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SPECIAL CORE ANALYSIS

GRADERINGEN GJELDER TIL ____________

FOR

STATOIL

DEN NORSKE STATS OLJESELSK

Stavanger, Norway

WATERFLOOD TESTS AT RESERVOIR CONDITIONS

OIL WELL NO 34/10 - 5

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EXTRACT

This report presents the results from two waterflood tests performed under simulated reservoir conditions on a core sample from well no. 34/10-5.

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INTRODUCTION

The present report presents the results of two reservoir condition waterflood tests on a core sample from well no. 34/10-5. Included is also results from air permeability measurements and a wettability test on the core after waterflooding.

The results of the waterflood experiments are presented as waterflood susceptibility data, and as relative permeability data. The relative permeability data are calculated after Jones & Roszelle*).

Flood rates were 402.5 cc/hour and 8.48 cc/hour respectively. Results from the high rate flood test is presented in table 4 and figures 1 and 2, and from the low rate flood test in table 5 and figures 3 and 4.

Results from the wettability test are presented in table 6 and figures 5 and 6, and from the air permeability test in table 7 and figure 7.

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*) Jones, S.C. and Roszelle, W.D.: "Graphical Techniques for Determining Relative Permeability from Displacement Experiments, Journal of Petr. Techn., May 1978.

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Table 1. Reservoir and Fluid Data (from well 34/10-4)

1.	Reservoir temperature	71.1	^{o}C
2.	Reservoir pressure	307.0	Bar.g.
3.	Bubble point pressure of reservoir oil	243.7	Bar.g.*)
4.	Reservoir oil viscosity	1.21	mPas
5.	Brine viscosity at reservoir conditions	0.47	mPas

*) In the laboratory the reservoir oil gave a bubble point pressure of 241.2 Bar.g. These data are reported in Table 8 and Figure 8.

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Table 2. Formation Water Analysis

Na^+	14000 mg/l
Ca^{++}	1275 "
Mg^{++}	335 "
Ba^{++}	50 "
Li^+	7.6 "
K^+	209 "
Cl^-	26200 "
HCO_3^-	415 "
SO_4^{--}	30.8 "
Br^-	62 "

Remarks

The above formation water is the same as the syntetic formation water used in the experiments, except that Ba^{++} and SO_4^{--} were excluded, due to precipitation problems.

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Table 3. Summary of rock properties

1.	Depth of sample		1925.50 - . 65 meters
2.	Porosity (per cent) Helium porosimeter		34.2
3.	Air permeability (Klinkenberg corrected)		1076 md
4.	Brine permeability at 100% saturation of brine		1006 md
5.	Irreducible water saturation (per cent)		33.1
6.	Oil permeability at irreducible water saturation		978 md
7.	Wettability index	$r_w - r_o =$	+0.30
8.	Core size used in experiments	Diameter :	3.37 centimeters
		Length :	8.00 centimeters

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Table 4. Experimental susceptibility data and relative permeability data for high rate waterflood, 402.5 cc/hour.

Porevolumes injected Qi	*Average water saturation* Sw	*Water saturation at outlet end* $Sw2$	*Fraction of water produced* fw	*Relative permeability to water* krw	*Relative permeability to oil* kro	*Oil recovery, per cent pore space* Np
0.000	0.331	0.331	0.0000	0.0000	0.9720	0.0
0.050	0.352	0.331	0.0000	-	-	5.0
0.100	0.431	0.331	0.0000	-	-	10.0
0.150	0.481	0.331	0.0000	-	-	15.0
0.200	0.537	0.331	0.0000	-	-	20.0
0.241 BT*)	0.572	0.470	0.5768	0.1514	0.2859	24.1
0.275	0.586	0.495	0.6691	0.1776	0.2261	25.5
0.300	0.593	0.516	0.7433	0.1988	0.1768	26.2
0.350	0.605	0.542	0.8200	0.2246	0.1269	27.4
0.400	0.613	0.558	0.8625	0.2429	0.0997	28.2
0.500	0.623	0.578	0.9100	0.2673	0.0681	29.2
0.600	0.630	0.594	0.9400	0.2871	0.0472	29.9
0.700	0.635	0.603	0.9543	0.3029	0.0373	30.4
0.800	0.639	0.612	0.9662	0.3176	0.0286	30.8
0.900	0.642	0.620	0.9756	0.3367	0.0217	31.1
1.000	0.644	0.626	0.9820	0.3404	0.0161	31.3
1.200	0.646	0.635	0.9908	0.3457	0.0083	31.5
1.400	0.647	0.640	0.9950	0.3498	0.0045	31.6
2.000	0.649	0.647	0.9990	0.3576	0.0009	31.8
2.500	0.650	0.648	0.9992	0.3624	0.0007	31.9
3.000	0.650	0.649	0.9997	0.3671	0.0003	31.9
4.000	0.651	0.650	0.9997	0.3744	0.0003	32.0
5.000	0.651	0.651	1.0000	0.3793	0.0000	32.0
19.713	0.651	0.651	1.0000	0.3793	0.0000	32.0

*) BT = Water breakthrough
Pore volumes injected at water breakthrough (fraction) : 0.241
Oil recovery at water breakthrough, per cent pore space : 24.1
Water saturation at end of experiment, per cent pore space : 65.1

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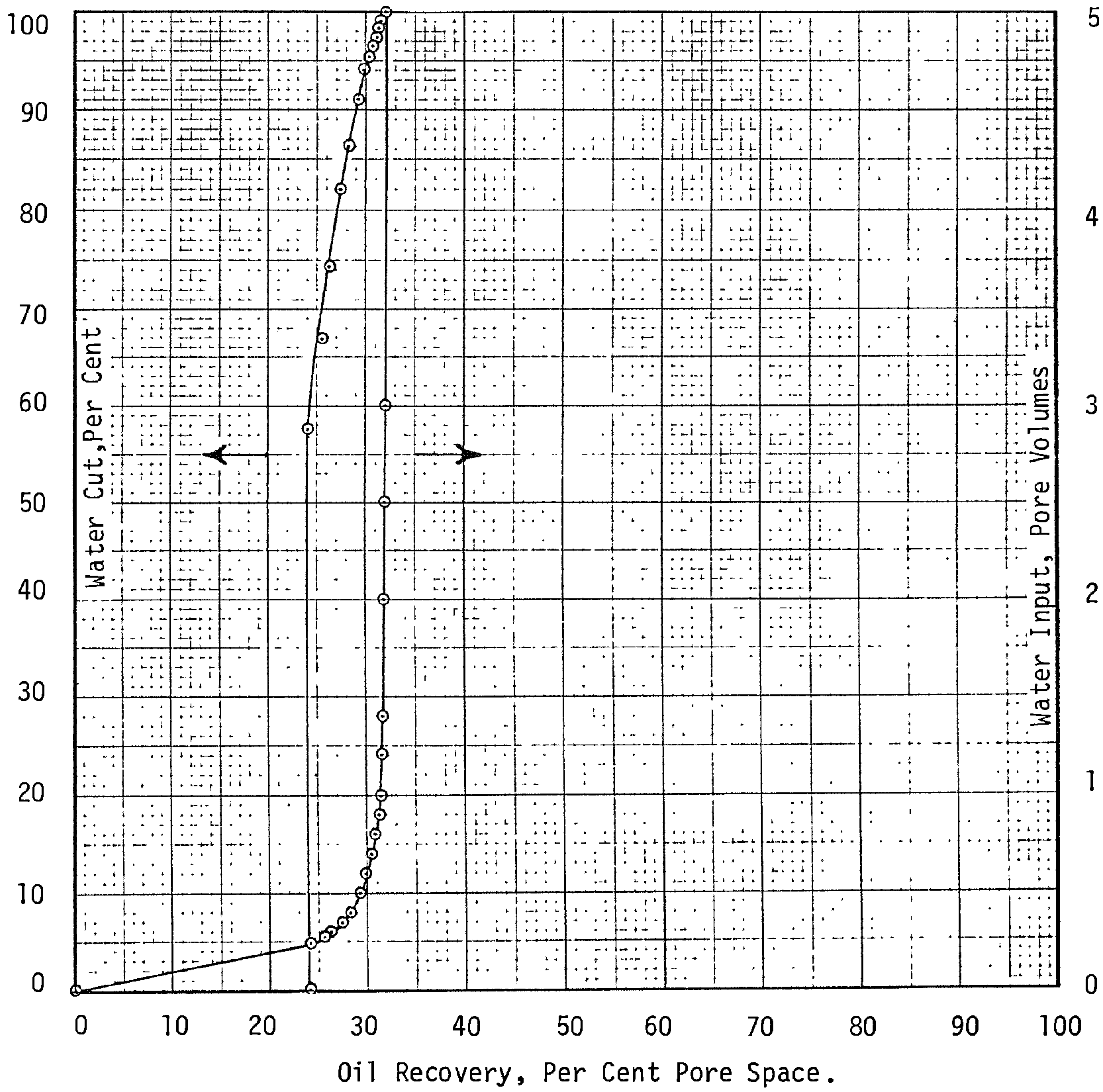

Figure 1. Water flood susceptibility. High rate (402.5 cc/hour) Oil recovery versus water cut and water input.

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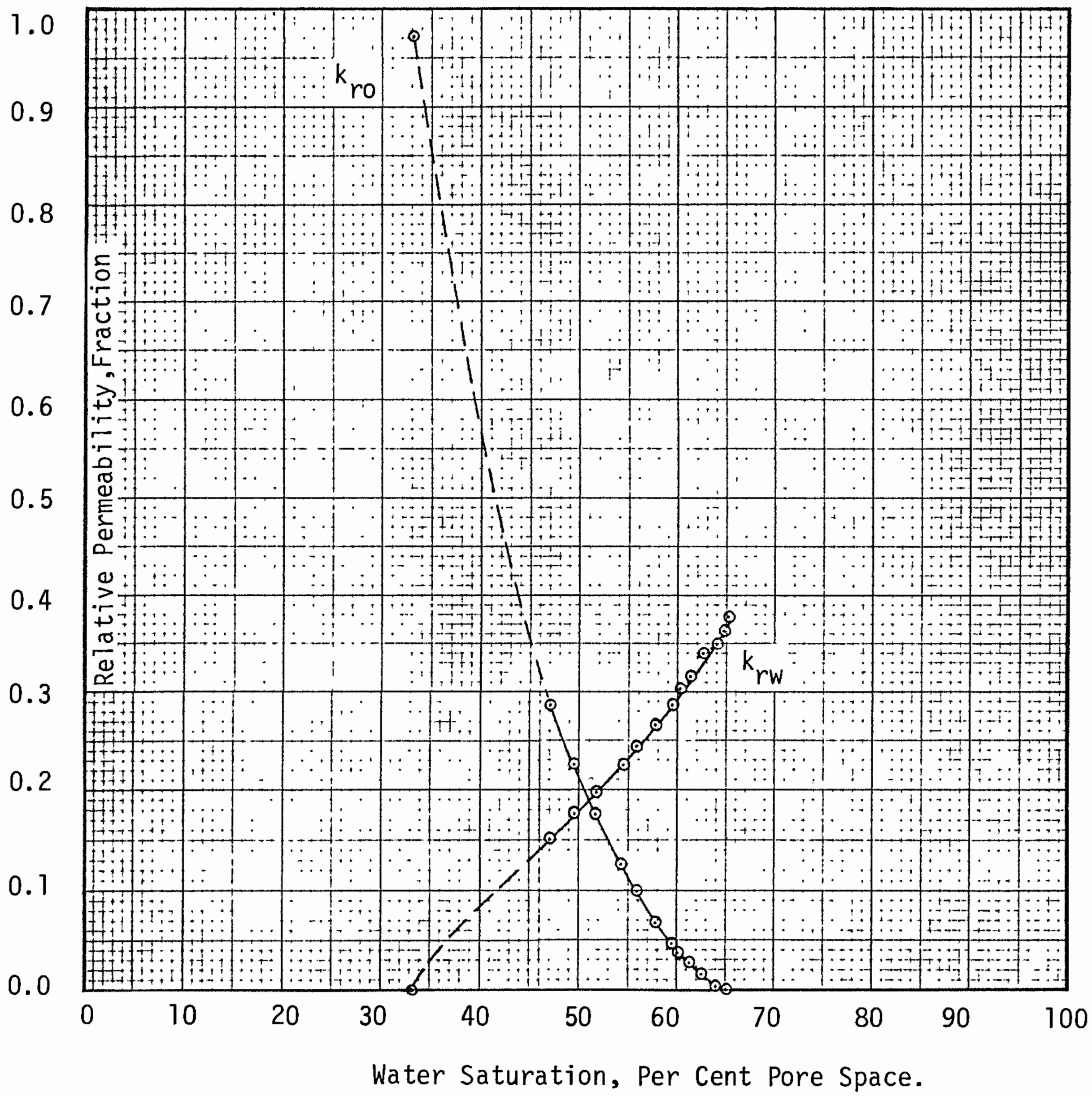

Figure 2. Relative permeability to oil and water versus water saturation. High rate (402.5 cc/hour).

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Table 5. Experimental susceptibility data and relative permeability data for low rate waterflood, 8.48 cc/hour.

Porevolumes injected *Qi*	*Average water saturation* *Sw*	*Water saturation at outlet end* *Sw2*	*Fraction of water produced* *fw*	*Relative permeability to water* *krw*	*Relative permeability to oil* *kro*	*Oil recovery, per cent pore space* *Np*
0.000	0.331	0.331	0.0000	0.0000	0.9720	0.0
0.050	0.352	0.331	0.0000	-	-	5.0
0.100	0.431	0.331	0.0000	-	-	10.0
0.150	0.481	0.331	0.0000	-	-	15.0
0.200	0.537	0.331	0.0000	-	-	20.0
0.258 BT*)	0.589	0.567	0.9147	0.0517	0.0124	25.8
0.300	0.593	0.573	0.9333	0.0536	0.0099	26.2
0.400	0.598	0.582	0.9600	0.0567	0.0061	26.7
0.500	0.601	0.589	0.9760	0.0597	0.0038	27.0
0.600	0.603	0.594	0.9850	0.0617	0.0024	27.2
0.800	0.605	0.599	0.9925	0.0647	0.0013	27.4
1.000	0.606	0.602	0.9960	0.0674	0.0007	27.5
2.000	0.609	0.605	0.9980	0.0810	0.0004	27.8
3.000	0.612	0.612	1.0000	0.0946	0.0000	28.1
4.000	0.612	0.612	1.0000	0.0946	0.0000	28.1
4.723	0.612	0.612	1.0000	0.0946	0.0000	28.1

*) BT = Water breakthrough
Pore volumes injected at water breakthrough (fraction) : 0.258
Oil recovery at water breakthrough,per cent pore space : 25.8
Water saturation at end of experiment,per cent pore space : 61.2

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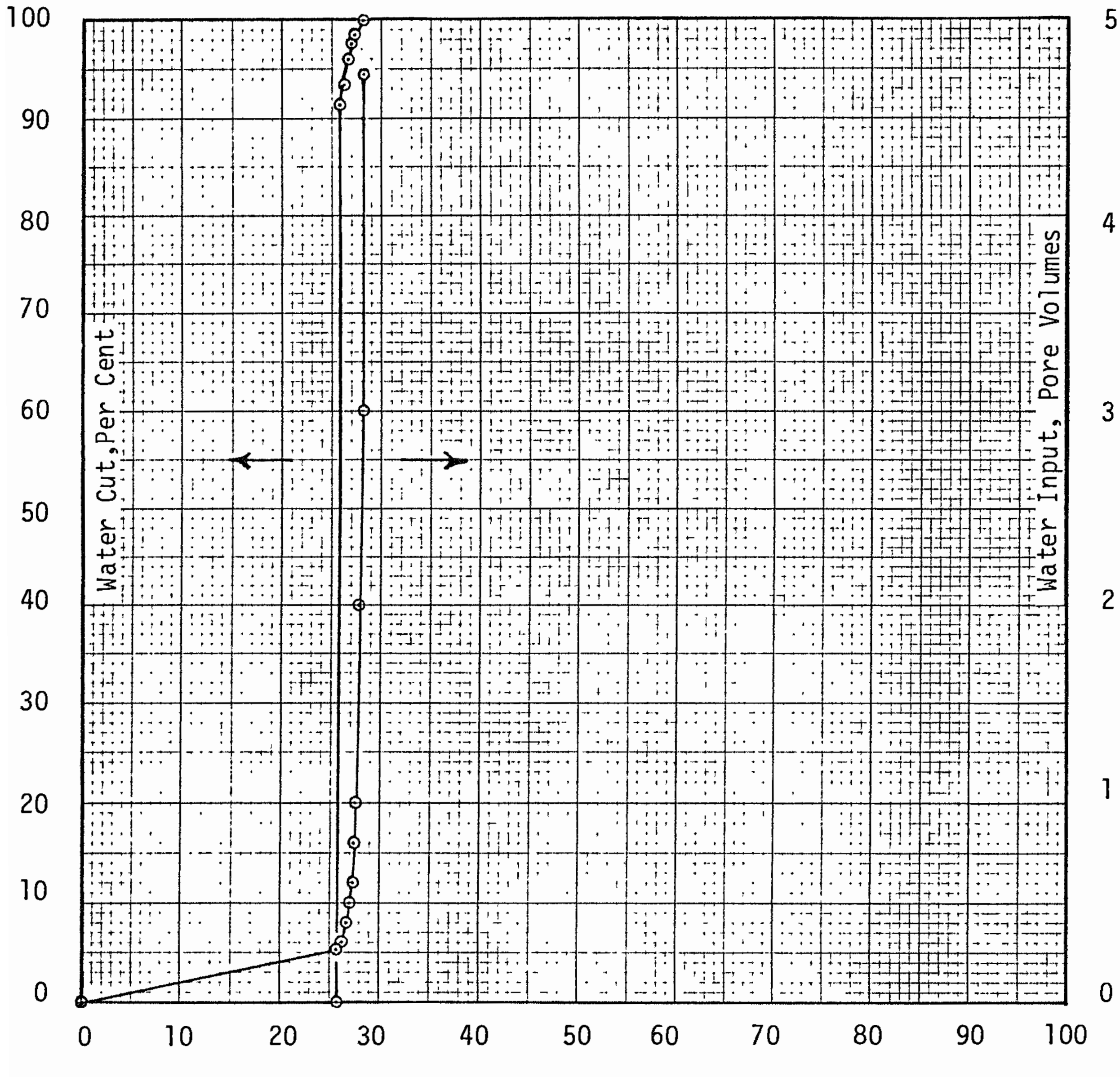

Figure 3. Water flood susceptibility. Low rate (8.48 cc/hour). Oil recovery versus water cut and water input.

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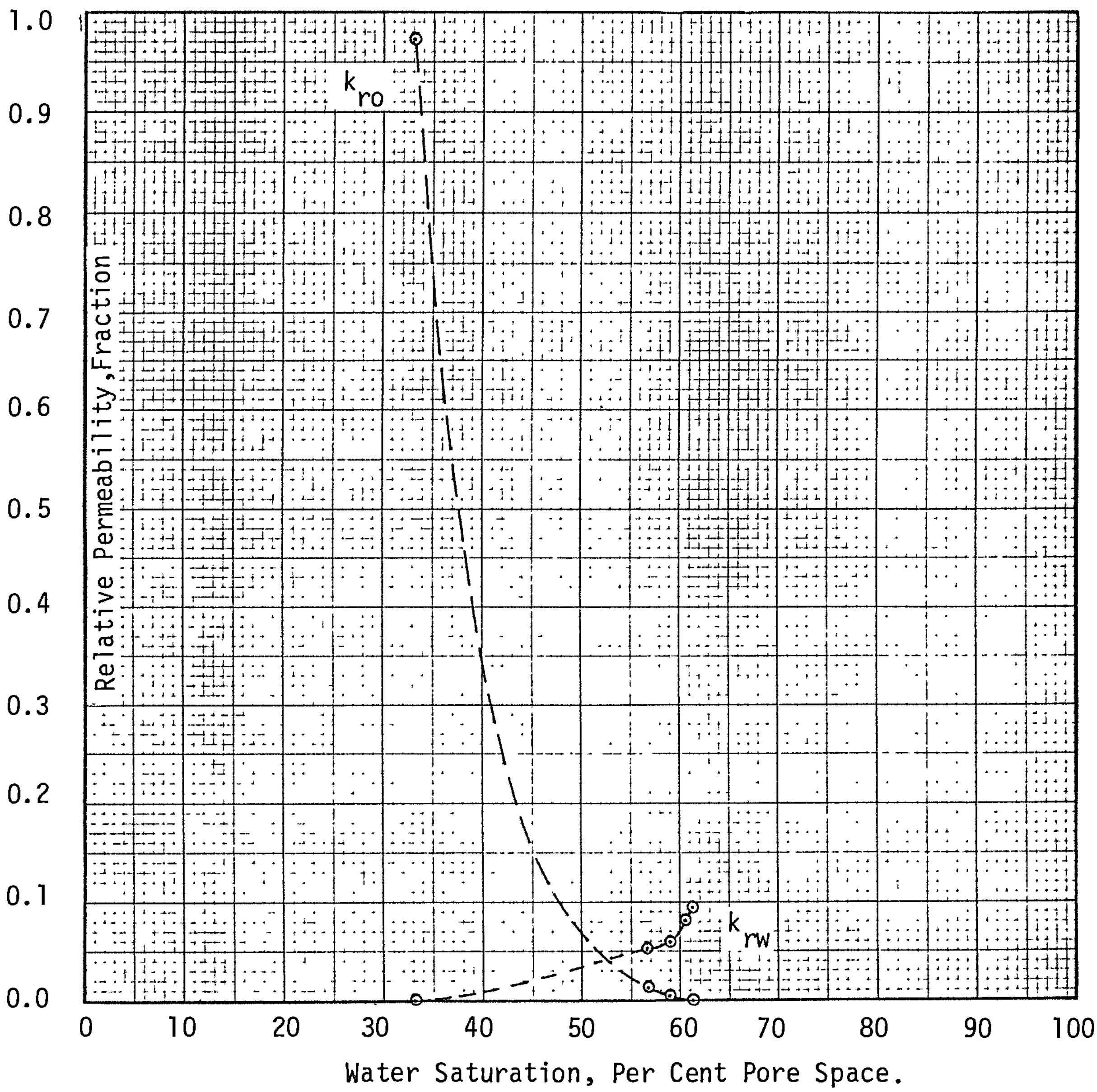

Figure 4. Relative permeability to oil and water versus water saturation. Low rate (8.48 cc/hour).

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Table 6. Experimental wettability test.

1. Oil produced by imbibition in brine	2.75	cubiccentimeters
2. Oil produced by displacement by brine	5.80	cubiccentimeters
3. Water produced by imbibition in oil	0.20	cubiccentimeters
4. Water produced by displacement by oil	8.10	cubiccentimeters

$$r_w = \frac{2.75}{2.75 + 5.80} = 0.32$$

$$r_o = \frac{0.20}{0.20 + 8.10} = 0.02$$

Wettability index : $r_w - r_o$ = +0.30

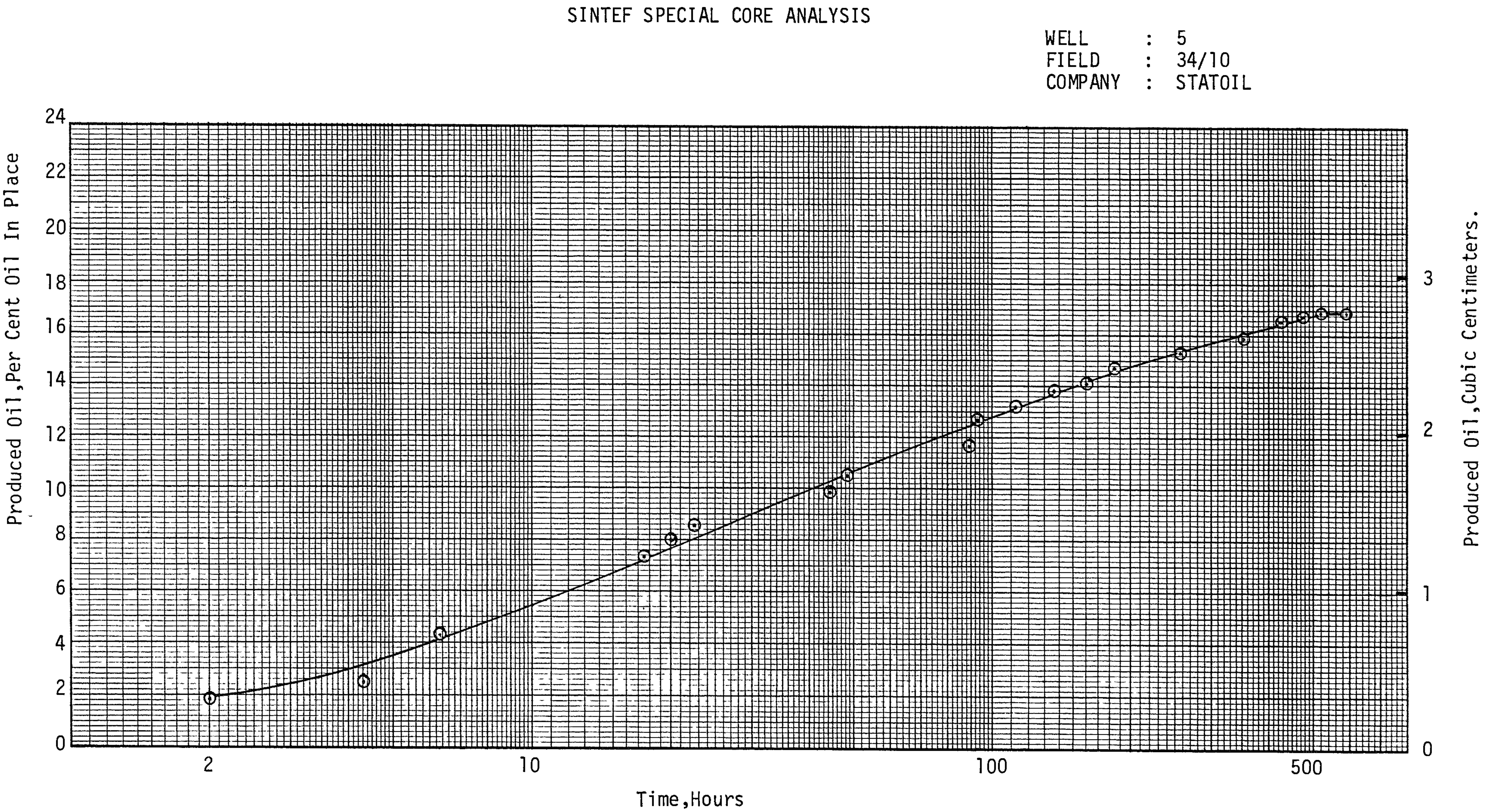

Figure 5. Wettability test.Imbibition in brine. Produced Oil versus time.

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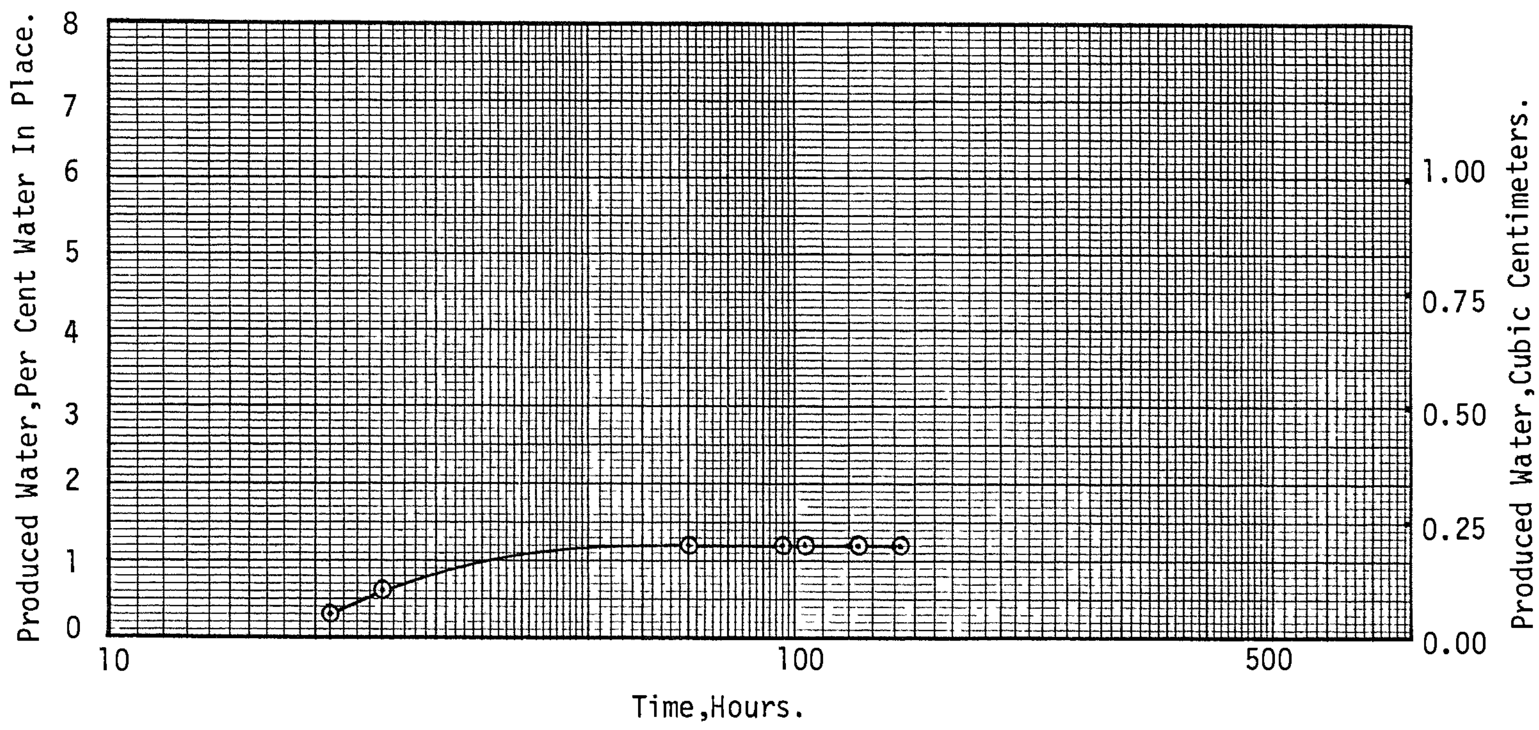

Figure 6. Wettability test. Imbibition in oil. Produced formation water (brine) versus time.

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Table 7. Experimental determination of permeability to dry air

Mean pressure, Bar	*Reciprocal mean pressure,* (Bar^{-1})	*Permeability to air,* mDarcys
5.855	0.1708	1092
4.854	0.2060	1098
4.352	0.2298	1092
3.848	0.2599	1097
3.342	0.2992	1099
2.869	0.3485	1129
2.356	0.4245	1136
1.829	0.5468	1135
1.291	0.7744	1148

Equation of best line fit of permeability in mDarcys:

$K_{air} = 1076.3 + 104.2 \cdot \frac{1}{pm}$, pm in Bar

Equivalent liquid permeability for $\frac{1}{pm} = 0 : K_L = 1076$ mDarcys

Klinkenberg factor : 0.097

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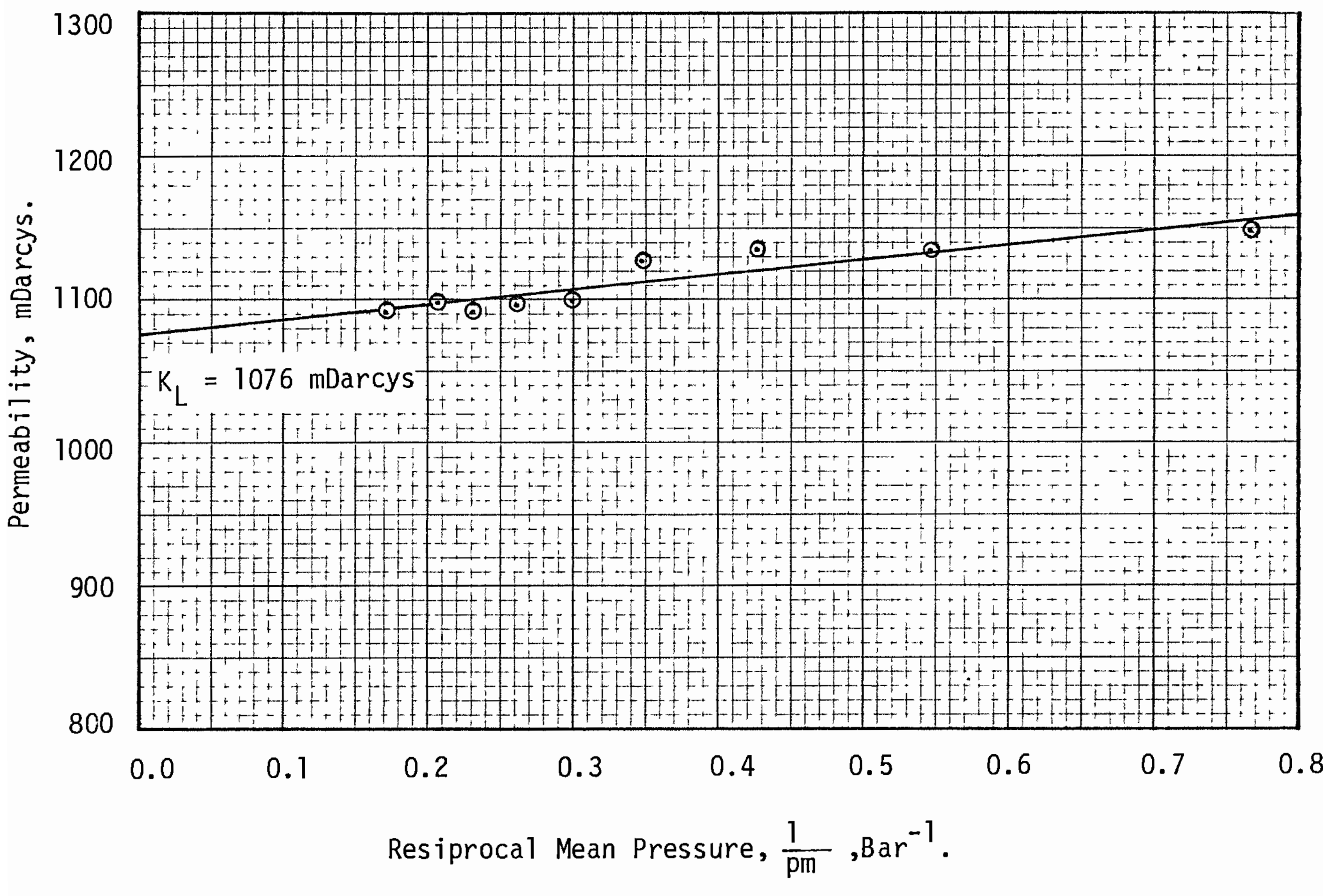

Figure 7 . Permeability to dry air.Experimental values.

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Table 8. Reservoir fluid, bubble point determination at 71.1 °C

Pressure Bar.g.	*Relative Vol.Fact.* V_R
343.2	0.9871
304.0	0.9919
269.7	0.9963
255.0	0.9983
245.2	0.9996
241.2 *)	1.0000
236.3	1.0050
226.5	1.0135
216.7	1.0233
206.9	1.0346
187.3	1.0625

*) Bubble point of reservoir fluid.

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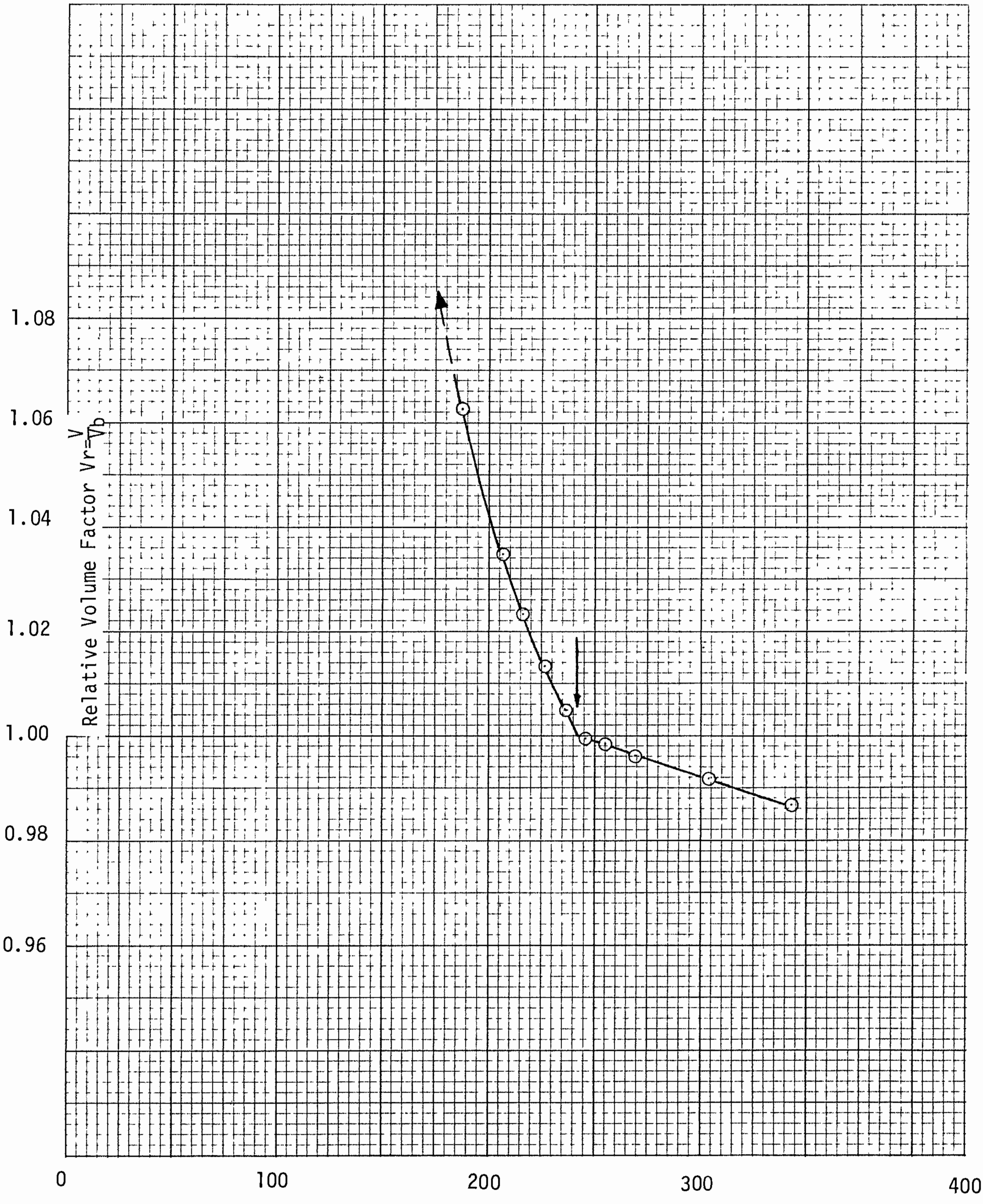

Figure 8. Reservoir fluid. Bubble point determination.
Temperature 71.1 °C.

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Appendix

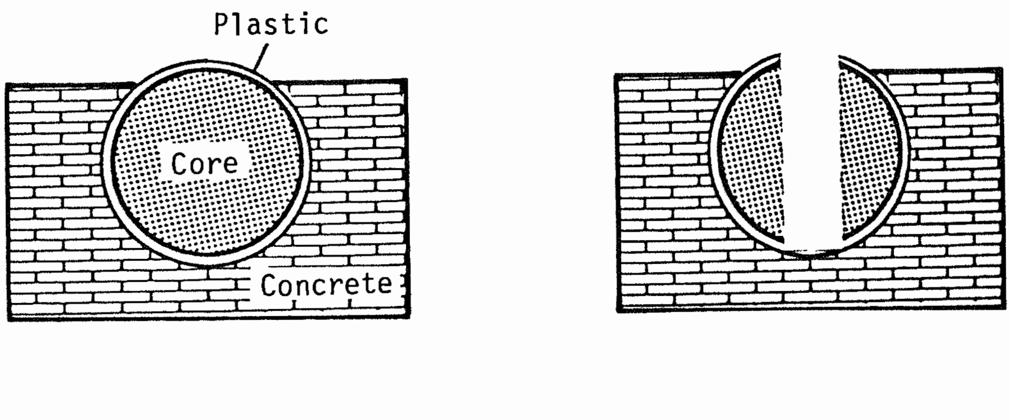
I. EXPERIMENTAL PROCEDURE

1. The received core was unpacked and photographed. The matrix of the core was very poorly consolidated.

2. The core was wrapped in thin plastic and casted in concrete, see figure.

3. A plug was tried drilled out by using synthetic formation water as cutting fluid. This turned out to be unsuccessful. The cutting fluid broke down the unconsolidated core.

   Using air as drilling fluid, and applying a very low drilling feed, it was succeeded to get the desired plug from the core.



4. The core plug was sealed in a coreholder by melting a tin-bismuth alloy between the plug and coreholder. The dimension of the mounted plug was : Diameter : 3.37 centimeters. Length : 8.00 centimeters.

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5. The plug was cleaned by flushing methanole and toulene, respectively, until no further discolouration of solvent was observed.

6. The plug mounted in the coreholder was dried at 60 ^{o}C and 40% relative humidity for 3 days.

7. The porosity was measured by using a helium porosimeter.

8. The permeability to air was measured, and Klinkenberg corrected.

9. The plug, mounted in the coreholder, was evacuated for approximate 24 hours and saturated with synthetic formation water by inflow. The inflowed water was consistent with the volume from helium porosity measurement.

10. The absolute permeability to formation water at Sw = 100 per cent was measured at room conditions.

11. Irreducible water saturation, Swi, was established by dynamic displacement using following fluids:

    a) Refined oil, 1.62 mPas at 21.5 ^{o}C.

    b) Refined oil, approximate 15 mPas at room conditions.

    c) Refined oil as point a).

    All refined oil was treated with silica and filtered through a 0.45 μ filter.

    The volume of produced water was measured and irreducible water saturation calcultated.

12. The absolute permeability to oil at irreducible water saturation was measured.

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The oil used was the same as in a) and c) above, a refined oil of 1.62 mPas viscosity.

13. Temperature and pressure was increased to reservoir conditions, pressure 307 Bar.g. and temperature 71.1 ^{o}C.

14. The absolute permeability to oil at irreducible water saturation at reservoir conditions was measured. The refined oil used had a viscosity of 0.76 mPas at reservoir conditions.

15. A constant-composition pressure-volume test was performed on the reservoir oil in order to check the bubble point.

16. Reservoir oil was used to displace the refined oil. Approximately 6 pore volumes of reservoir oil were put through the core plug.

17. The sample was aged for ten days at reservoir temperature and pressure.

18. The reservoir oil was then displaced at reservoir pressure and temperature with synthetic reservoir brine using a constant rate of 402.5 cc/hour. The following parameters were registrated continously:
    a) Pressure drop across the core versus time.
    b) Oil produced versus time.
    Special care was taken to observe the oil recovery at water breakthrough.

19. Water permeability at residual oil saturation was measured at the end of the waterflood experiment.

20. The core sample was brought back to irreducible water saturation by the procedure described in point 11 but now under reservoir conditions.

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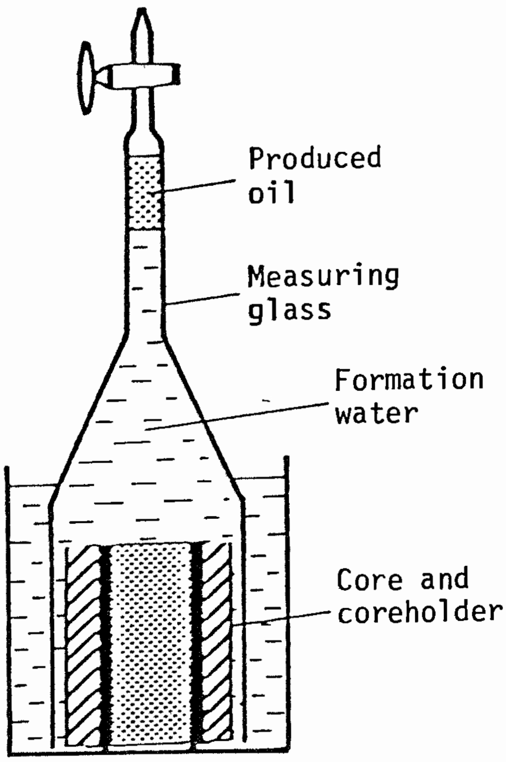
21. Point 17 through 20 was repeated, now with a low rate water flood. (8.48 cc/hour).

22. Temperature and pressure in the core was lowered to room conditions.

23. The core, saturated with refined oil at irreducible water saturation was taken out of the high pressure equipment and prepared for wettability test.

24. The procedure followed in the wettability test, is that developed by IFP*) based on Amott's wettability method. The steps followed were:

    a) The endcaps of the coreholder was dismounted and placed with the core in the imbibition apparatus as shown in figure. Produced refined oil (1.62 mPas) versus time was registrated.



*) Cuiec et al: "Détermination de la Mouillabilité d'un Echantillon de Roche-Réservoir", Revue de L'Institut Francais du Pétrole, pp. 705-728, Sept.-Oct. 1978.

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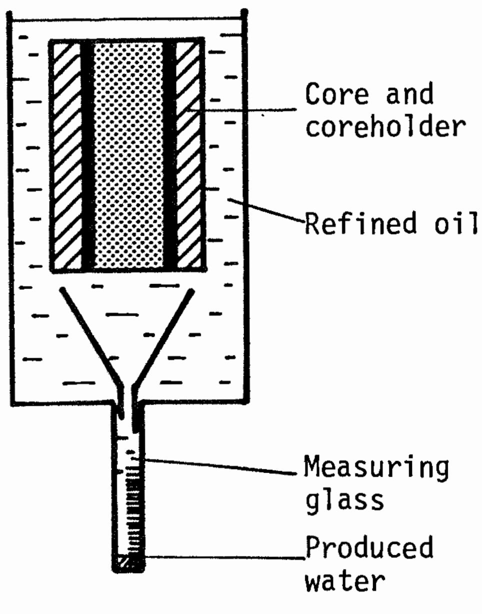
b) After 25 days the coreholder was taken out of the apparatus. Formation water was then injected at a rate of 150 cc/hour. Produced oil was registrated. Approximately 18 pore volumes of formation water were put through the core plug.

c) Core plug and coreholder were placed in the apparatus shown in the figure below. Produced formation water versus time was registrated.



d) After 6 days the coreholder was dismounted from apparatus. Oil was then injected at a rate of 150 cc/hour. Approximately 25 pore volumes of oil were put through. Produced formation water was registrated.

Photographs 1 and 2. The received core.

Photograph 3. The drilled plug.

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Photographs 4 and 5.Closeup of drilled plug.