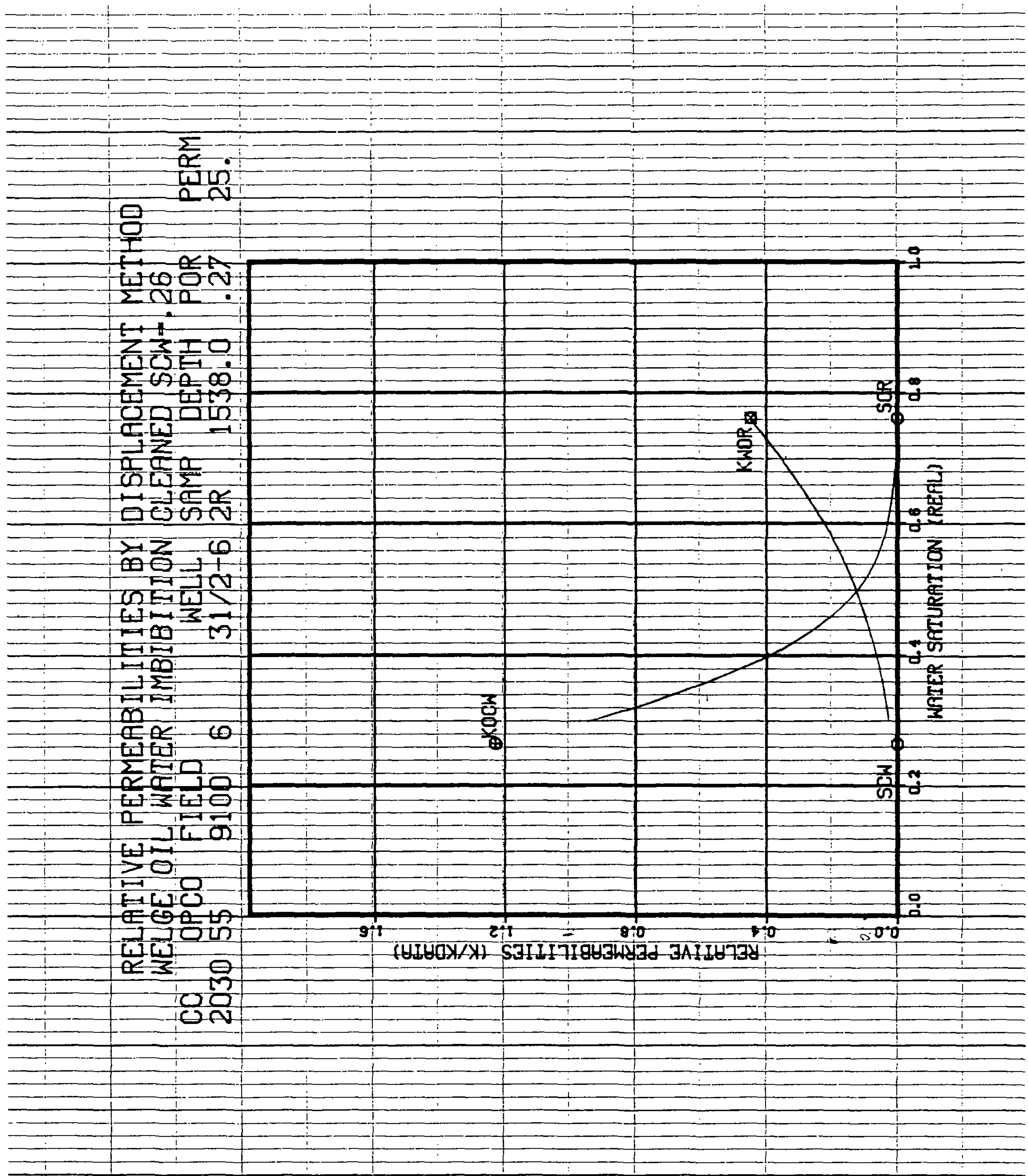

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL WATER IMBIBITION CLEANED SCW= .26
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 6 31/2-6 2R 1538.0 .27 25.
RELATIVE PERMEABILITIES (K/KDATA)
WATER SATURATION (REAL)
KOCW
KWOR
SCW
SOR
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.6

Figure 2

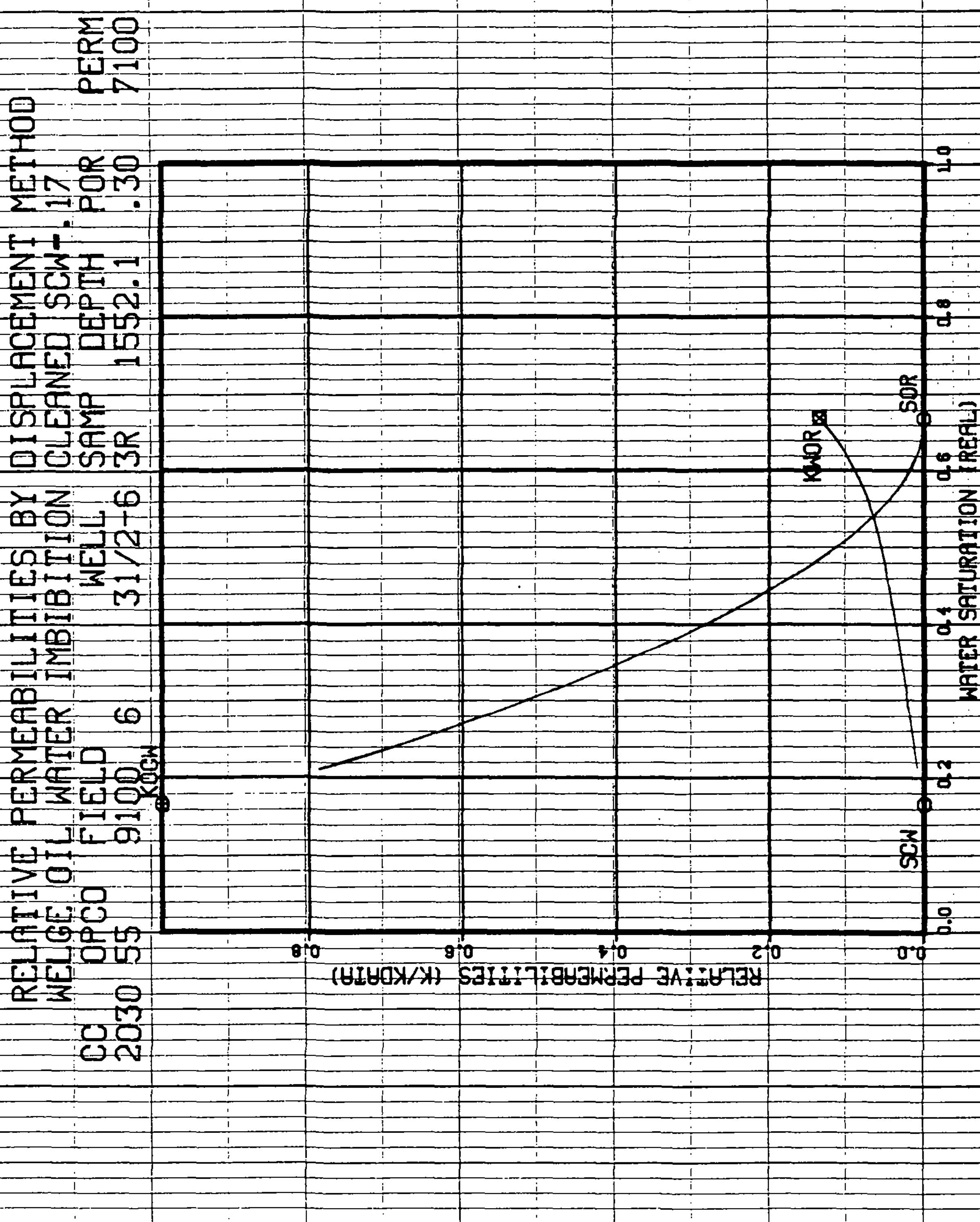

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL WATER IMBIBITION CLEANED SCW=.17
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 6 31/2-6 3R 1552.1 .30 7100
KOGW
KWOR
SOR
SCW
RELATIVE PERMEABILITIES (K/KDATA)
WATER SATURATION (REAL)
0.0
0.2
0.4
0.6
0.8
1.0

Figure 3

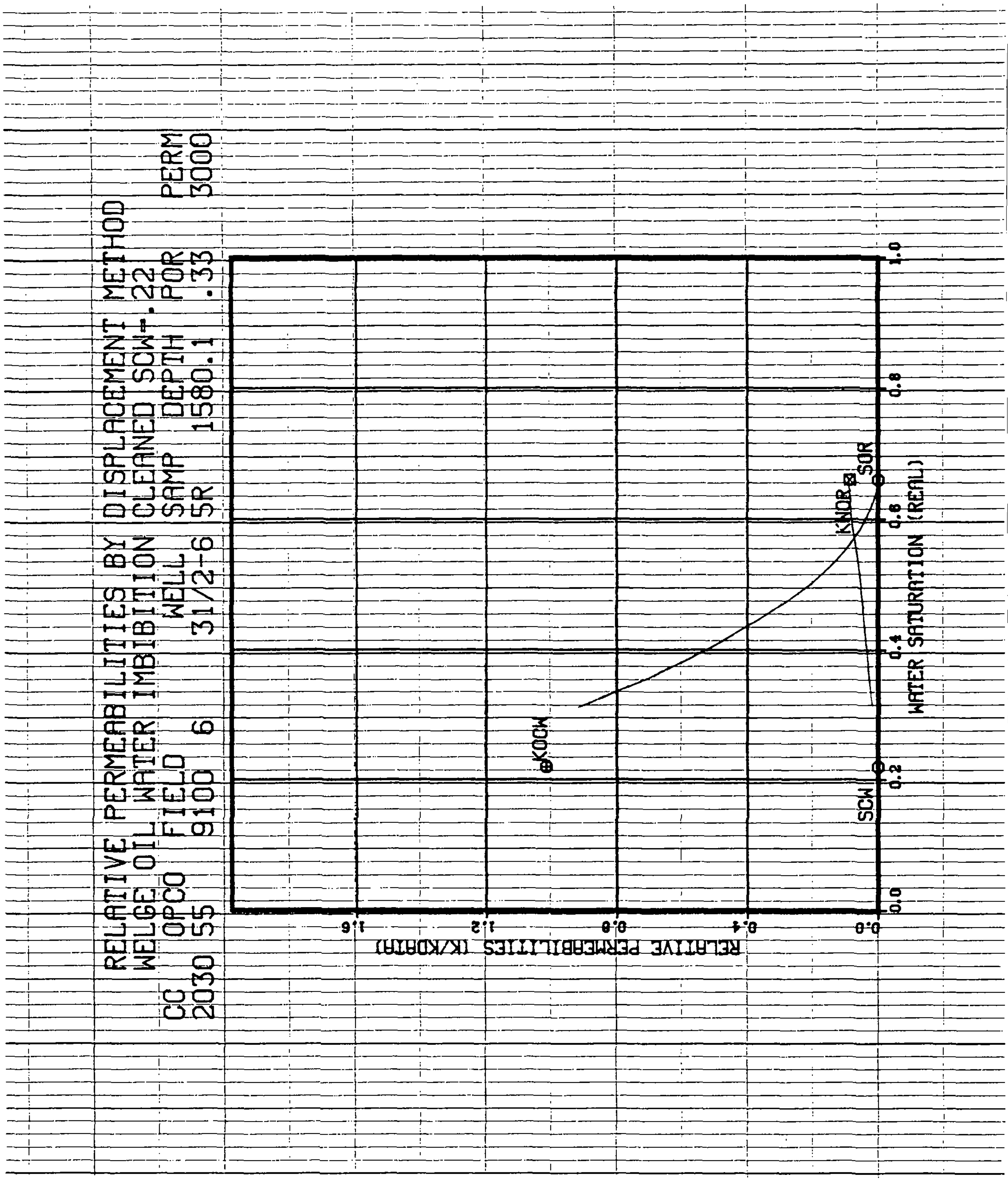

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL WATER IMBIBITION CLEANED SCW=.22
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 6 31/2-6 SR 1580.1 .33 3000
KOOW
KNOR
SOR
SCW
0.0
0.2
0.4
0.6
0.8
1.0
WATER SATURATION (REAL)
0.0
0.4
0.8
1.2
1.6
RELATIVE PERMEABILITIES (K/KDATA)

Figure 4

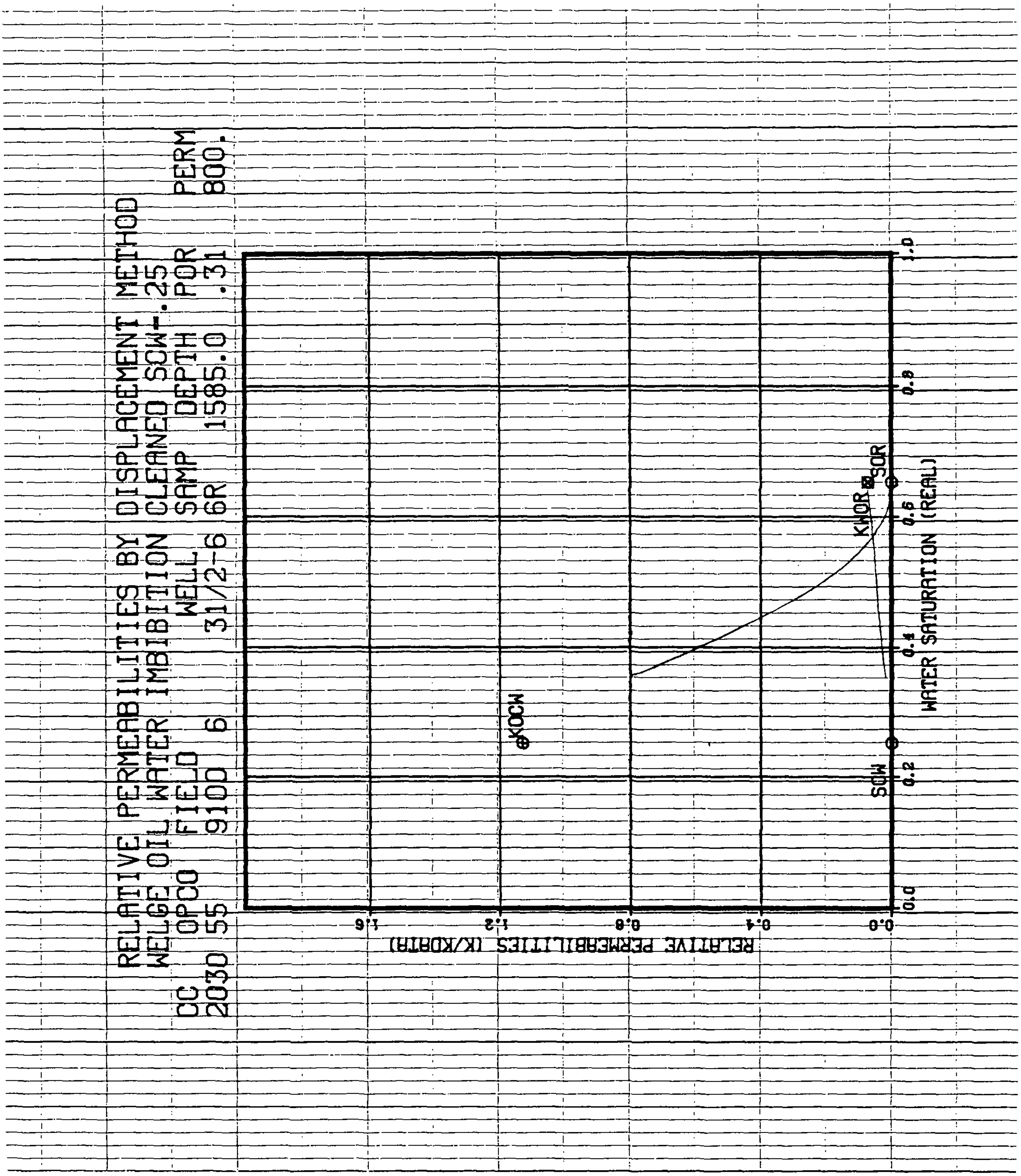

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL WATER IMBIBITION CLEANED SOW=.25
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 6 31/2-6 6R 1585.0 .31 800.
KOCW
KWOR
SOR
SOW
WATER SATURATION (REAL)
RELATIVE PERMEABILITIES (K/KOATA)

Figure 5

GAS-OIL DISPLACEMENT METHOD

RELATIVE PERMEABILITIES IN DRAINAGE MODE AT SCW-.19

CC	OPCO	FIELD	WELL	SAMP	DEPTH	POR	PERM
2030	55	9100	6	G1	1526.8	.335	4800.

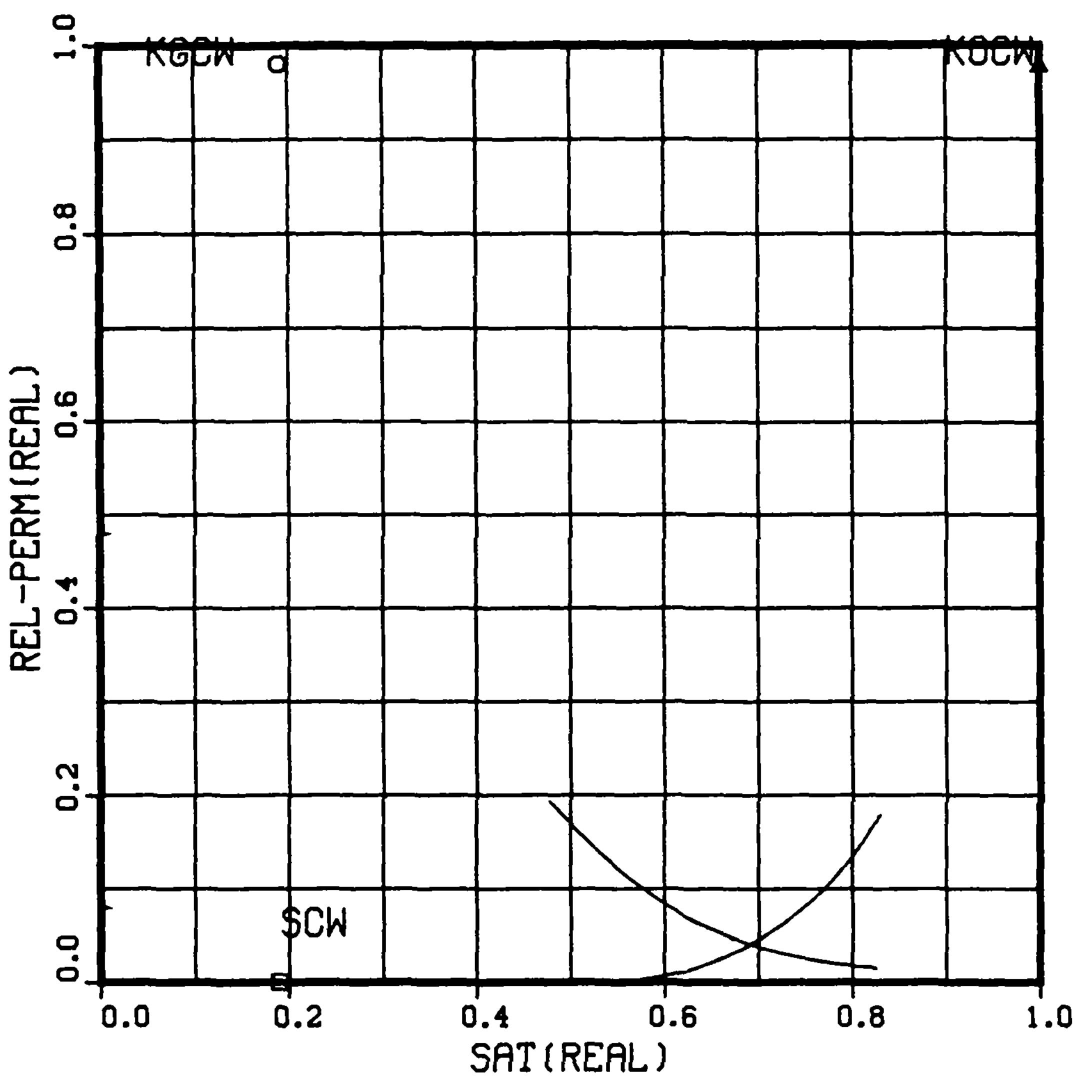
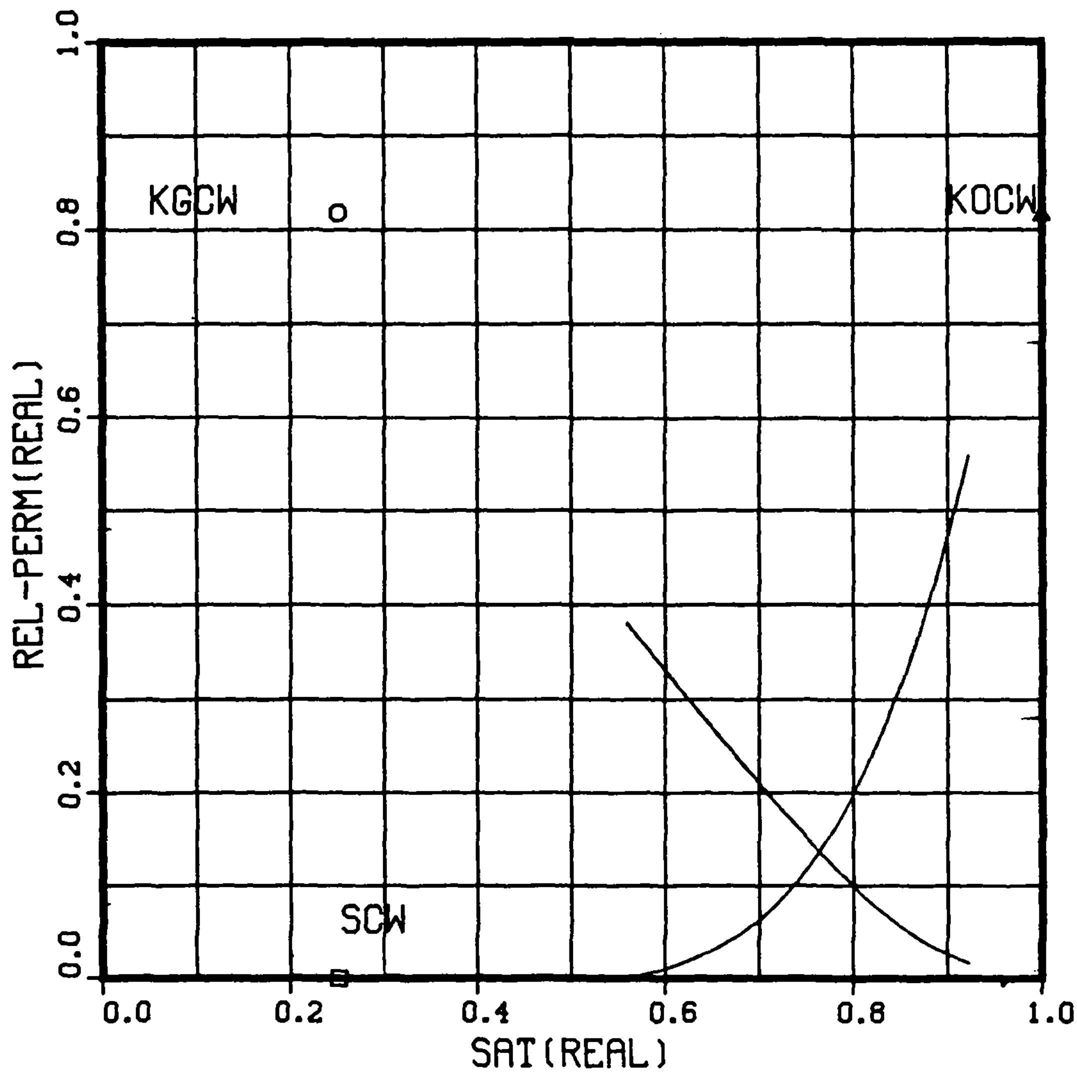


Figure 6

GAS-OIL DISPLACEMENT METHOD

RELATIVE PERMEABILITIES IN DRAINAGE MODE AT SCW-.25

CC	OPCO	FIELD	WELL	SAMP	DEPTH	POR	PERM
2030	55	9100	6	G2	1538.0	.293	33.



GAS-OIL DISPLACEMENT METHOD

RELATIVE PERMEABILITIES IN DRAINAGE MODE AT SCW-.17

CC	OPCO	FIELD	WELL	SAMP	DEPTH	POR	PERM
2030	55	9100	6	G6	1585.0	.259	2000.

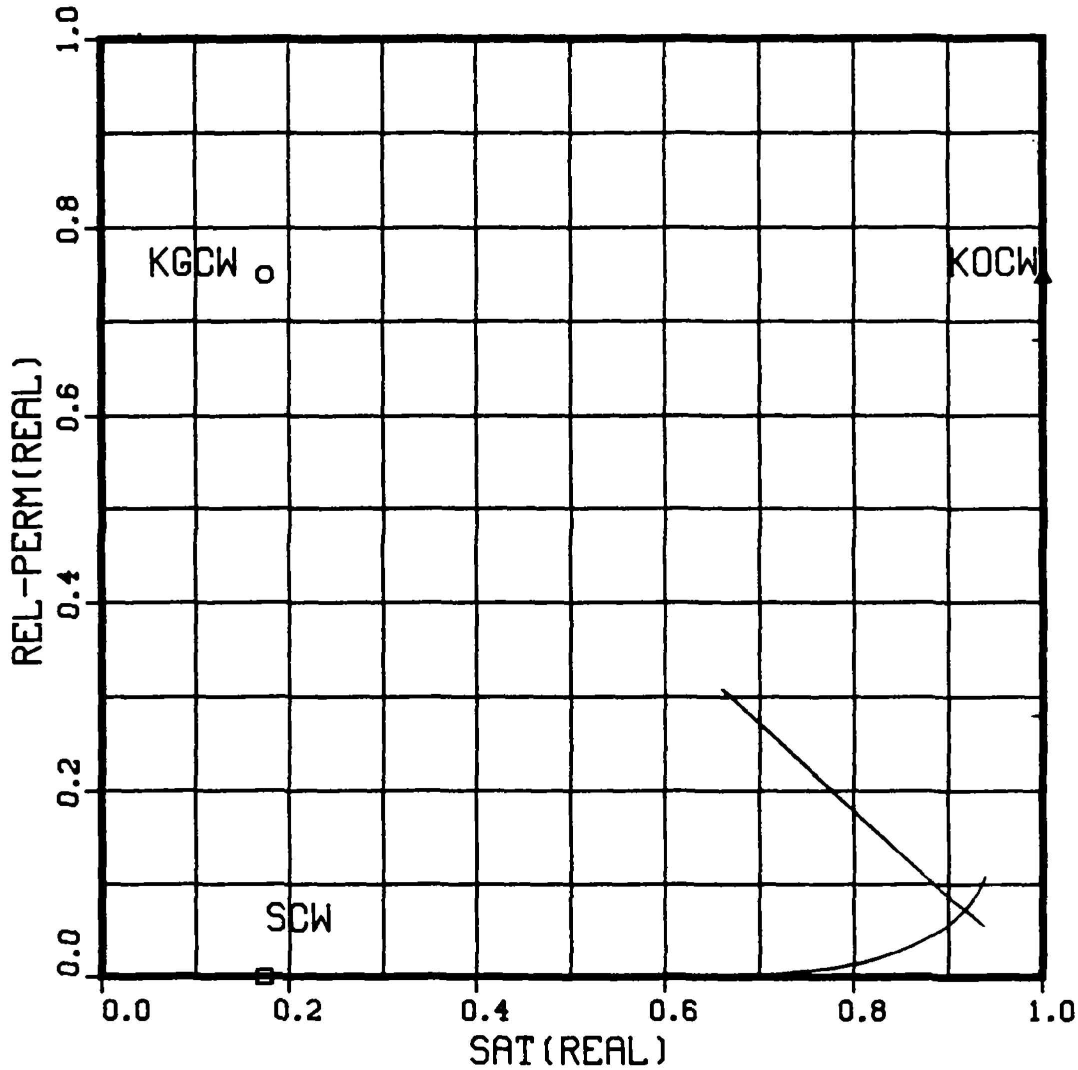
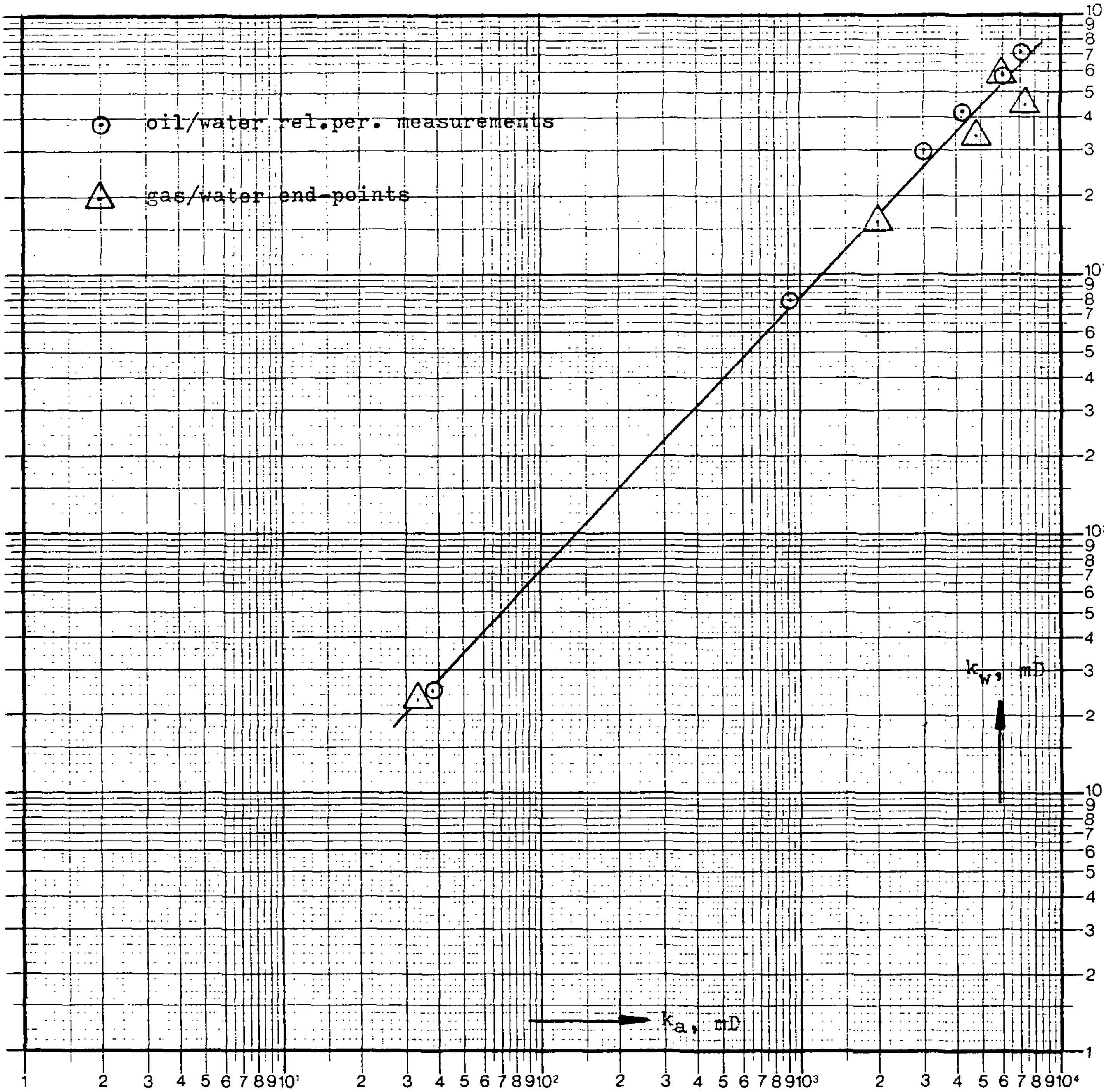


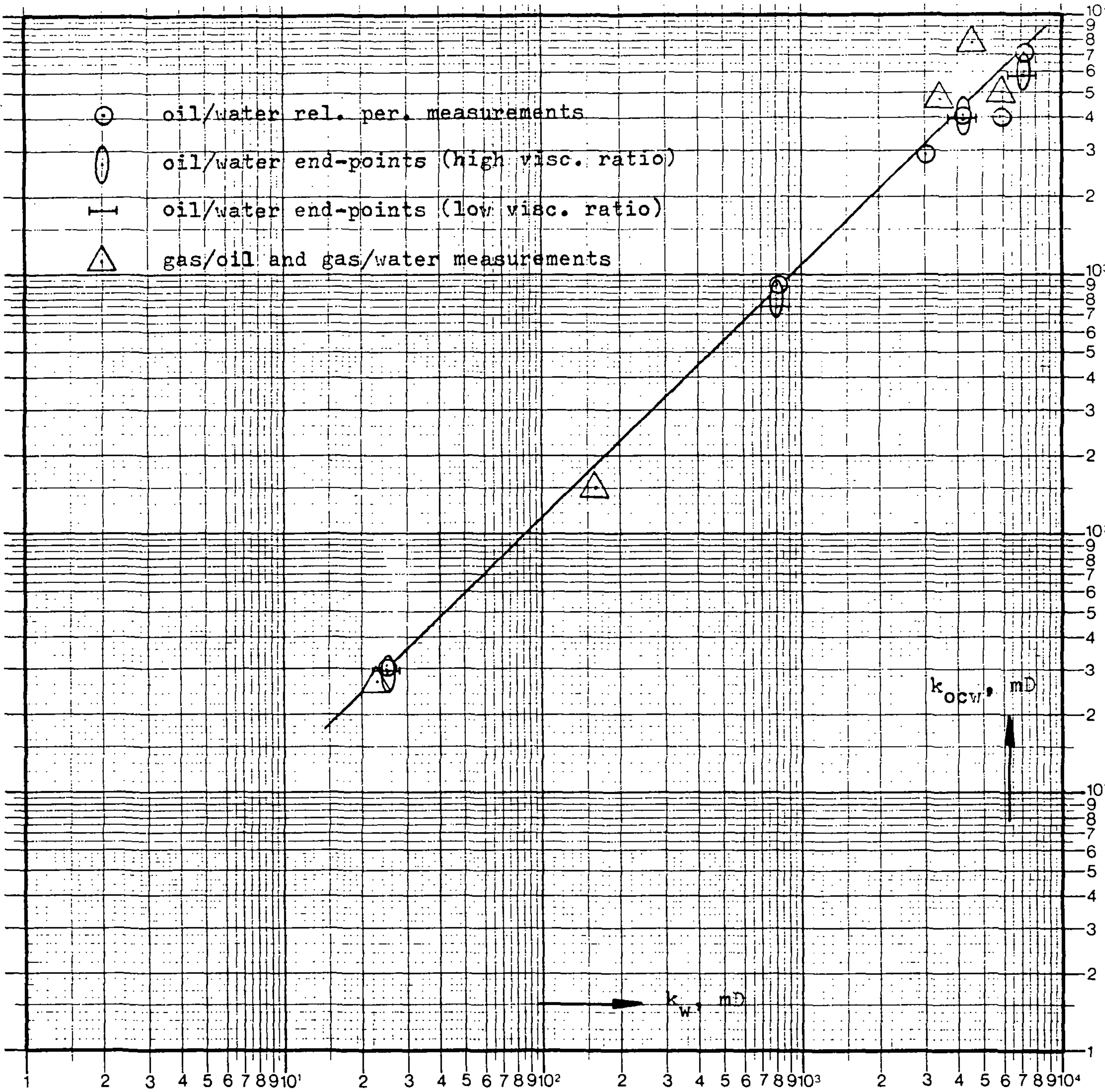
Figure 8



Absolute water permeability (k_w) as a function of air permeability (k_a)

Well 31/2-6

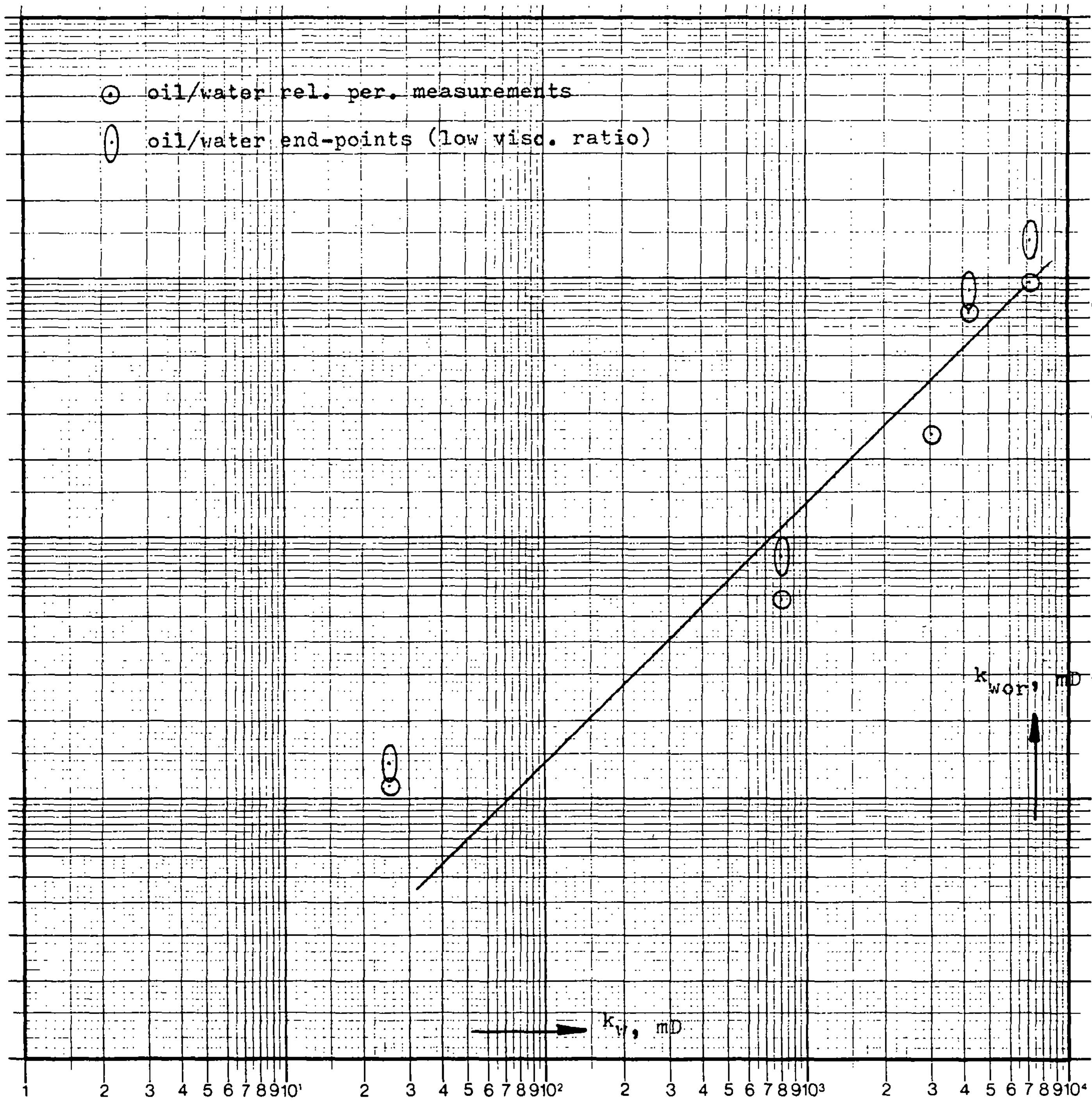
Figure 9



Effective oil permeability (k_{ocw}) as a function of absolute water permeability

Well 31/2-6

Figure 10



Effective water permeability (k_{wor}) as a function of absolute water permeability

Well 31/2-6

Figure 11

APPENDIX A

WELGE METHOD[A1]

In this method relative oil- and water-permeability curves are obtained by waterflooding a core sample saturated with oil (at connate-water saturation).

The sample (a standard core plug) is saturated with (artificial) formation water, and the absolute water permeability (k_w) determined.

Subsequently connate-water saturation is established by flooding with oil followed by determination of the effective oil permeability (k_{ocw}) and connate-water saturation (S_{cw}).

At this point the waterflood is started by water injection at constant rate. The relative oil- and water-permeability curves are computed from the pressure differential across the sample and from oil and water production, all recorded as a function of time[A2,3].

At the end of the experiment the effective water permeability (k_{wor}) is determined at residual oil saturation (S_{or}). In the experiment a diffuse oil and water flow is assumed. The basis of these calculations is the oil/water-flow and -saturation defined at the outflow end of the core plug.

Curves are presented as a function of water saturation and (usually) relative to the absolute water permeability.

A schematic drawing of the experimental set-up is given in Fig. A1.

Remarks

I. Confining stress

At KSEPL a special core holder is used in which a (radial) confining stress of 50 kg/cm^2 is applied on the samples.

II. Wetting

Before carrying out relative-permeability determinations all samples are cleaned by extraction or flooding with solvents. In general, consolidated samples are tested to ascertain whether they are preferentially water-wet, to ensure that relative-permeability curves are obtained in the imbibition cycle (if required, the drainage cycle can be determined, but not, at this stage, for the Welge method).

For unconsolidated core samples, testing of the wettability, is only possible after completion of the experiment.

III. Interaction

Interaction between the water-phase and the core material (e.g. clay minerals) may significantly influence (reduce) water permeability, and hence the results of the Welge test. It is therefore essential that the original formation water should be used for the experiment (if this is not available, artificial formation water may be used).

Even then measurement is only possible if a constant water permeability (at $S_w = 1$) can be achieved.

IV. Sample homogeneity

As Welge's theory assumes homogeneous samples, selection of samples must be very critical.

V. Permeability limit

Low-permeability samples cannot be subjected to the Welge test. At present the lower limitation is approx. 10 mD.

VI. Limited curve

Relative-permeability curves can only be calculated after water breakthrough. Hence, they cover only part of the (movable) saturation range.

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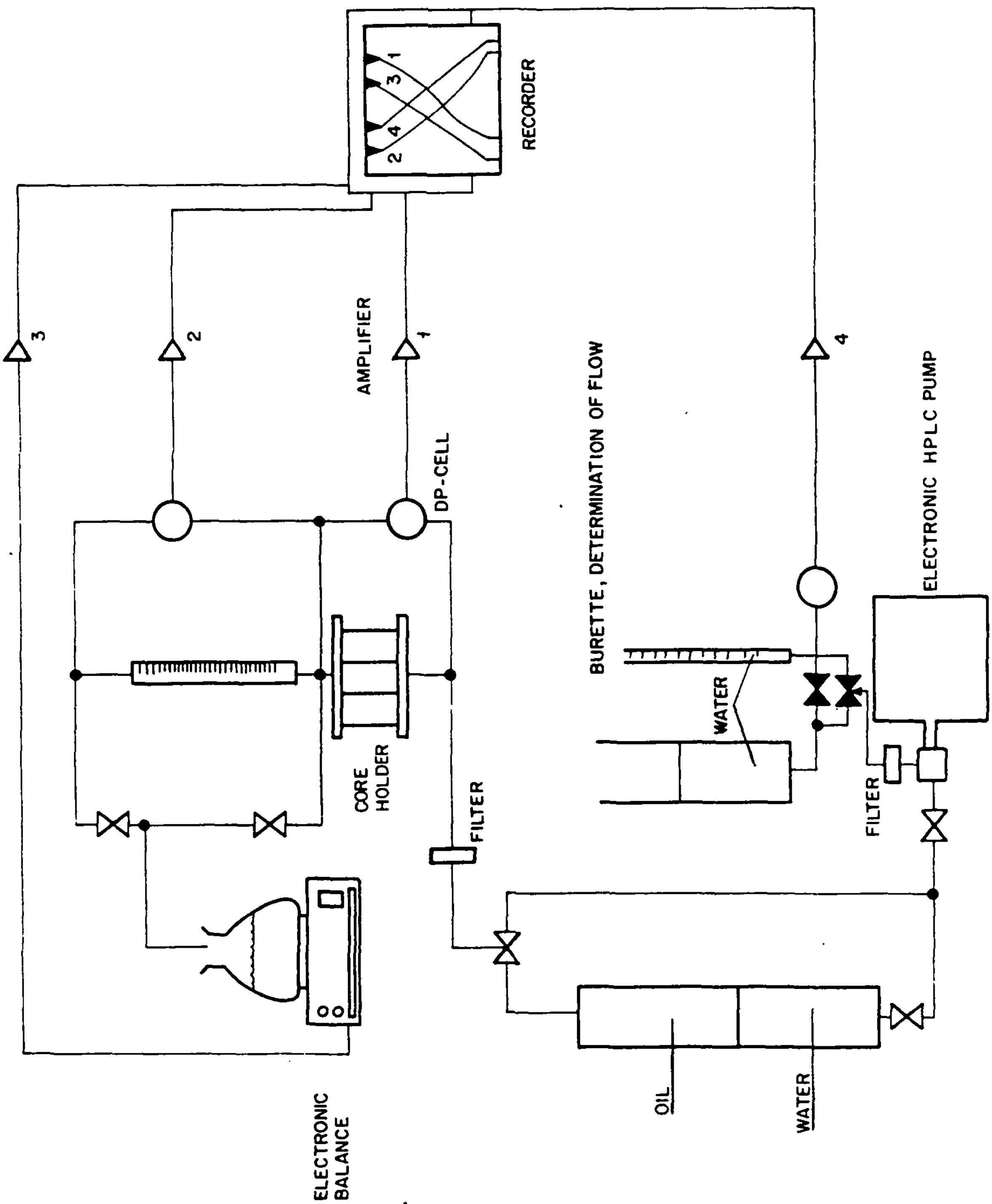

WELGE FLOODING APPARATUS, KSEPL

APPENDIX B

GAS-DRIVE DRAINAGE METHOD[B1]

In this method oil is displaced from an oil-saturated core sample (if required at connate water saturation) by gas drive. The displacement occurs at a constant pressure differential and during the experiment the production of oil and gas are recorded as a function of time (see Fig. B1). Both gas and liquid relative permeability are calculated as a function of total liquid saturation, derived from defined fractional flows, saturation and pressure gradient at the outflow end of the core plug.

Remarks (disturbing effects)

I. Capillary end-effect

As a result of capillary forces, the wetting fluid is held up at the outflow end of the core sample, thus affecting the saturation of that part of the sample.

Therefore, proper test conditions have to be selected to reduce the end effect as much as possible (e.g. $\frac{\Delta P}{Pc} > 10$).

II. Gas expansion

The experiment is based on the Welge[B2] type displacement technique, in which the use of incompressible "fluids" is assumed.

Therefore, gas compressibility has to be reduced by elevation of the average pressure level (by applying an appropriate back pressure) in combination with the smallest allowable pressure differential across the core sample.

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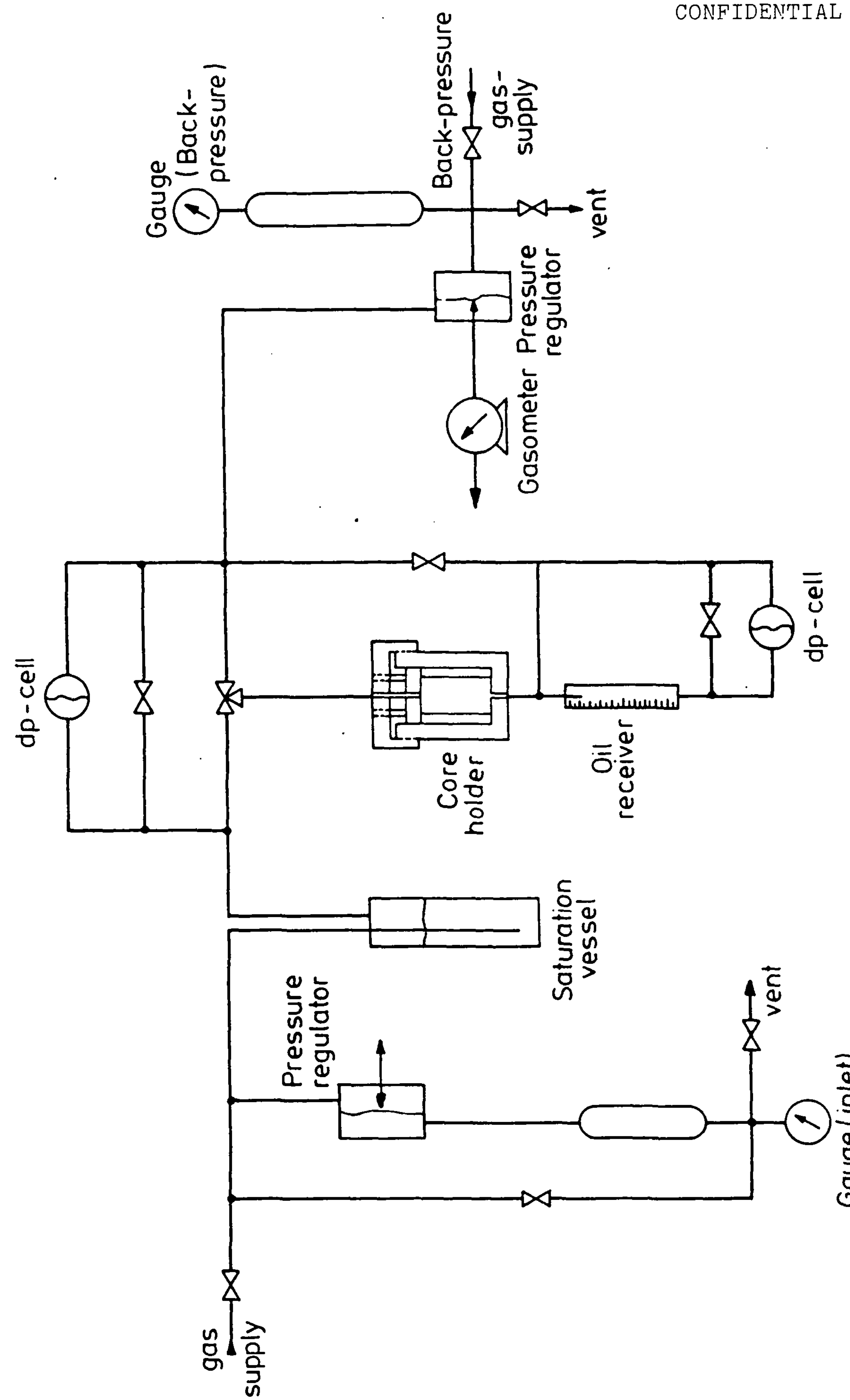

FLOW SCHEDULE OF GAS-DRIVE DRAINAGE EXPERIMENTS

FIG. B1

APPENDIX C

GAS/WATER END-POINT PERMEABILITY MEASUREMENTS

Procedure

Selected plugs are mounted in a special core holder (Fig. C1) in which by means of a rubber stopper a radial stress of 50 kg/cm^2 is applied on the sample. After cleaning, drying and determination of the air permeability (k_a) the sample is saturated with (artificial) formation water and the pore volume (porosity) is determined. Subsequently, the absolute water permeability is measured and the sample is then flushed with water-saturated gas ($\Delta P/Pc > 10$) until is no longer produced and the effective water permeability can be determined.

After this, the sample is flooded with gas-saturated water to establish residual gas saturation. This has to be done at a very small pressure difference, because otherwise solution of gas into the waterphase will cause too low gas saturations. The effective water permeability of residual gas saturation is determined upon flooding approx. 5 - 10 pore volumes.

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