July 1983

RKER.83.131

# RELATIVE-PERMEABILITY MEASUREMENTS ON CORE SAMPLES FROM WELL 31/2-4, NORWAY

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RIJSWIJK, THE NETHERLANDS

(Shell Research B.V.)

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Investigation 9.25.162



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CONTENTS



KEYWORDS
Norway, well 31/2-4, relative permeability, drainage, imbibition.

# RELATIVE-PERMEABILITY MEASUREMENTS ON CORE SAMPLES FROM WELL 31/2-4, NORWAY

Ref.: Telex for 140822, dated 14-8-1981, from Shell Forus Norway to KSEPL, Rijswijk.
Telex for 270507, dated 27-5-1982, from Shell Forus Norway to KSEPL, Rijswijk.

## INTRODUCTION

At the request of Shell Forus, the following relative-permeability measurements were carried out on core samples from well 31/2-4:

I Measurement of full-curve (drainage) gas/oil relative permeability by the so-called "modified" Welge displacement method (see Appendix A).

II Measurement of full-curve (imbibition) oil/water* relative permeability by the Welge displacement method (see Appendix B).

III Measurement of gas/water end-point relative permeability, including determination of residual water saturation (see Appendix C).

IV Measurement of oil/water end-point relative permeability, including determination of oil and water saturations.

## 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 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.

* Salinity 73 g NaCl/l

I. Gas-drive drainage oil/gas curves

Full-curve gas/oil relative-permeability measurements in the drainage mode had been requested for three samples.

The low permeability of sample no. 1R (tight and consolidated after removal from core holder) prevented successful completion of the measurements.

The results, given in Table I and Figs. 1 & 2 indicate a residual oil saturation of 14% PV, although theoretically in the experiments the entire oil phase has to be considered mobile next to the immobile connate-water saturation. In practice, however, gas-drive experiments always suffer to some extent from the capillary end-effect and, as the oil-phase is part of the wetting phase (with respect to the gas phase), this will result in a certain amount of residual oil saturation.

Furthermore, the gas/oil mobility ratio was very unfavourable to displacement which, combined with the limited duration of the tests, also attributed to residual oil saturation at the end of the experiments.

The high irreducible water saturation of 53% PV determined on sample no. 2R can, at least partly, be explained by assuming a so-called "clay-bound water volume" of 10% PV, calculated from Qv (0.33 meq/ml PV) and water salinity (73 g NaCl/l).

II. Welge tests

Full-curve oil/water relative-permeability measurements were carried out on three samples. The results, given in Table II and Figs. 3-5, again showed one high $S_{cw}$ value: 52% PV for sample no. 4R.

This may also be attributed partly to the relatively high Qv of 0.19 meq/ml PV[1].

III. Gas/water end-point relative permeabilities

Three samples were subjected to gas/water end-point measurements; the results are given in Table III.

Determination of the effective gas permeability could be performed fairly smoothly but several attempts to establish residual gas saturation failed.

The effective water permeability is probably rather low; hence, water flooding of the (partly) gas-saturated plugs had to be performed at a too high pressure differential or prolonged for a long period.

In both cases the excessive solution of gas (which could hardly be prevented) yielded meaningless data.

## IV Oil/water end-point permeabilities

One sample, which had already been used for gas/water measurements, was also subjected to oil/water end-point permeability determinations.

The procedure was almost identical with that in the oil/water Welge experiments (Appendix B); however, upon water injection no incremental data for oil production were recorded but only the end-point data after oil production had ceased. The results are given in Table IV.

Figures 6-8 show the correlation between air permeability and water permeability, effective oil permeability and effective water permeability, respectively.

REFERENCE

1. Benten, J.A. van, Investigation of cores from well 31/2-4, Norway.
   - Petrophysical properties of core samples -
   RKER.82.243, December 1982.

## TABLE I

REVIEW OF DATA OBTAINED FROM OIL/GAS RELATIVE-PERMEABILITY MEASUREMENTS BY THE "MODIFIED" WELGE METHOD ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-4

| Sample, no. | 1R[1)] | 2R | 3R |
|---|---|---|---|
| Depth, m | 1423 | 1473 | 1550 |
| Porosity, % of bulk volume | 1. | 22.9 | 31.7 |
| Grain density, g/ml | nd | 2.60 | 2.68 |
| Air permeability, $k_a$, mD | 0.02 | 4.1 | 230 |
| Irreducible water saturation, $S_{cw}$, % of pore volume | nd | 53 | 23 |
| Effective oil permeability at $S_{cw}$, $k_{ocw}$, mD | nd | 2.2 | 160 |
| Residual oil saturation at the end of the drainage experiment, "$S_{or}$"[2)], % of pore volume | nd | 14 | 14 |
| Gas permeability at the end of the drainage experiment, $k_{giw}$ | nd | 2.2 | 60 |
| Qv, meq/ml pv | | 0.33 | |
| Clay-bound water[3)], Vs/Vp fraction of pore volume | | 0.10 | |

1) Permeability of consolidated sample 1R too low for experiment to be continued
2) Residual oil saturation at the end of the experiment mainly due to:
- capillary forces
- unfavourable oil/gas mobility ratio
- limited duration of experiment.
3) Calculated according to H.J. Hill., O.J. Shirley and G.E. Klein, Bound water in shaly sands The Log Analyst, May-June 1979.

## TABLE II

REVIEW OF DATA OBTAINED FROM OIL/WATER RELATIVE-PERMEABILITY MEASUREMENTS ON UNCONSOLIDATED CORE SAMPLES FROM WELL 31/2-4

| Sample, no. | 4R | 5R | 6R |
|---|---|---|---|
| Depth, m | 1571 | 1579 | 1581 |
| Porosity, % of bulk volume | 27.8 | 29. | 32.3 |
| Grain density, g/ml | 2.70 | 2.73 | 2.68 |
| Air permeability, $k_a$, mD | 6.2 | 81 | 190 |
| Absolute water permeability, $k_w$, mD | 3.6 | 79 | 187 |
| Irreducible water saturation, $S_{cw}$, % of pore volume | 52 | 36 | 28 |
| Effective oil permeability at $S_{cw}$, $k_{ocw}$, mD | 3.9 | 82 | 120 |
| Residual oil saturation, $S_{or}$, % of pore volume | 29 | 17 | 17 |
| Effective water permeability at $S_{or}$, $k_{wor}$, mD | 1.6 | 7.2 | 17.4 |
| Qv, meq/ml pore volume | 0.19 | | |
| Clay-bound water[1)], Vs/Vp, fraction of pore volume | 0.06 | | |

1) Calculated according to H.J. Hill, O.J. Shirley and G.E. Klein, Bound water in shaly sands. The Log analyst, May-June 1979.

## TABLE III

### RESULTS OF GAS/WATER END-POINT RELATIVE-PERMEABILITY MEASUREMENTS[1)] ON CORE SAMPLES FROM WELL 31/2-4

| Sample, no. | 2R | 3R | |
|---|---|---|---|
| Depth, m | 1473 | 1550 | 1579.-1579.08 |
| Porosity, % of bulk volume | 22.9 | 31.7 | 21.5 |
| Grain density, g/ml | 2.60 | 2.68 | nd |
| Air permeability ($k_a$), mD | 4.1 | 230 | 1.3 |
| Water permeability ($k_w$), mD | nd | 200 | 0.7 |
| Residual water saturation ($S_{rw}$)[2)], % of pore volume | 65 [3)] | 50 | 41 |
| Effective gas permeability at $S_{rw}$ ($k_{grw}$), mD | 2.1 | 60 | 1.1 |

1) Establishing residual gas saturation failed because excessive solution of gas in the water-phase led to meaningless data.

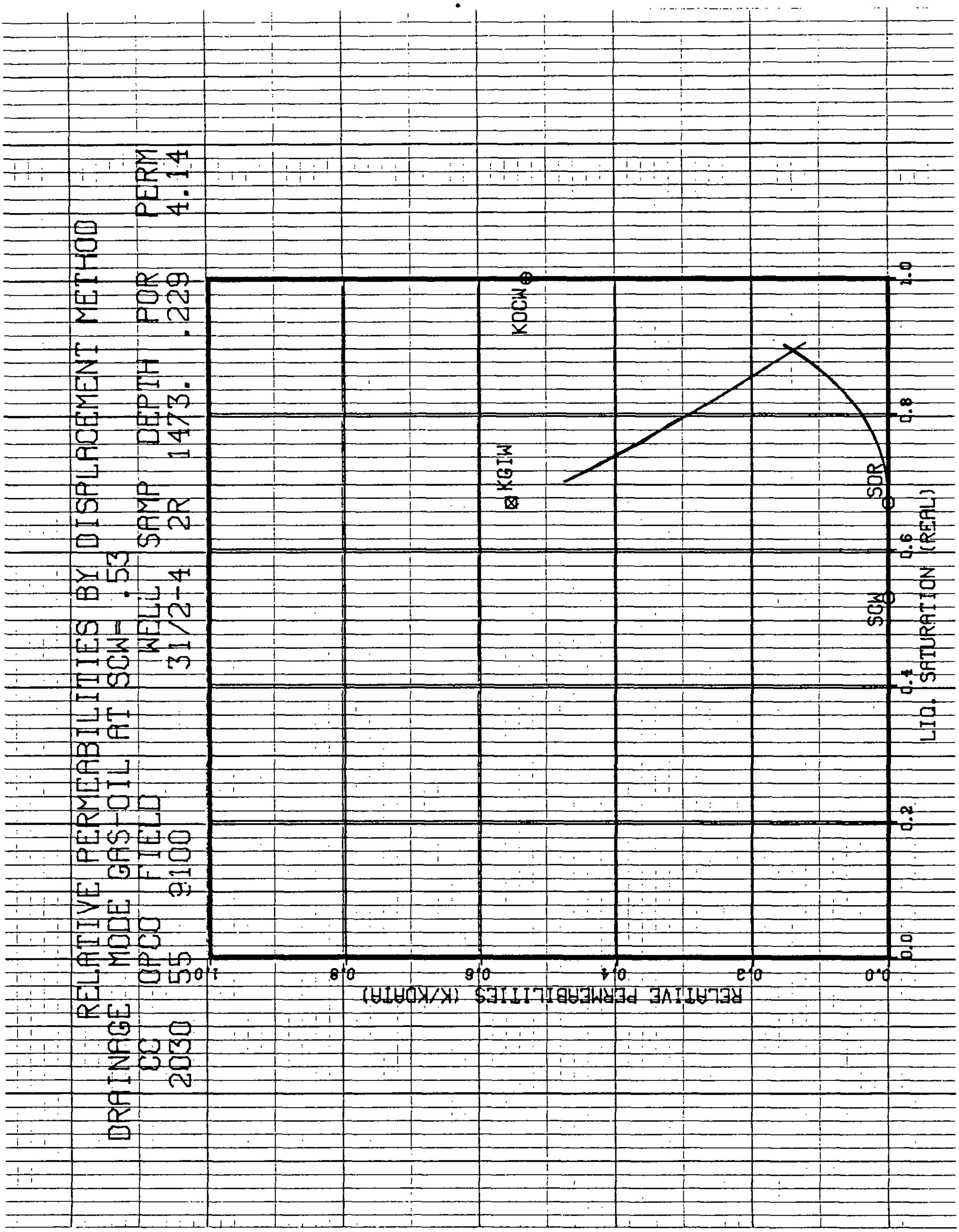
2) Probably somewhat too high because of capillary end-effect in combination with the limited duration of the gas drive at unfavourable mobility ratio.

3) The high $S_{cw}$ figure is also due to the Qv of 0.33 meq/ml pore volume (see Table I).

TABLE IV

RESULTS OF OIL/WATER END-POINT RELATIVE-PERMEABILITY MEASUREMENTS ON A CORE SAMPLE FROM WELL 31/2-4

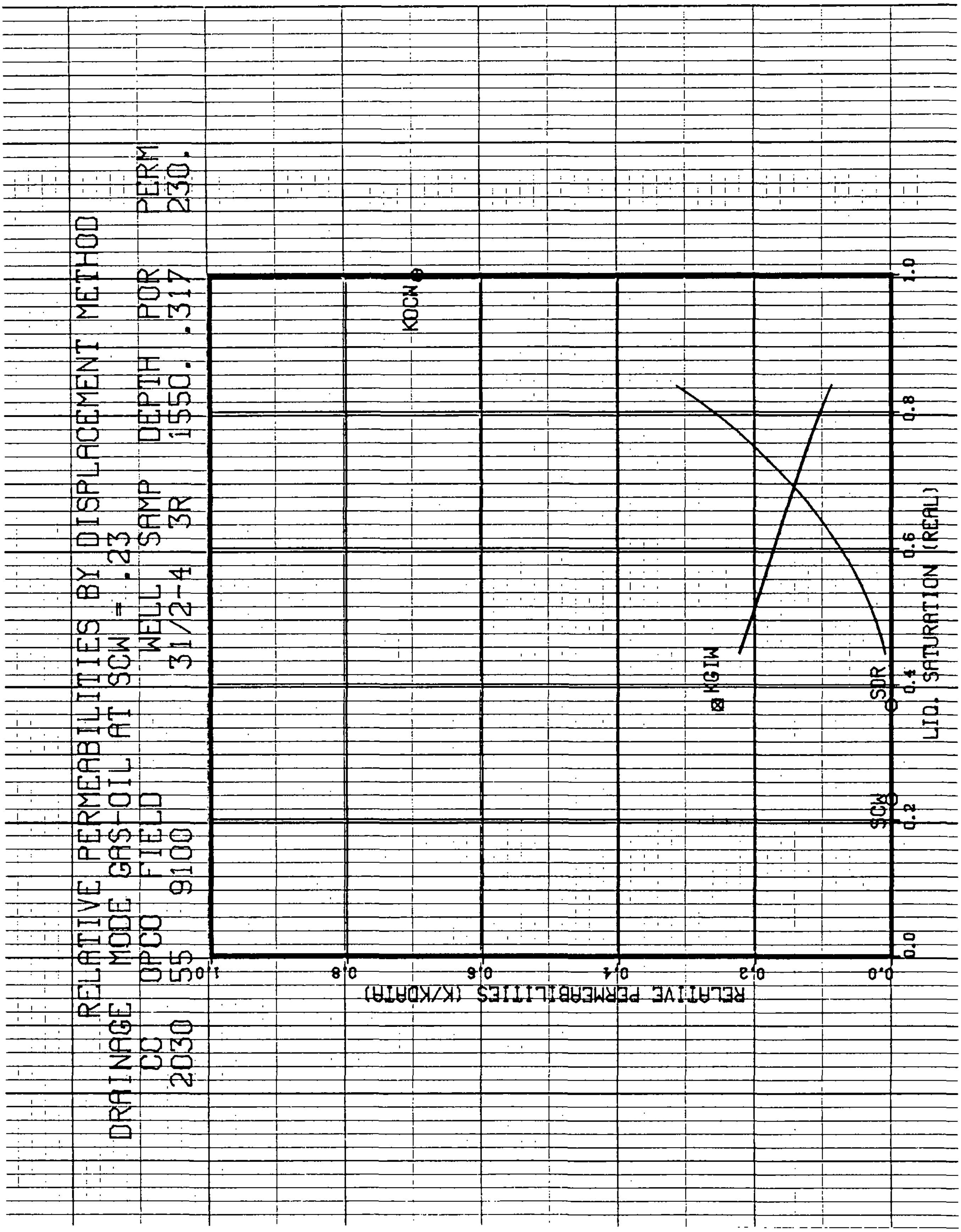
| | |
|---|---|
| Sample depth interval, m | 1579.00–1579.08 |
| Porosity, % of bulk volume | 21.5 |
| Air permeability ($k_a$), mD | 1.3 |
| Water permeability ($k_w$), mD | 0.7 |
| Irreducible water saturation ($S_{cw}$), % of pore volume | 38 |
| Effective oil permeability at $S_{cw}$ ($k_{ocw}$), mD | 0.5 |
| Residual oil saturation ($S_{or}$), % of pore volume | 26 |
| Effective water permeability at $S_{or}$ ($k_{wor}$), mD | 0.1 |



RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
DRAINAGE MODE GAS-OIL AT SCW= .53
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 31/2-4 2R 1473. .229 4.14
KOCW
KGIW
SOR
SCW
LIQ. SATURATION (REAL)
RELATIVE PERMEABILITIES (K/KDATA)
0.0
0.2
0.4
0.6
0.8
1.0




Fig. 1



RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
DRAINAGE MODE GAS-OIL AT SCW = .23
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 31/2-4 3R 1550. .317 230.
KOCW
KGIW
SDR
SCW
LIQ. SATURATION (REAL)
RELATIVE PERMEABILITIES (K/KDATA)
0.0
0.2
0.4
0.6
0.8
1.0


Fig. 2

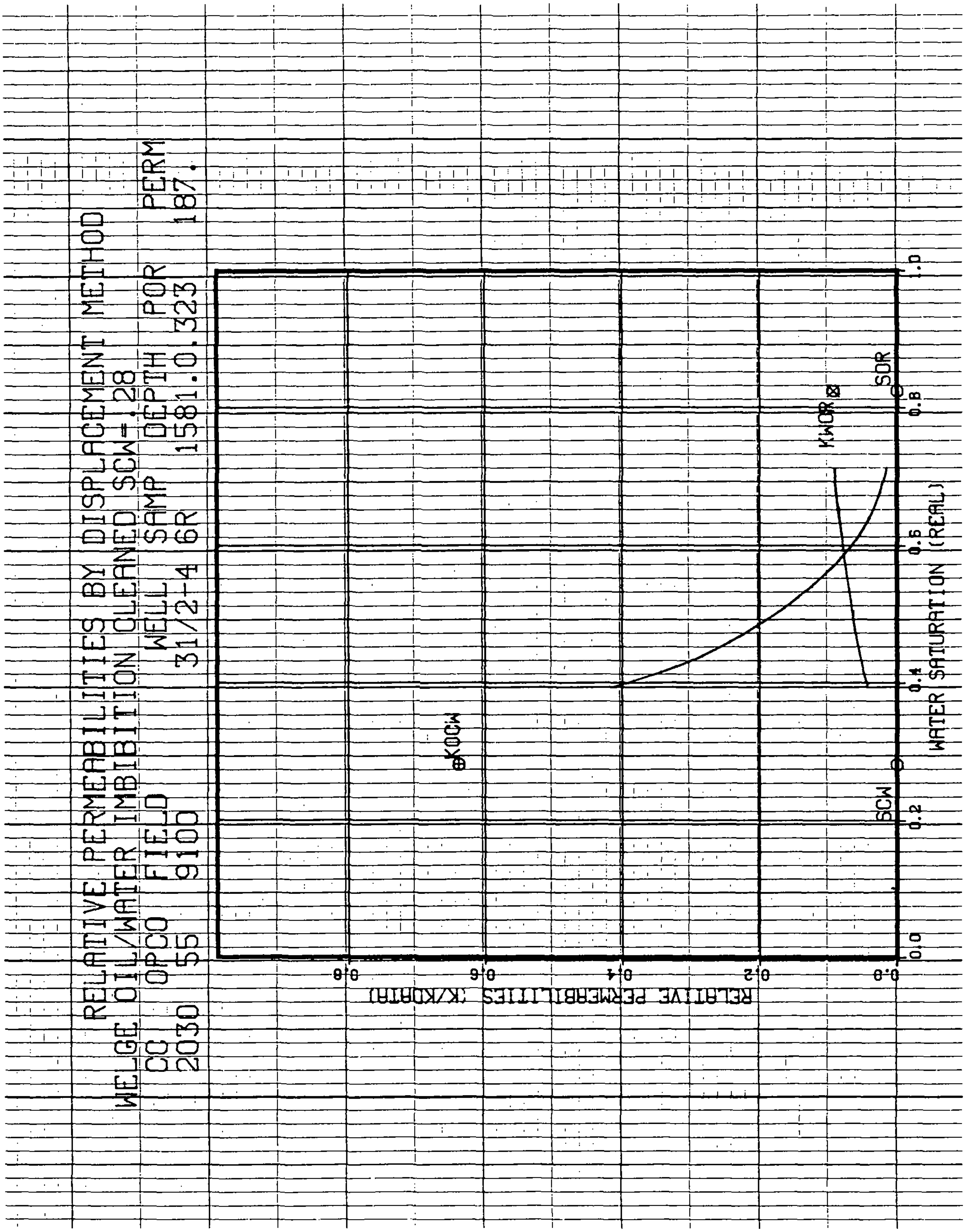

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL/WATER IMBIBITION CLEANED SCW=.28
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 31/2-4 6R 1581.0 .323 187.
KOCW
KWOR
SOR
SCW
WATER SATURATION (REAL)
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE PERMEABILITIES

Fig. 3

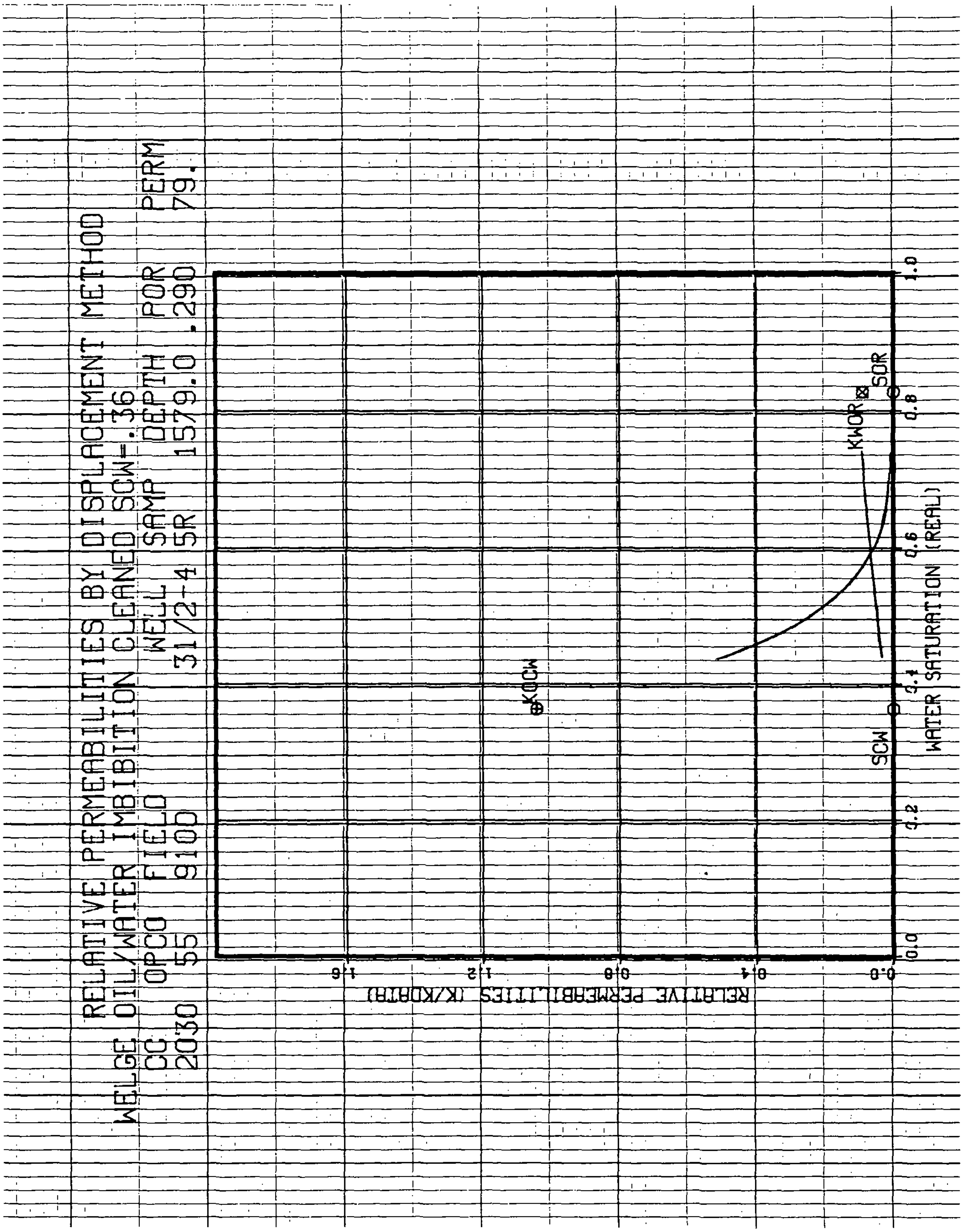
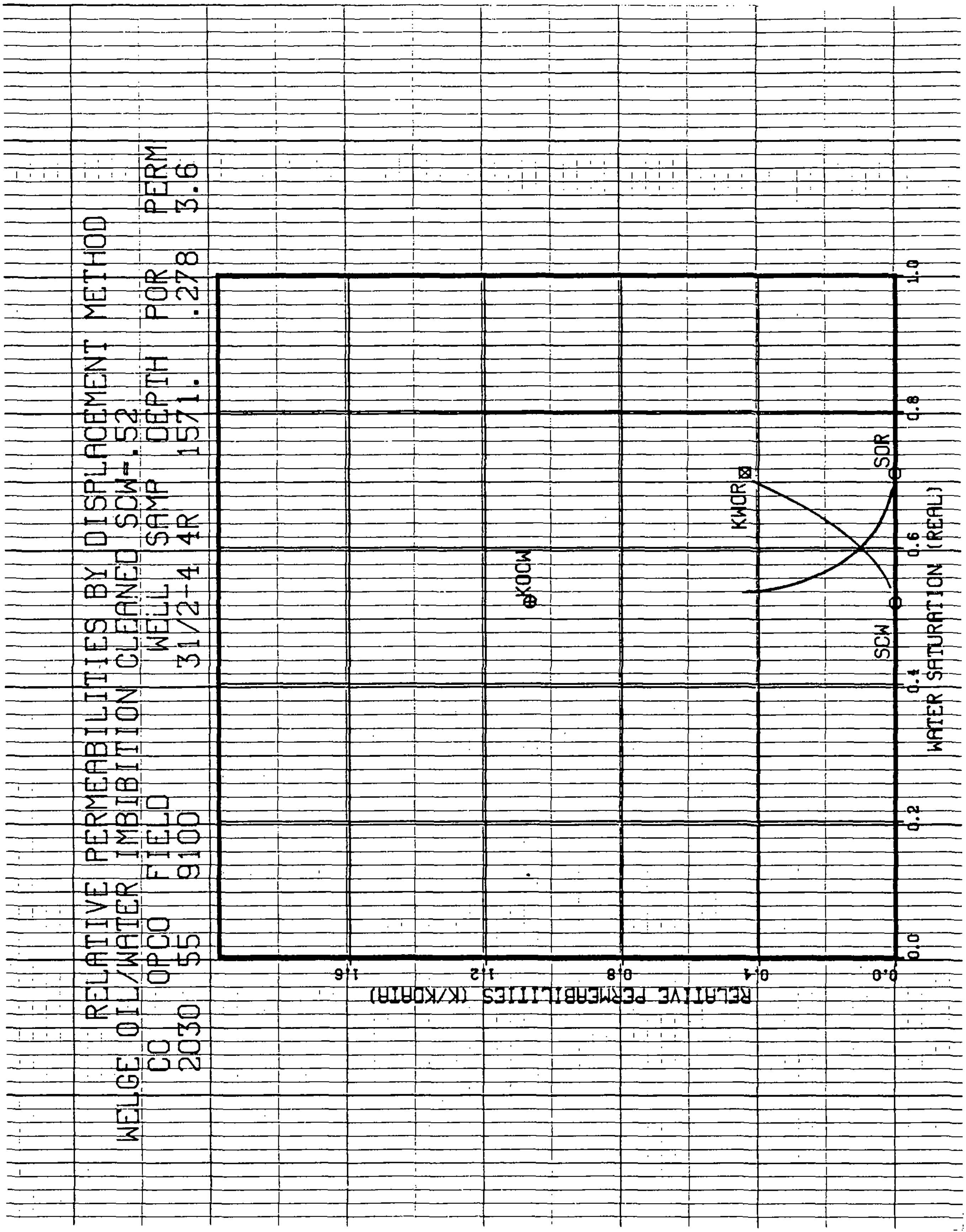
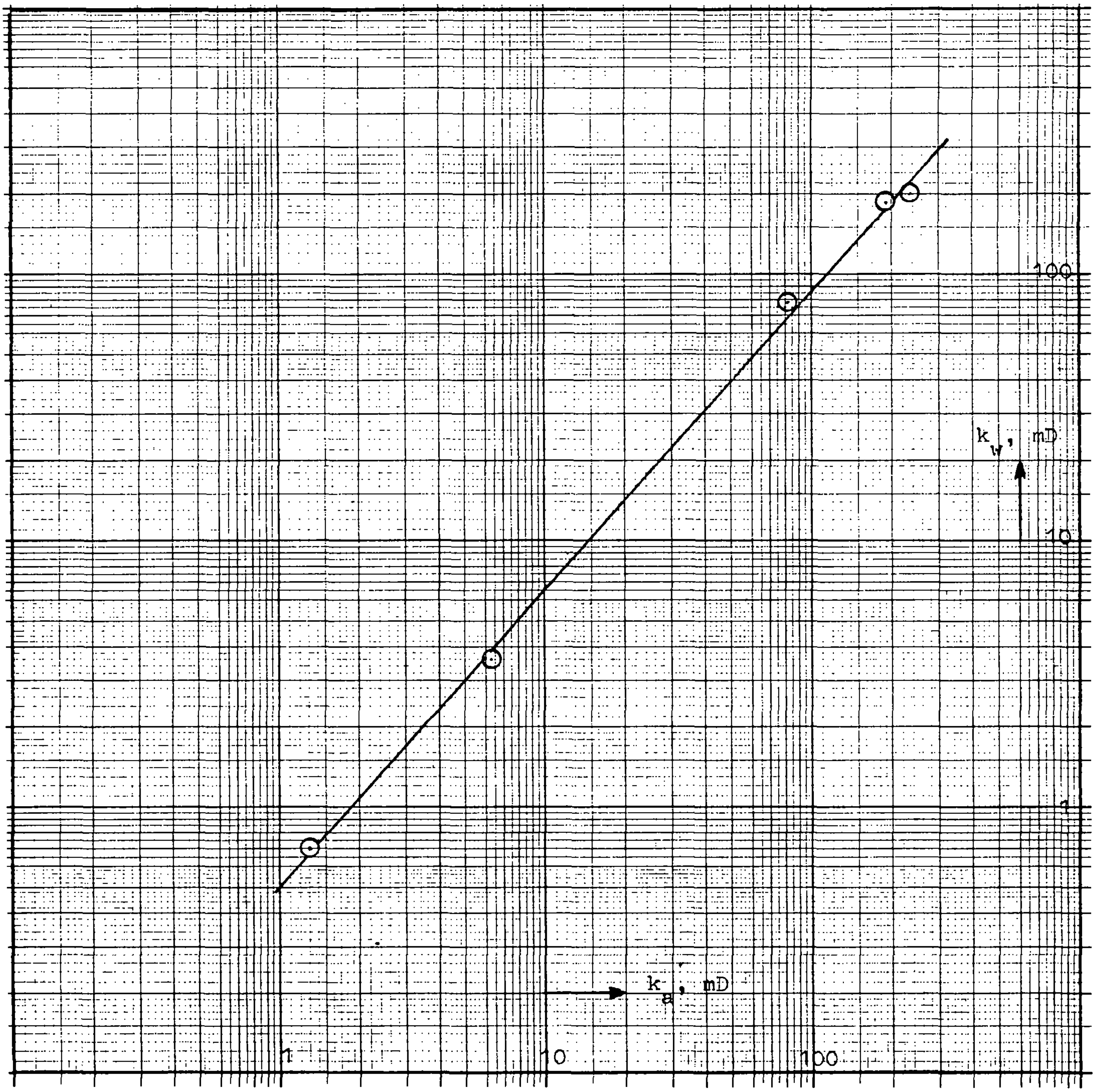

RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL/WATER IMBIBITION CLEANED SCW= .36
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 31/2-4 5R 1579.0 .290 79.
KOCW
KWOR
SOR
SCW
0.0
0.2
0.4
0.6
0.8
1.0
WATER SATURATION (REAL)
0.0
0.4
0.8
1.2
1.6
RELATIVE PERMEABILITIES (K/KDATA)

Fig. 4



RELATIVE PERMEABILITIES BY DISPLACEMENT METHOD
WELGE OIL/WATER IMBIBITION CLEANED SCW=.52
CC OPCO FIELD WELL SAMP DEPTH POR PERM
2030 55 9100 31/2-4 4R 1571. .278 3.6
KOOW
KWOR
SOR
SCW
WATER SATURATION (REAL)
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE PERMEABILITIES (K/KOAIR)
0.0
0.4
0.8
1.2
1.6


Fig. 5

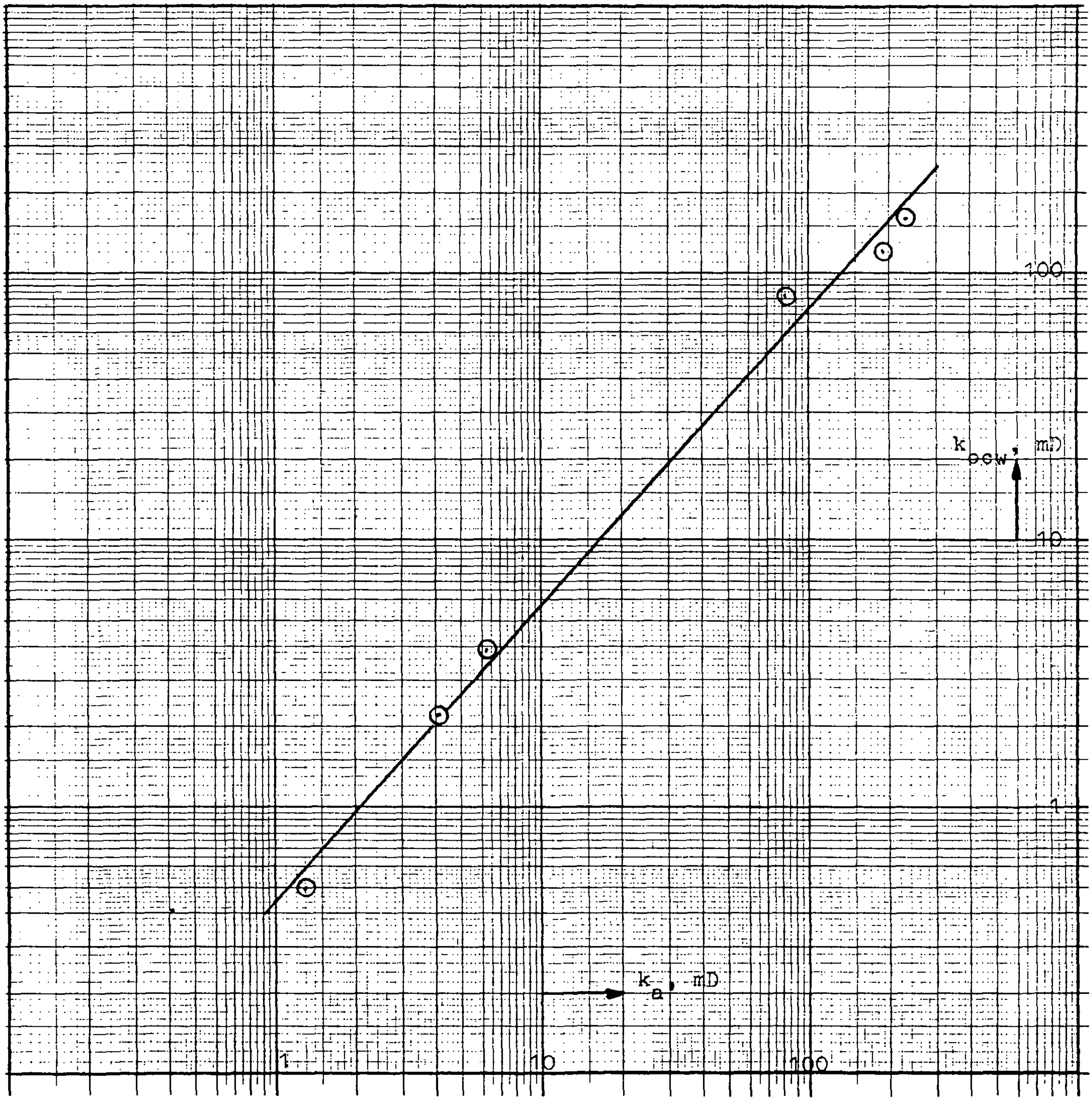



Water permeability ($k_w$) at Sw=1 as a function of air permeability ($k_a$)

Well 31/2-4

Fig. 6

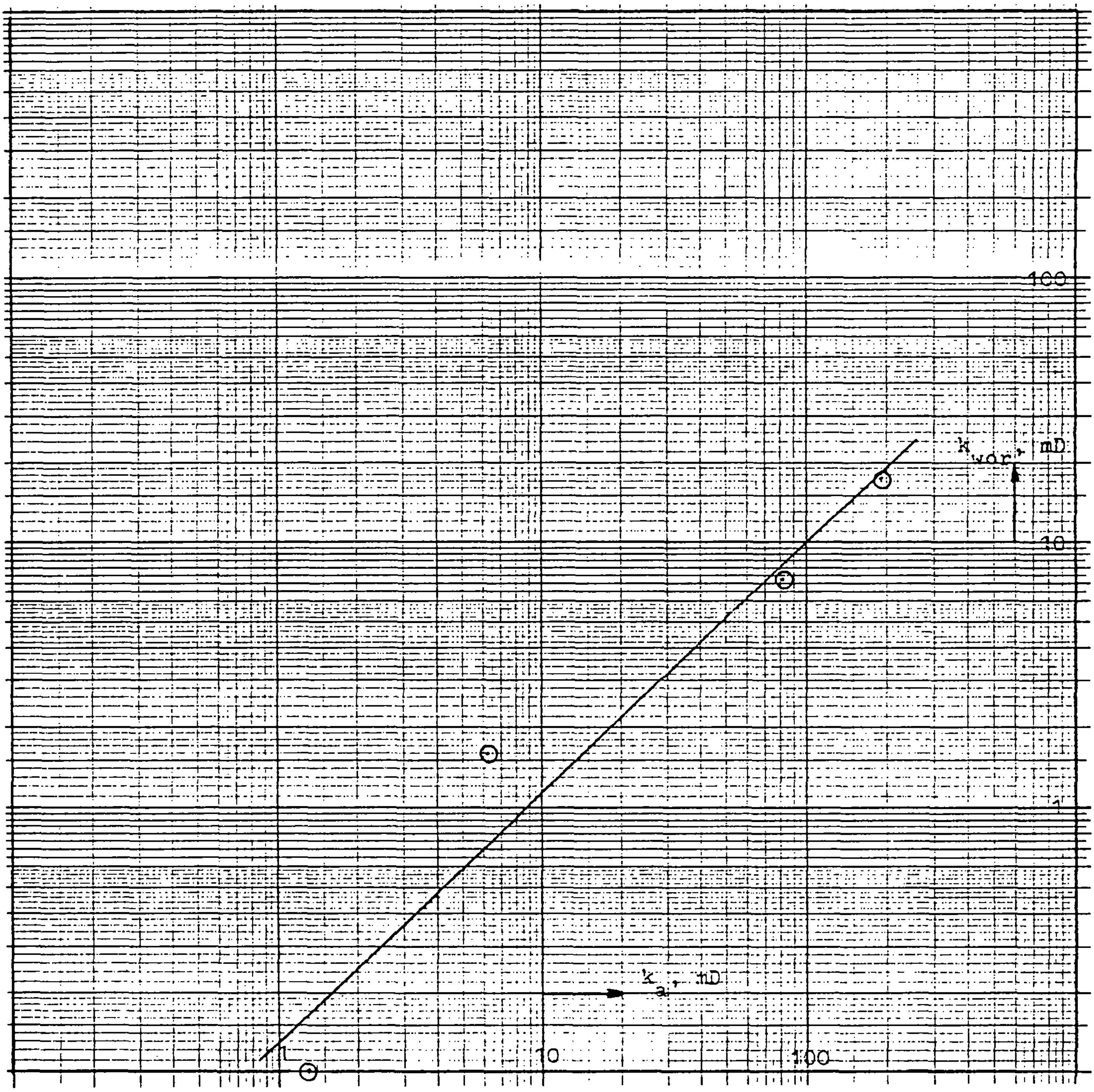
RKER 83.131




Effective oil permeability ($k_{ocw}$) at Scw as a function of air permeability ($k_a$)

Well 31/2-4

Fig. 7




Effective water permeability ($k_{wor}$) at Sor as a function of air permeability ($k_a$)

Well 31/2-4

Fig. 8

APPENDIX A

## GAS-DRIVE DRAINAGE METHOD[A1]

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. A1). 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[A2] 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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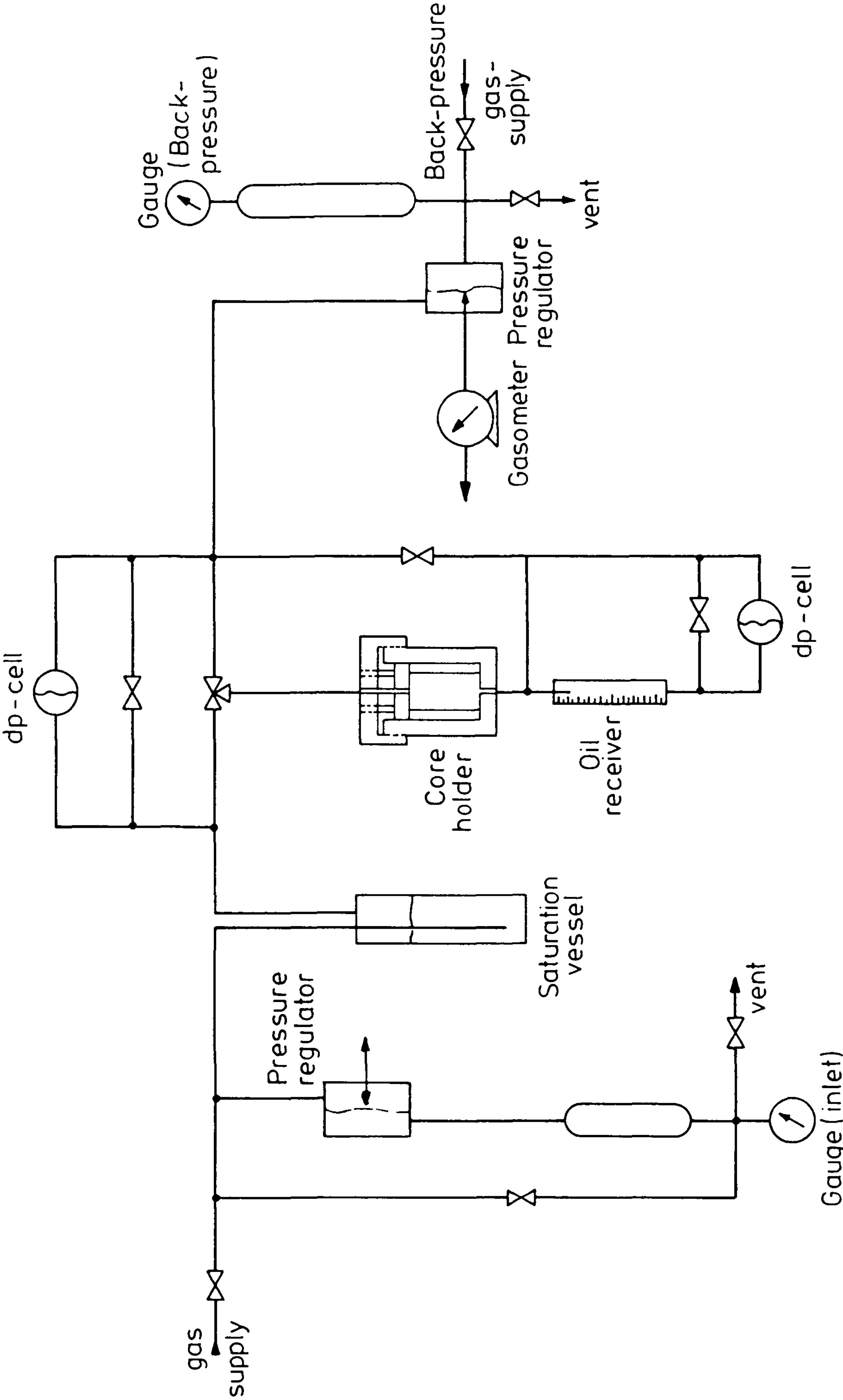
Petroleum Transactions, AIME vol. 207, 1956 (p.275).

A2. Welge, H.G., Simplified Method for computing oil recovery by gas or water drive.
Trans AIME 195 (1952), p. 91.




FLOW SCHEDULE OF GAS-DRIVE DRAINAGE EXPERIMENTS

Fig. A – 1

Author Lgd
Drawn

Dr.nr. 45623

APPENDIX B

## WELGE METHOD[B1]

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[B2,3].

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. B1.

### 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.

Dashed parts of the curves therefore represent only a (subjective) interpolation between $S_{cw}$ and the water saturation at water breakthrough.

REFERENCES

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Trans AIME 195 (1952), p. 91.

B2. Johnson, E.F., Bossler, D.P. & Naumann, W.O., Calculation of relative permeability from displacement experiments.
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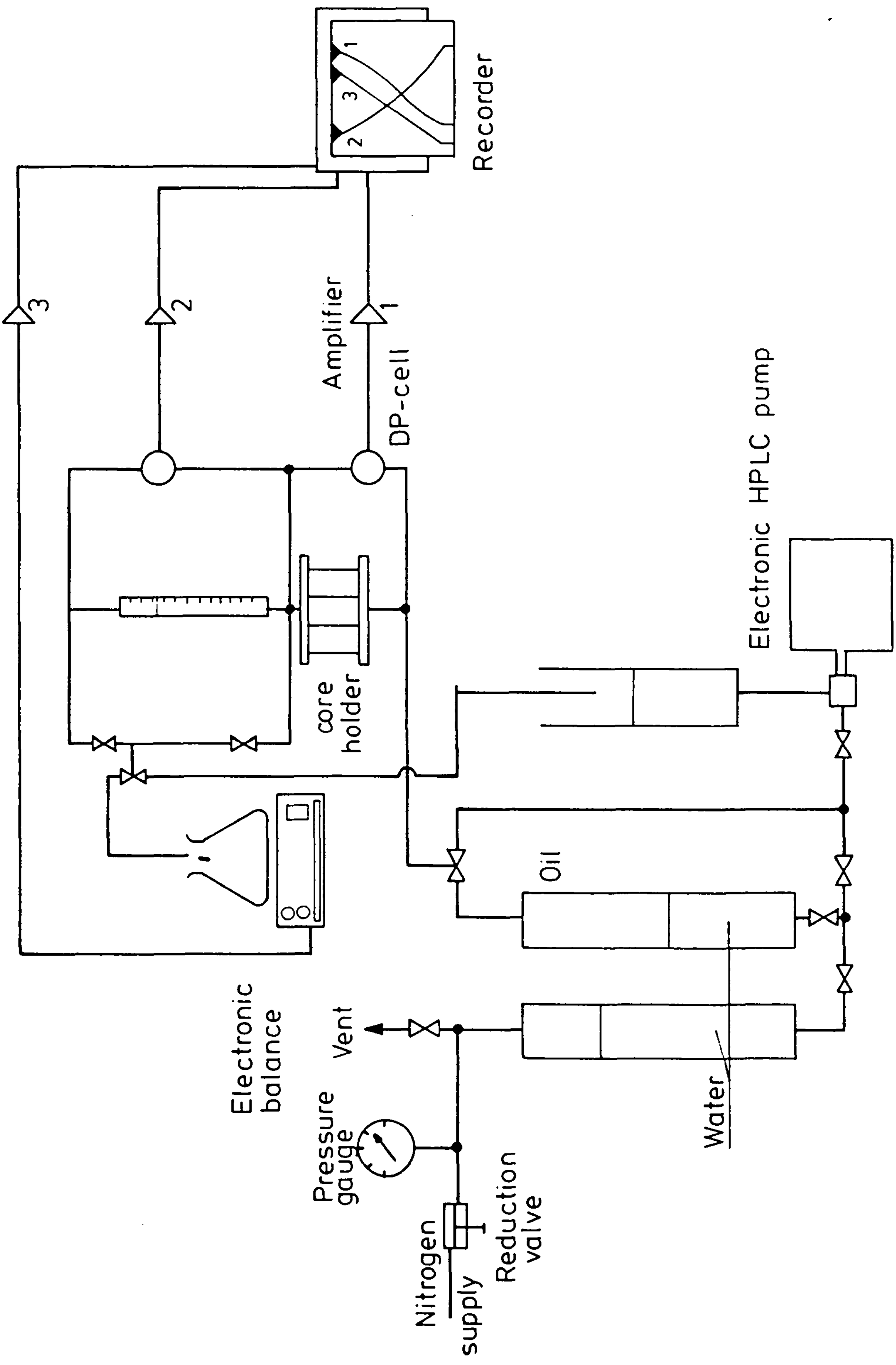
SPE paper 6045, 1976.

Di.nr. 45624




WELGE FLOODING APPARATUS, KSEPL 3rd VERSION

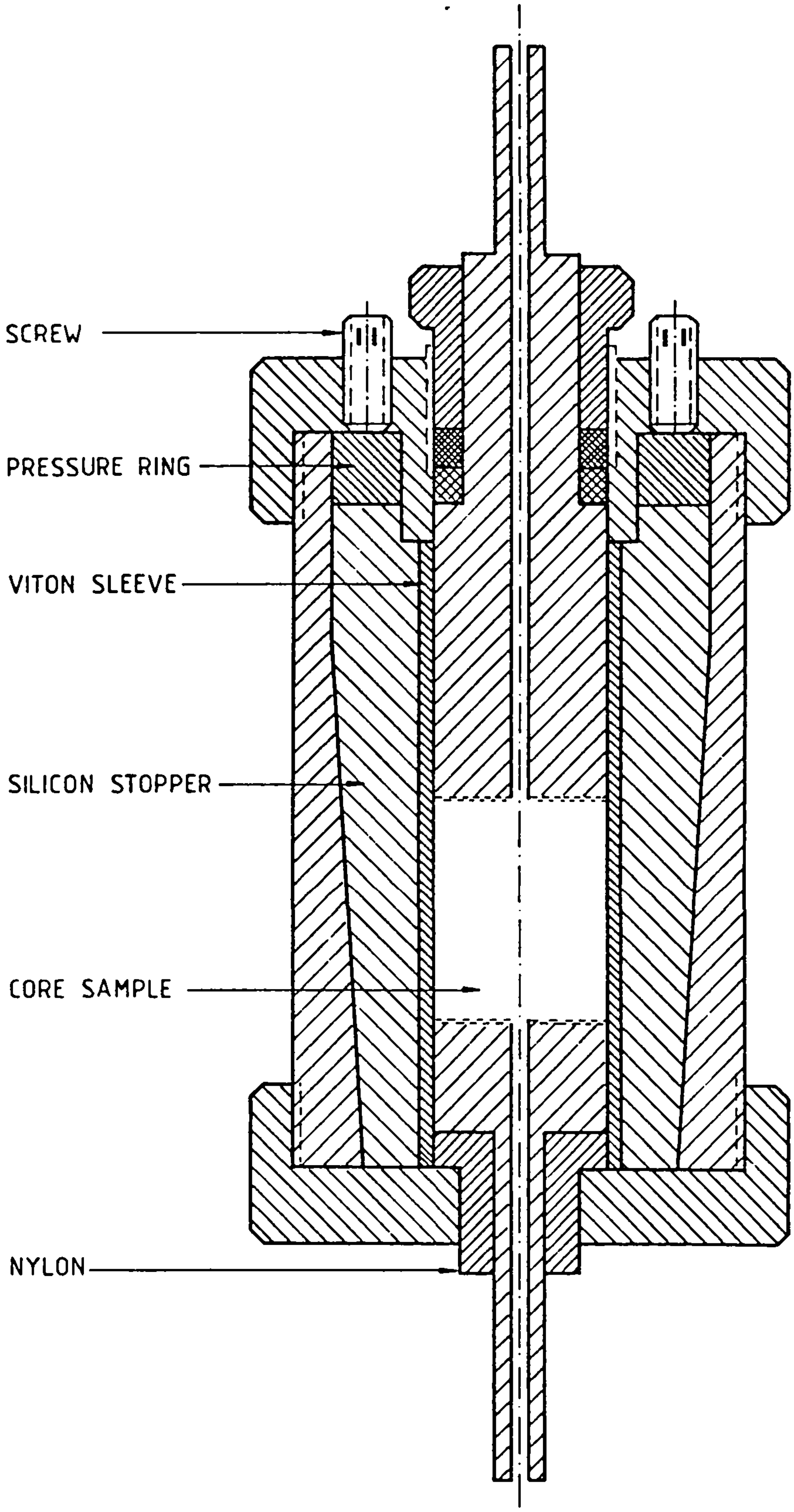
APPENDIX C

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 water 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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CORE HOLDER

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