

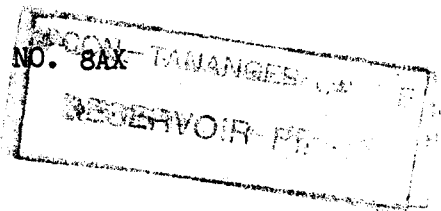
PHILLIPS PETROLEUM COMPANY
RESEARCH AND DEVELOPMENT DEPARTMENT
RESERVOIR ENGINEERING LABORATORY
BARTLESVILLE, OKLAHOMA

LABORATORY REPORT

Report No. RL-205-R-8-72

Date: January 9, 1973

NORWAY SECTOR, NORTH SEA, LICENSE 2, BLOCK 4, WELL NO. 8AX
TORFELT FIELD, DANIAN FORMATION
CAPILLARY PRESSURE, GAS-OIL AND WATER-OIL
RELATIVE PERMEABILITY TESTS ON CORE SAMPLES



By

W. F. Buce, C. E. Bailey and B. J. Kellogg

Capillary pressure curves, gas-oil and water-oil relative permeability and relative permeability ratio curves were measured on the Danian formation core samples from the Torfelt 2/4-8AX, Norwegian Sector, North Sea.

cc: R & D Files
B. M. Boyce (8)
M. J. Fetkovich
R. V. Smith (r) RBN
W. F. Buce

I. INTRODUCTION

Twenty Danian formation core samples from the Torfelt Well 2/4-8AX, Norwegian Sector, North Sea, were shipped on June 13, 1972 to this laboratory by Core Laboratories, Inc. as instructed by Mr. R. M. Archambeault in his letter of December 21, 1971 to Core Laboratories, Inc. These samples were representative of the different lithologic types encountered throughout the cored section. Four of these samples were selected by Mr. J. K. Feters and Mr. J. D. Owen for the measurement of capillary pressures and relative permeabilities. These measurements are in compliance with Mr. J. Tate Clark's letter of March 22, 1972 to Mr. T. J. Jobin.

II. EXPERIMENTAL

The core plugs used for this study were drilled with fresh water and cleaned for two weeks with tetrahydro-2-methylfuran and dried at a temperature less than 212°F.

Nitrogen gas was used in obtaining the specific gas permeabilities, and simulated formation water was used for the specific water permeabilities. The composition of the simulated formation water is listed in Table I. The Boyle's law technique using helium gas was employed in obtaining the porosity and grain density measurements of the samples which are listed in Table II.

Four permeability plugs, approximately 1.85 cm in diameter by 3.5 cm in length, were partly saturated under vacuum with the simulated formation water and was then pressured to 2,500 psi in the same water to attain the complete saturation of the permeability plug samples. Capillary pressures were determined by the centrifuge method with air as the displacing fluid. The temperature was maintained at 76°F, at which the density of the simulated formation water was 1.0851 g/ml. Pressure curves and other permeability data are presented in Figures 1 through 4.

The gas-oil relative permeability measurements were made on four permeability plugs, 3.17 cm in diameter and with lengths varying from 4.37 to 5.90 cm. The porosities and pore volumes obtained by the Boyle's law method were used as a reference in determining whether the samples were saturated with the simulated formation water. The samples were only partly saturated with the simulated formation water by vacuum and were completely saturated by applying a pressure of 2,500 psi on the samples while in the simulated formation brine. Specific permeabilities to brine were measured after complete saturation to brine. The samples were partly desaturated by centrifugation and the residual water saturations were determined after measuring the effective gas permeabilities. The samples were then evacuated and saturated with refined oil. A small amount of water was removed and accounted for on each sample during the resaturation of the samples. Effective permeabilities to oil with residual water in place were measured and calculated in accordance with the procedures described by E. T. Guerrero⁽¹⁾. The data are presented graphically on Figures 5 through 12. The viscosities of the gas and oil are noted on each figure, together with other pertinent data.

(1) Guerrero, E. T., Practical Reservoir Engineering, the Petroleum Publishing Co., Tulsa, Oklahoma, 1968.

Water-oil relative permeability measurements were made on only three of the same samples on which the gas-oil relative permeability measurements were made because sample No. 18 fractured. These samples were again cleaned and dried at a temperature less than 212°F.

All of the procedures used to prepare the samples for these tests were the same as in the gas-oil relative permeability tests, except for the deletion of the measurement of the effective permeabilities to gas with residual water saturation in the samples. These calculations were also based on the procedures described by E. T. Guerrero⁽¹⁾. The results are presented graphically on Figures 13 through 18. The viscosities of the water and oil are noted on each figure together with other pertinent data.

TABLE I

COMPOSITION OF SIMULATED DANIAN FORMATION WATER, PPM

Calcium Chloride	49,286	Sodium Sulfate	296
Magnesium Chloride	6,513	Sodium Bicarbonate	94.1
Sodium Chloride	65,218		

III. DISCUSSION

The capillary pressure curves for the Danian formation have unusually high values of threshold pressures (40 to 70 psig) and suggest that a water zone at least 200 to 350 feet thick exists below the oil layer in formations having specific permeabilities to nitrogen gas in the 1.2 to 2.0 millidarcy range with porosities above 26 per cent. In addition, the slopes of the capillary pressure curves indicate that the fine pore structure is relatively uniform in size. These characteristics of the capillary pressure curves are consistent with those of the Ekofisk 2/4-2X well which were reported in Reservoir Engineering Laboratory Report No. RL-141-R-2-71, entitled: "Norway Sector, North Sea, License 2, Block 4, Well No. 2X, Ekofisk Field, Danian Formation Capillary Pressure Measurements."

None of the gas-oil relative permeability tests was continued to zero production, however, the tests were continued until high gas-oil ratios were attained. The average oil recovery of the gas flood was 47.3 pore volume per cent, with samples No. 15 and 16 being the extreme cases having oil recoveries of 43.9 and 51.0 per cent of the pore volume, respectively. The average recovery of oil displaced by water injection was 57.3 per cent, with samples No. 14 and 16 being the extreme cases having oil recoveries of 56.6 and 58.7 pore volume per cent, respectively. In all of the above displacement tests an irreducible water saturation was established in the core prior to the initiation of the displacement.

The characteristics of the relative permeability curves from this well are similar to those from the Ekofisk 2/4-2X well which were reported in Reservoir Engineering Laboratory Report No. RL-118-R-6-70, entitled: "Norway Sector, North Sea, License 2, Block 4, Well No. 2X, Ekofisk Field, Danian Formation, Gas-Oil and Water-Oil Relative Permeabilities."

IV. CONCLUSION

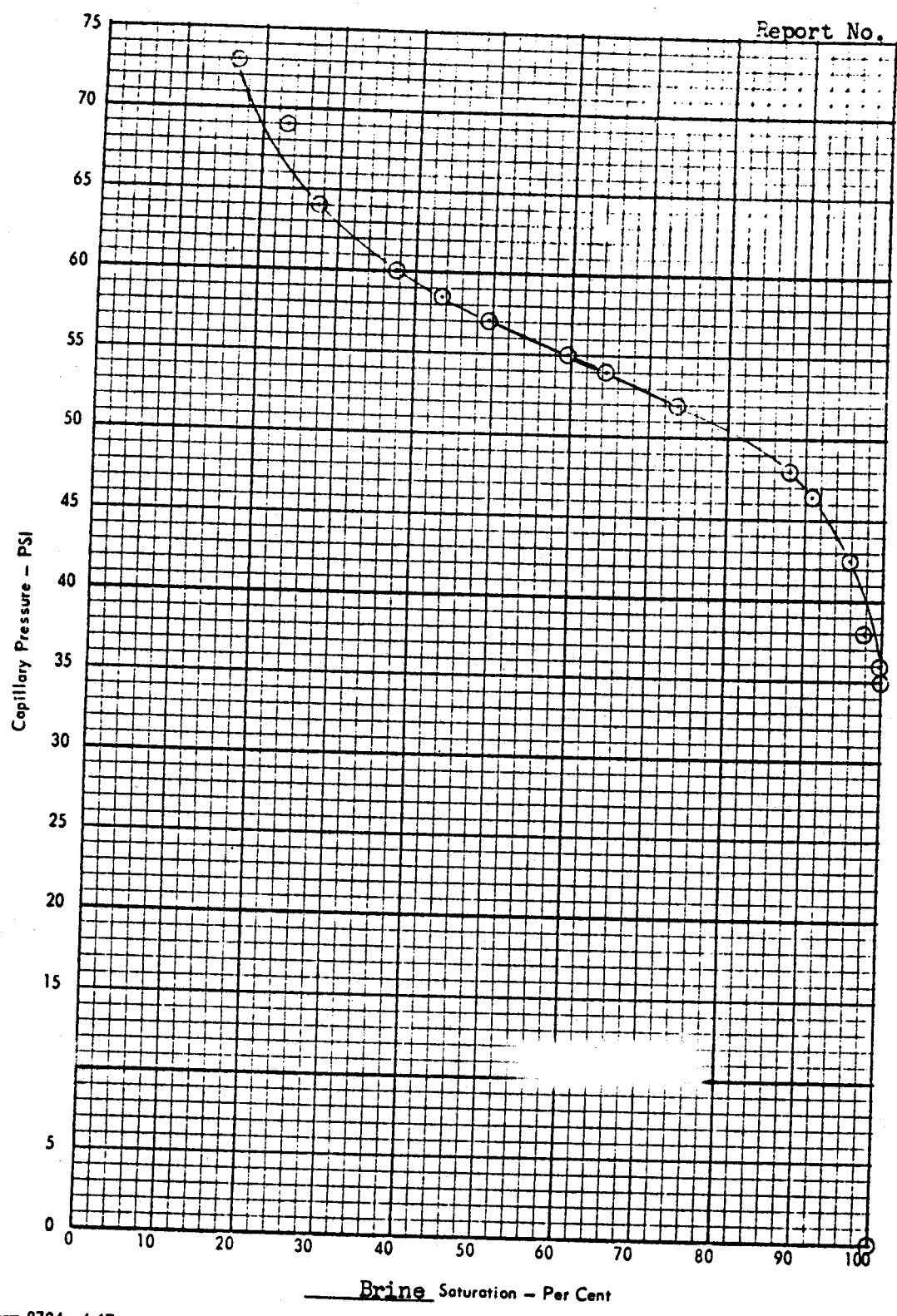
1. The capillary pressure curves have unusually high threshold pressures of 40 to 70 psig which suggests that a water zone at least 200 to 350 feet thick exists below the oil zone. In addition, the capillary pressure curves indicate a relatively small, uniform pore size by the sharp break-over of the curves.
2. The average oil recovery was 47.3 per cent of the pore volume using gas as the displacement fluid.
3. The average oil recovery was 57.3 per cent of the pore volume using water as the displacement fluid.
4. The capillary pressure curves, gas-oil and water-oil relative permeability curves have characteristics similar to the corresponding curves previously measured and reported for Well 2/4-2X, Norway Sector, North Sea.

TABLE II

TORFELT 2/4-8AXPERMEABILITY, POROSITY AND GRAIN DENSITY MEASUREMENTS
BOYLES LAW METHOD

Sample Number	Depth, Feet		Diameter, cm		Diameter, cm		Diameter, cm	
	From	To	1.85	3.17	1.85	3.17	1.85	3.17
			Permeability, md		Porosity, Per Cent		Grain Density, g/ml	
1	9,799.08	9,799.75	.06	.08	20.9	21.6	2.71	2.71
3	9,862.83	9,863.58	.04	.06	21.3	17.1	2.71	2.71
5	9,916.92	9,917.25	.02	.06	15.4	15.1	2.71	2.71
6	9,937.58	9,937.33	.25	.33	26.5	27.7	2.70	2.70
7	9,968.67	9,969.25	.10	.05	22.0	13.5	2.70	2.70
8	9,994.25	9,994.75	.32	.34	28.6	29.2	2.71	2.71
9	10,026.50	10,027.08	.04	.04	21.2	20.0	2.71	2.71
10	10,036.42	10,036.75	.02	.04	9.2	25.8	2.65	2.65
11	10,143.67	10,144.50	.27	.30	18.7	18.2	2.71	2.71
12A	10,183.08	10,183.75	.03	.03	11.9	11.5	2.71	2.71
12B	10,159.08	10,159.83	.60	.77	24.4	24.6	2.71	2.71
13	10,200.75	10,201.08	.32	.36	20.2	21.5	2.71	2.71
*14	10,261.09	10,261.75	1.56	2.11	27.2	27.6	2.71	2.71
*15	10,294.33	10,295.08	1.95	1.10	23.2	24.8	2.71	2.71
*16	10,332.66	10,333.33	1.77	2.14	31.0	30.9	2.71	2.71
17A	10,450.25	10,450.83	.06	.09	14.0	14.4	2.71	2.71
17B		395.0	.28	.35	19.0	8	2.71	2.71
*18	10,478.21	10,498.58	1.16	2.28	26.2	20.5	2.71	2.71
19	10,540.25	10,540.67	<.01	.01	0.9	1.3	2.66	2.66
20	10,578.50	10,578.92	.02	.03	7.1	9.2	2.70	2.70

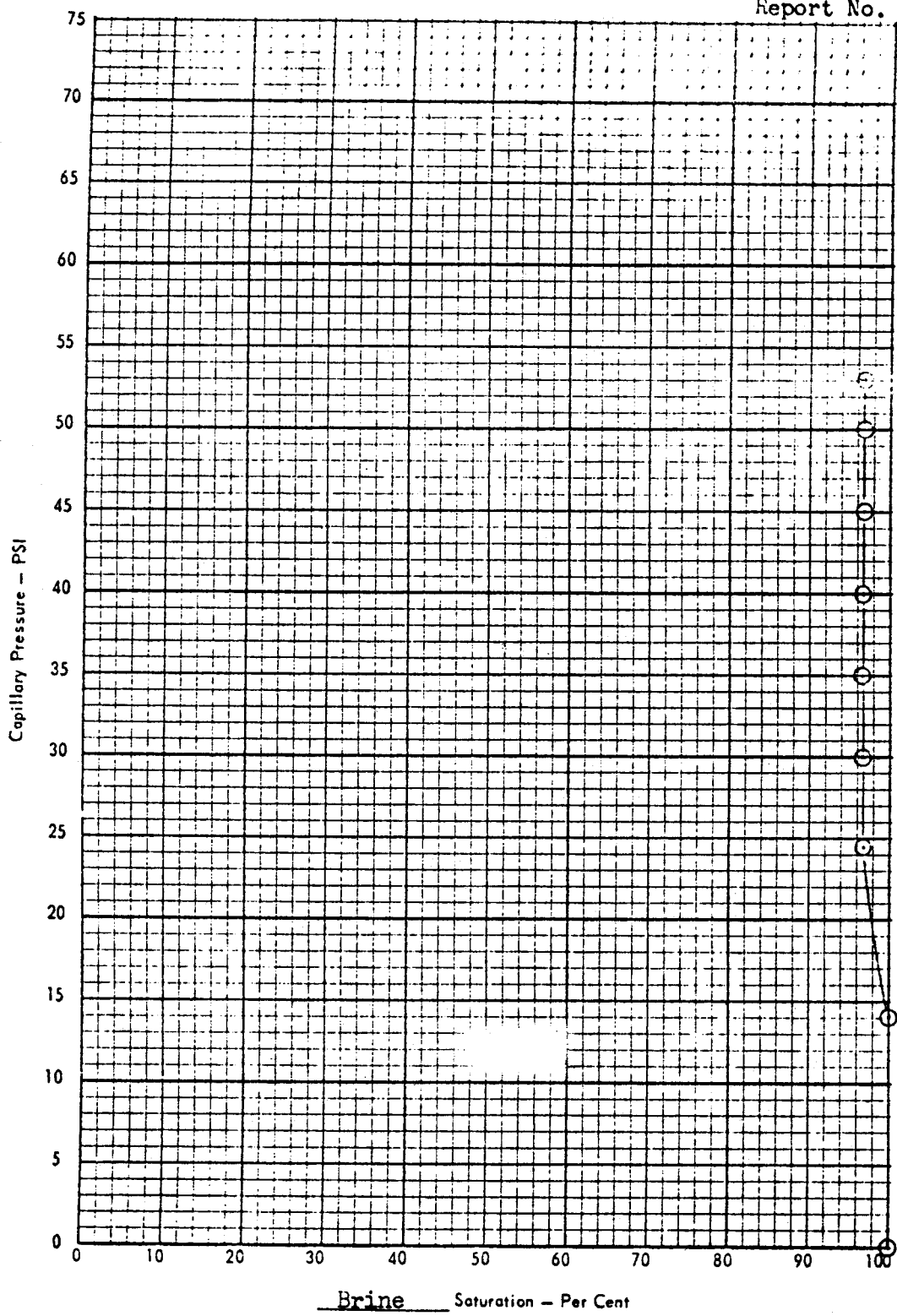
*Samples selected for relative permeability and capillary pressure tests.



Brine Saturation - Per Cent
CAPILLARY PRESSURE CURVE

Form 8794 4-67
 Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
 Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Grain Density-gm/ml
		From	To			
	14	10,261.09	10,261.75	1.562	27.2	2.71



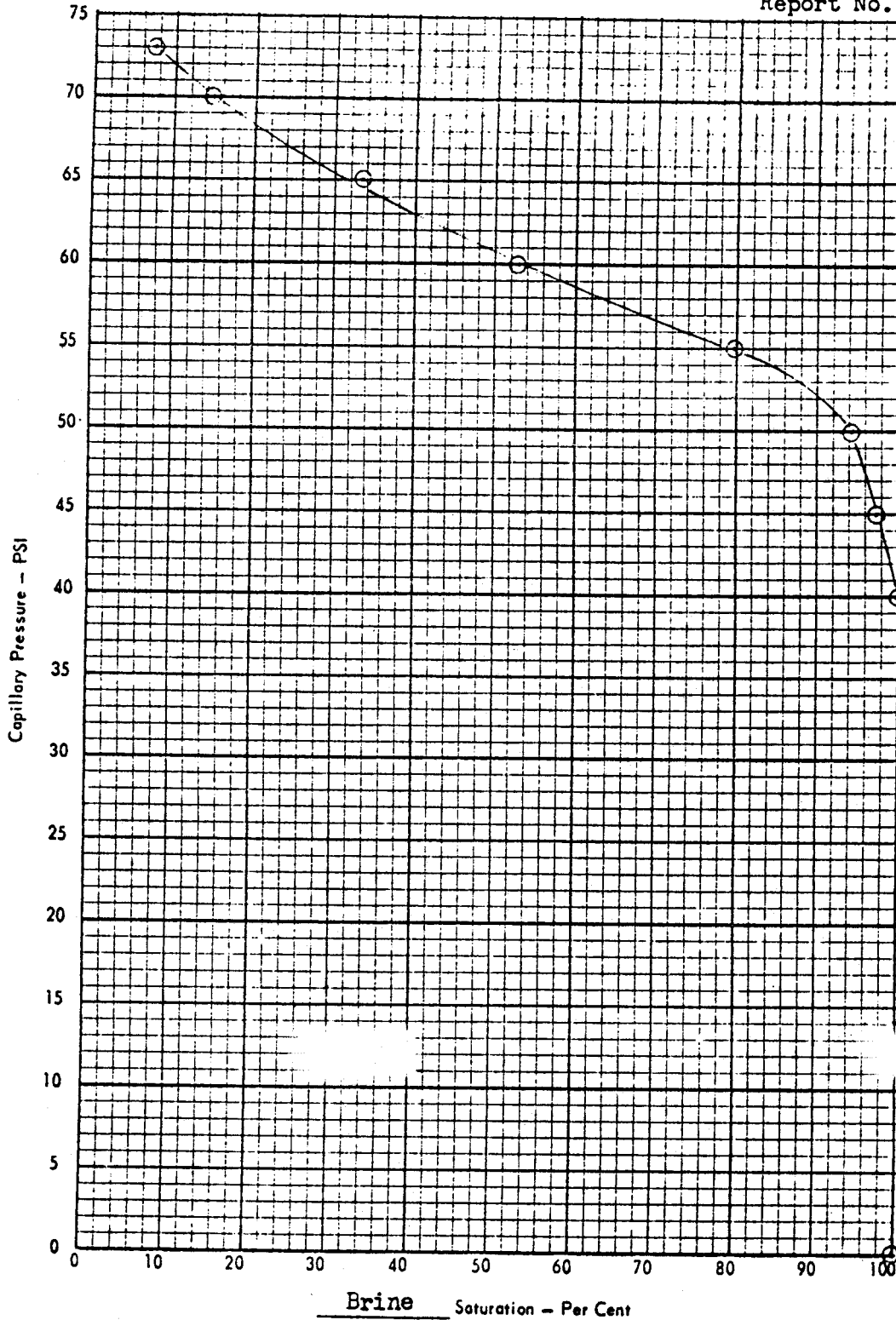
Form 8794 4-67

CAPILLARY PRESSURE CURVE

Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Grain Density-gm/ml
		From	To			
	15	10,294.33	10,295.08	1.952	23.2	2.71



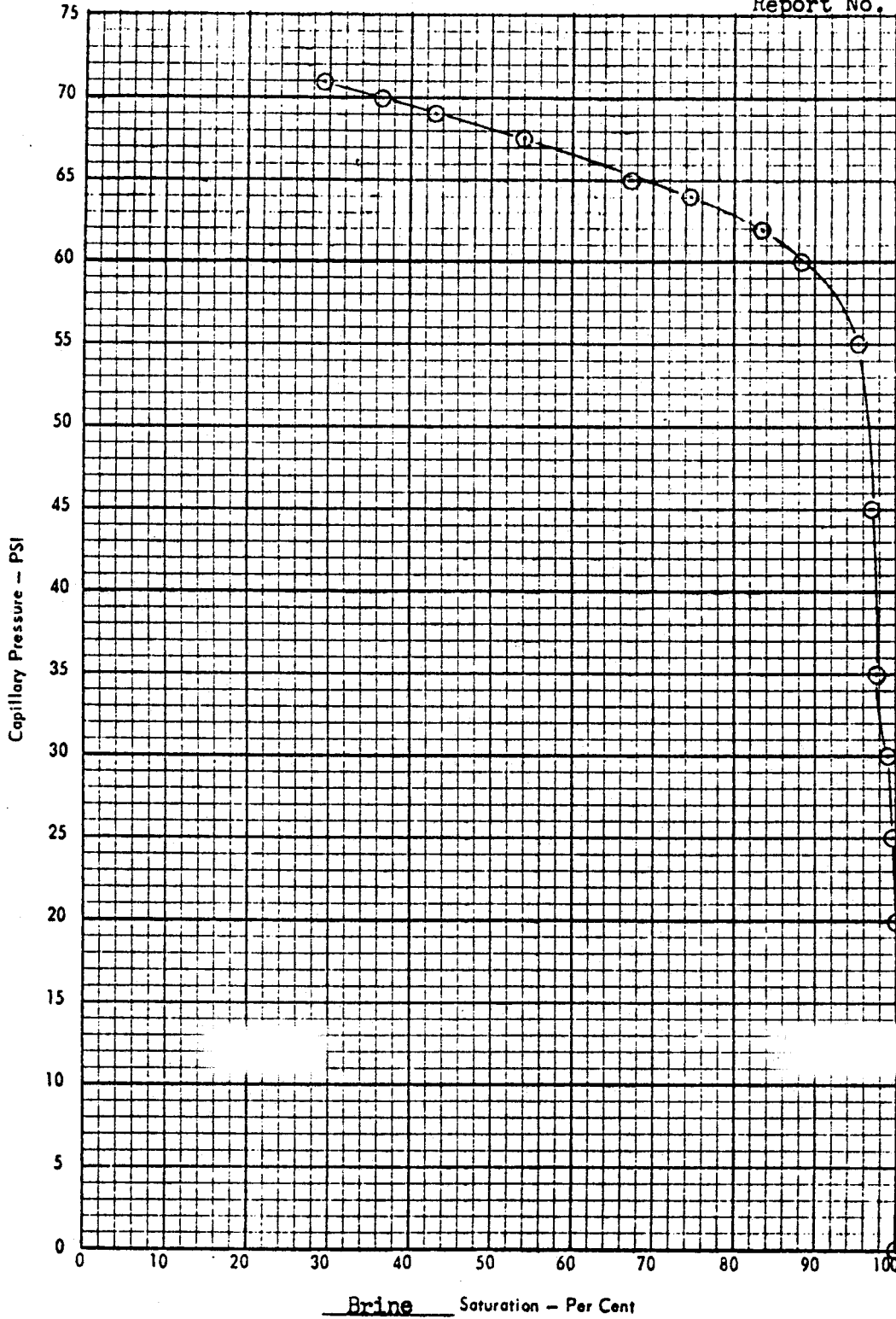
Form 8794 4-67

CAPILLARY PRESSURE CURVE

Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Grain Density-gm/ml
		From	To			
	16	10,332.66	10,333.33	1.769	31.0	2.71



Brine Saturation - Per Cent
CAPILLARY PRESSURE CURVE

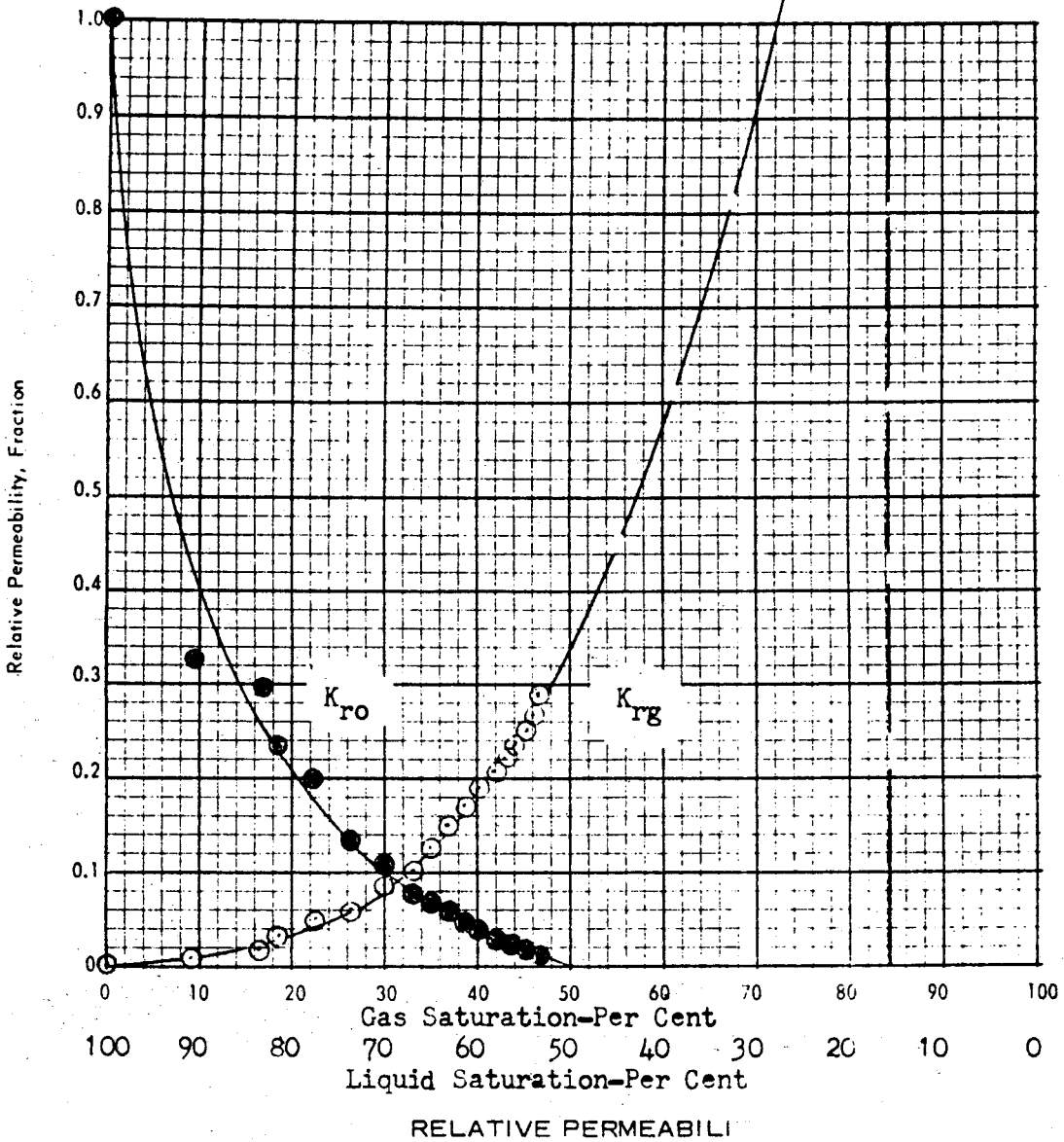
Form 8794 4-67

Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Grain Density-gm/ml
		From	To			
	18	10,498.17	10,498.58	1.158	26.2	2.71

To 1.5E

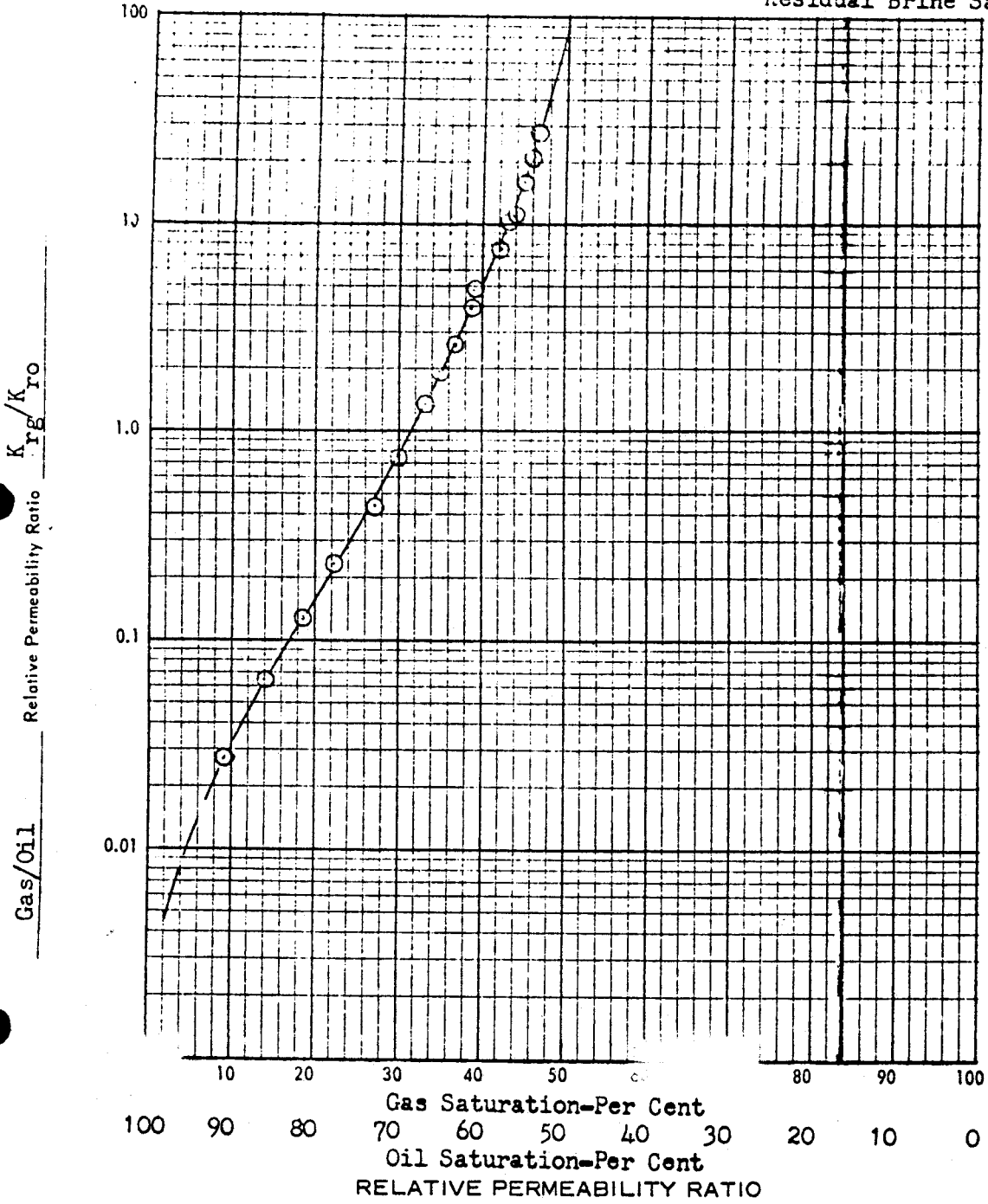
Residual Brine Saturation = 16.1%



Company	Phillips Petroleum	Lease	Torfelt 2/4	Well No.	8 AX
Field	Torfelt	County	Norway Sector	State	North Sea
Sample No.	14	Depth, Feet	10,261.09 To 10,261.75	Permeability Millidarcys	0.73*
				Porosity Per Cent	27.6
				Formation	Danian

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.11 and 0.76 md, respectively. The effective permeability to gas with residual brine present was 1.15 md. The viscosities of the gas and oil were 0.0176 and 23.47 centipoises, respectively.

Fig. 5 By Bailey, Buce and Kellogg Date 10-20-72

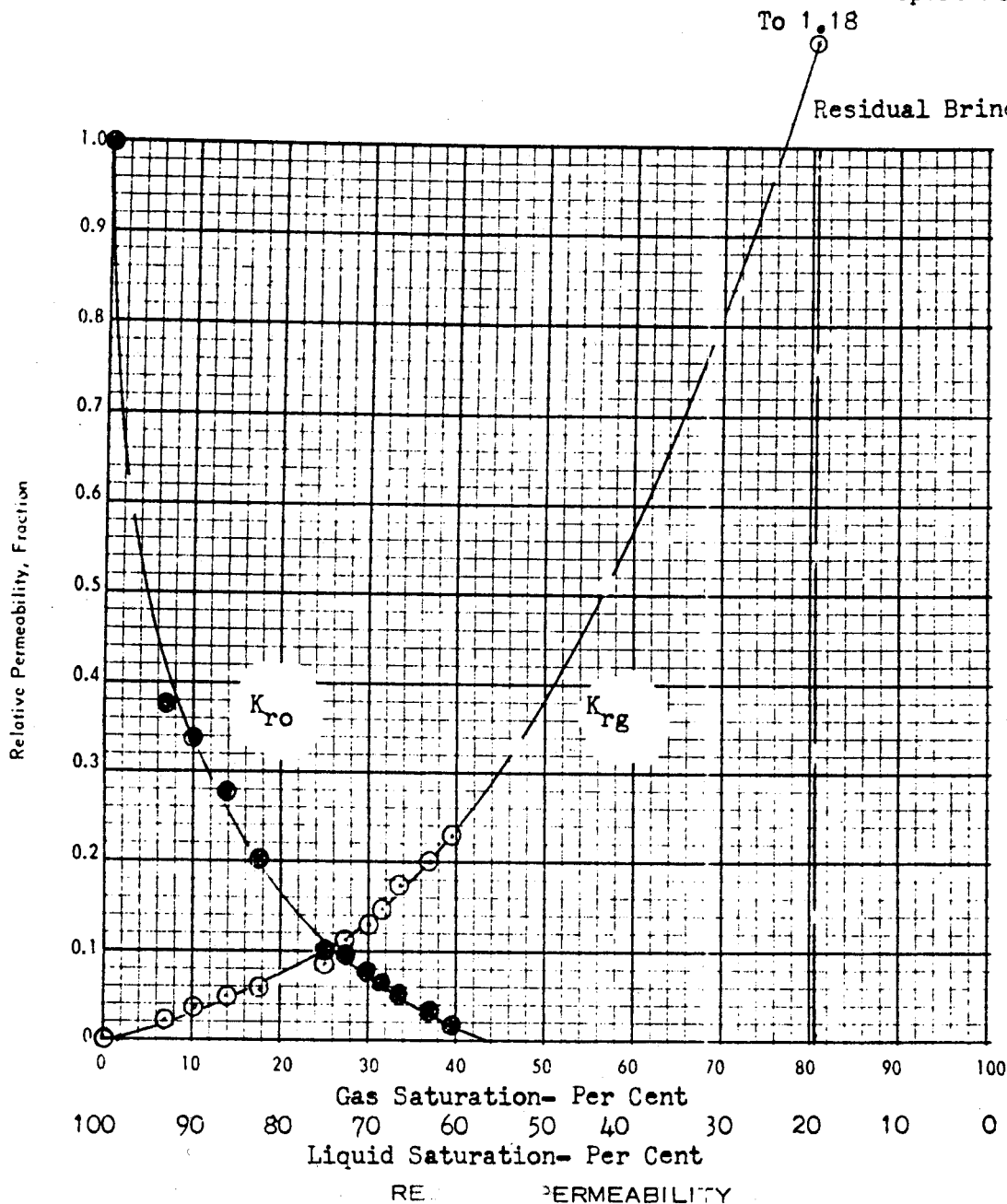


Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
 Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	14	10,261.09	10,261.75	0.73*	27.6	Danian

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.11 and 0.76 md, respectively. The effective permeability to gas and residual brine present was 1.15 md. The viscosities of the gas and oil were 0.0176 and 23.47 centipoises, respectively.

Fig. 6 By Bailey, Buce & Kellogg Date 10-20-72

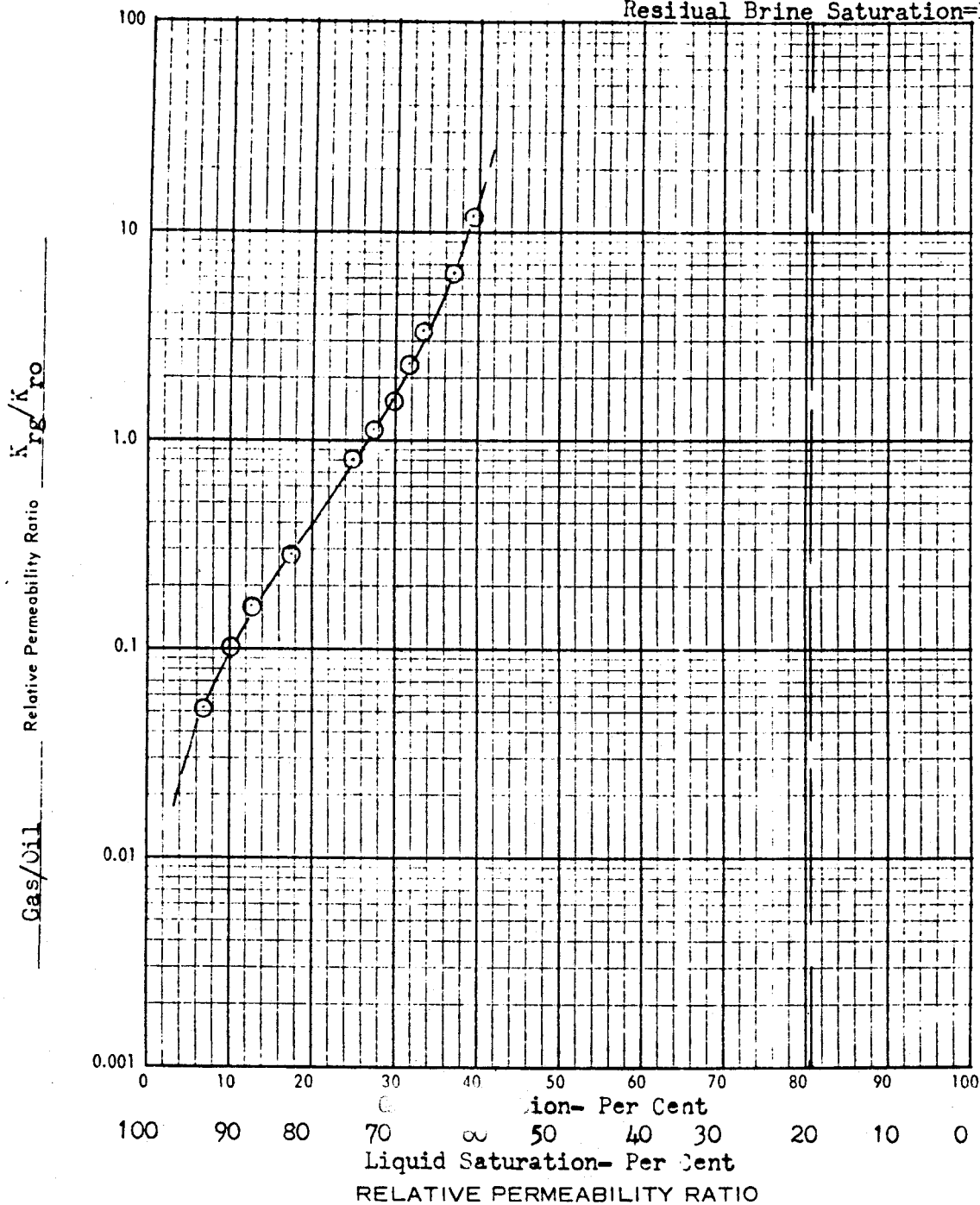


Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
 Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	15	10,294.33	10,295.08	0.28*	20.4	Danian

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 1.10 and 0.31 md, respectively. The effective permeability to gas with residual brine present was 0.33 md. The viscosities of the gas and oil were 0.0170 and 23.95 centipoises, respectively.

Fig. _____ By Bailey, Duce & Kellogg Date 10-20-72



Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
 State Torfelt County Norway Sector State North Sea

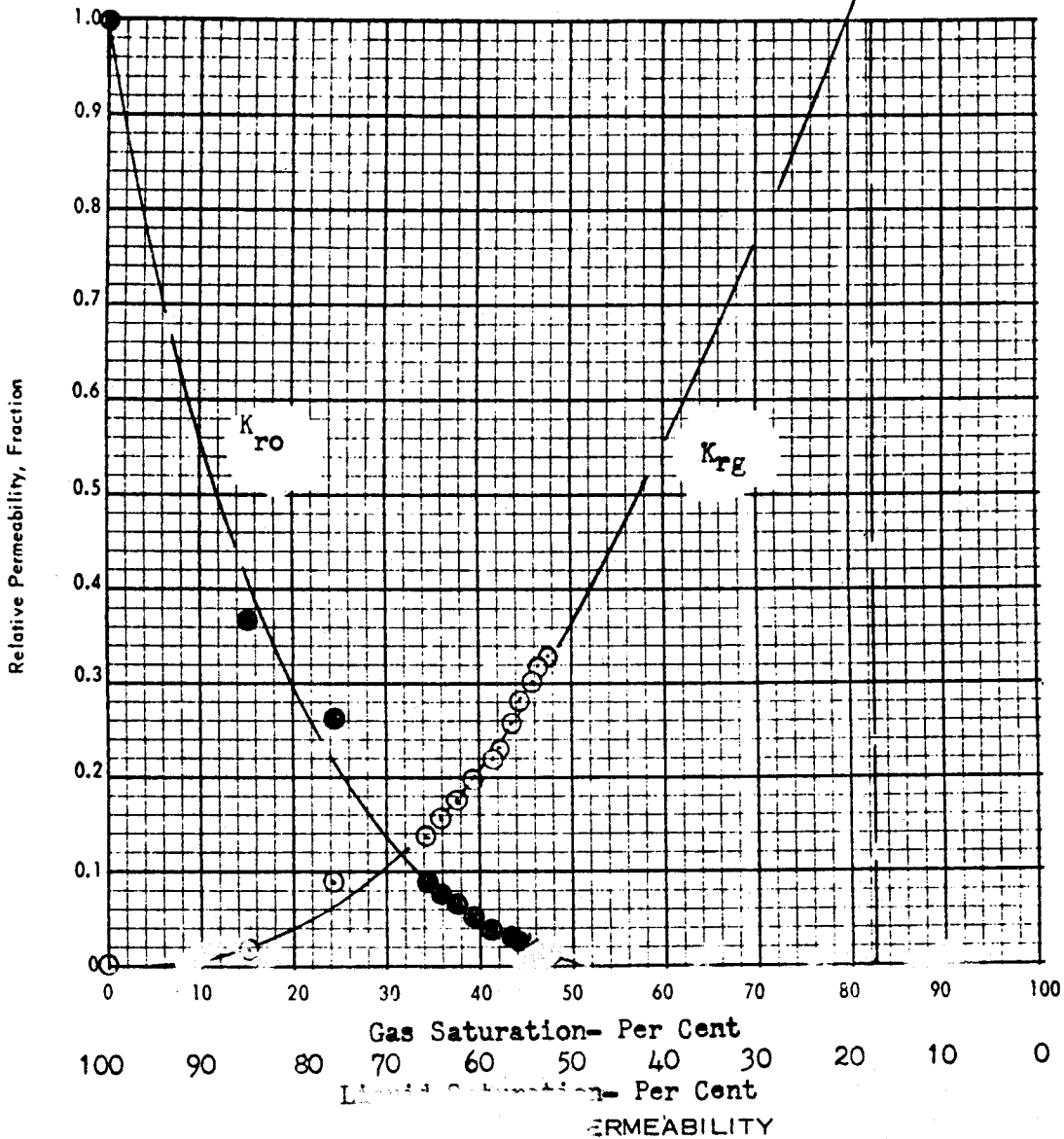
Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	15	10,294.33	10,295.08	0.28*	20.4	Danian

* Effective permeability to oil with indicated residual brine present.
 The relative permeability is related to this effective permeability to oil.
 The specific permeabilities to gas and brine were 1.10 and 0.31 md, respectively.
 The effective permeability to gas with residual brine present was 0.33 md.
 The viscosities of the gas and oil were 0.017 and 23.95 centipoises, respectively.

Fig. 5 by S. Bailey, Bruce and Kellogg Date 10-20-72

To 1.07

Residual Brine Saturation=17.



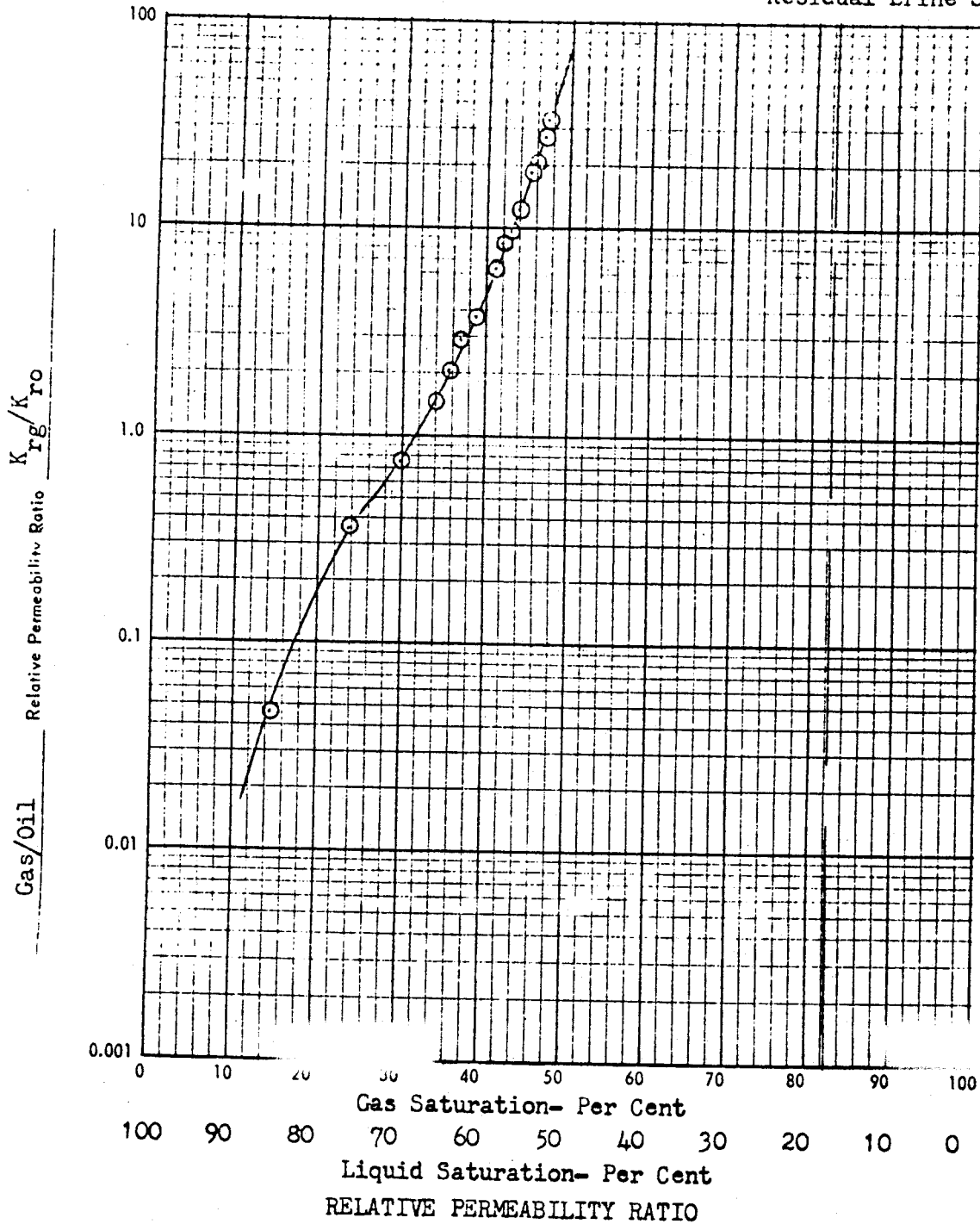
Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	16	10,332.66	10,333.33	0.67*	30.9	Danian

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.14 and 0.87 md, respectively. The effective permeability to gas with residual brine present was 0.71 md. The viscosities of the gas and oil were 0.0176 and 21.77 centipoises, respectively.

Fig. 9 By Sailey, Duce & Kellogg Date 10-20-72



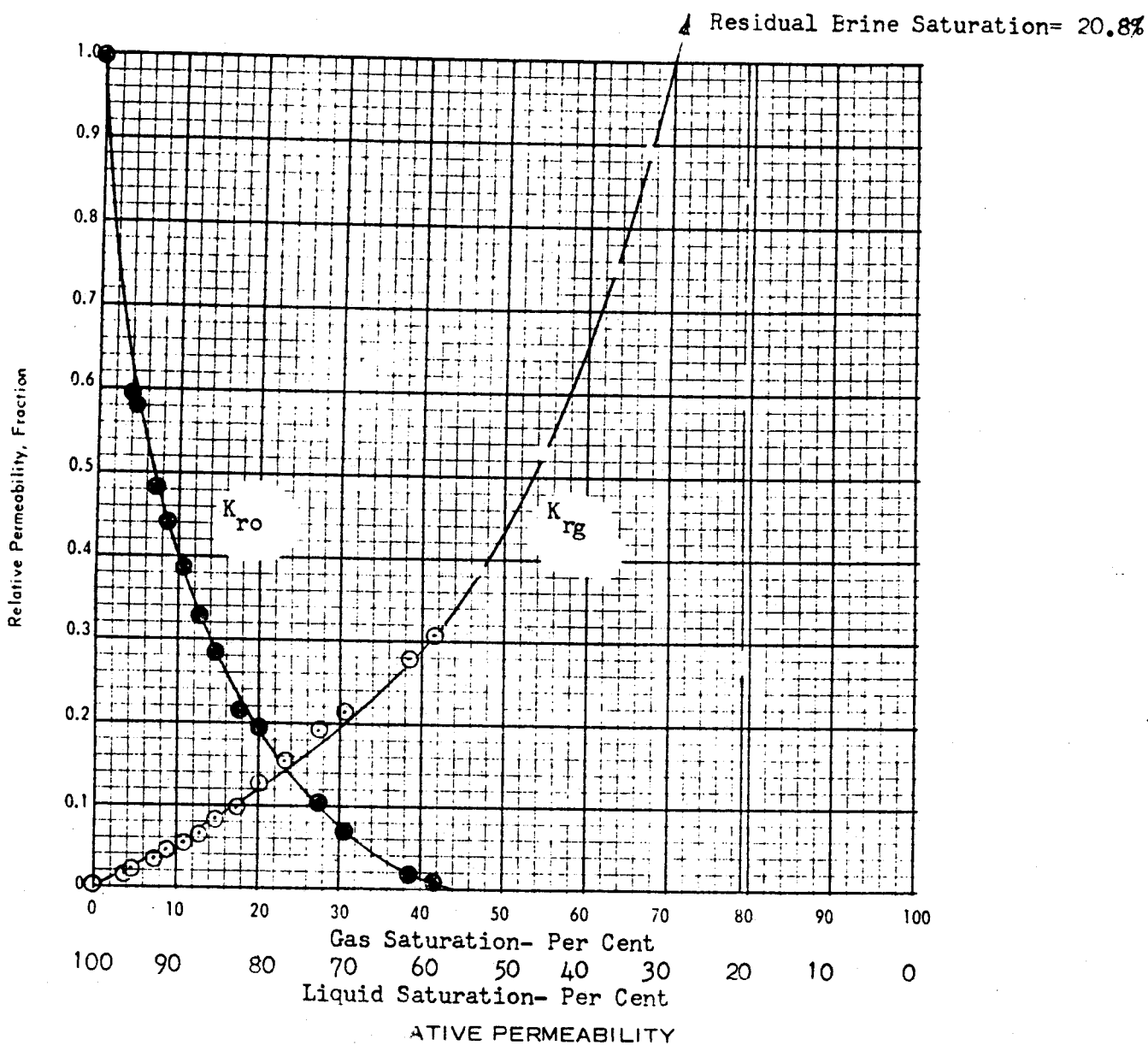
Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	16	10,332.66	10,333.33	0.67*	30.9	Danian

* Effective permeability to oil with indicated residual brine present.
The relative permeability is related to this effective permeability to oil.
The specific permeabilities to gas and brine were 2.14 and 0.98, respectively.
The effective permeability to gas with residual brine present was 0.71 md.
The viscosities of the gas and oil were 0.0176 and 24.97 centipoises, respectively.

Fig. 10 By Bailey, Buce and Kellogg Date 10-20-72

To 1.46



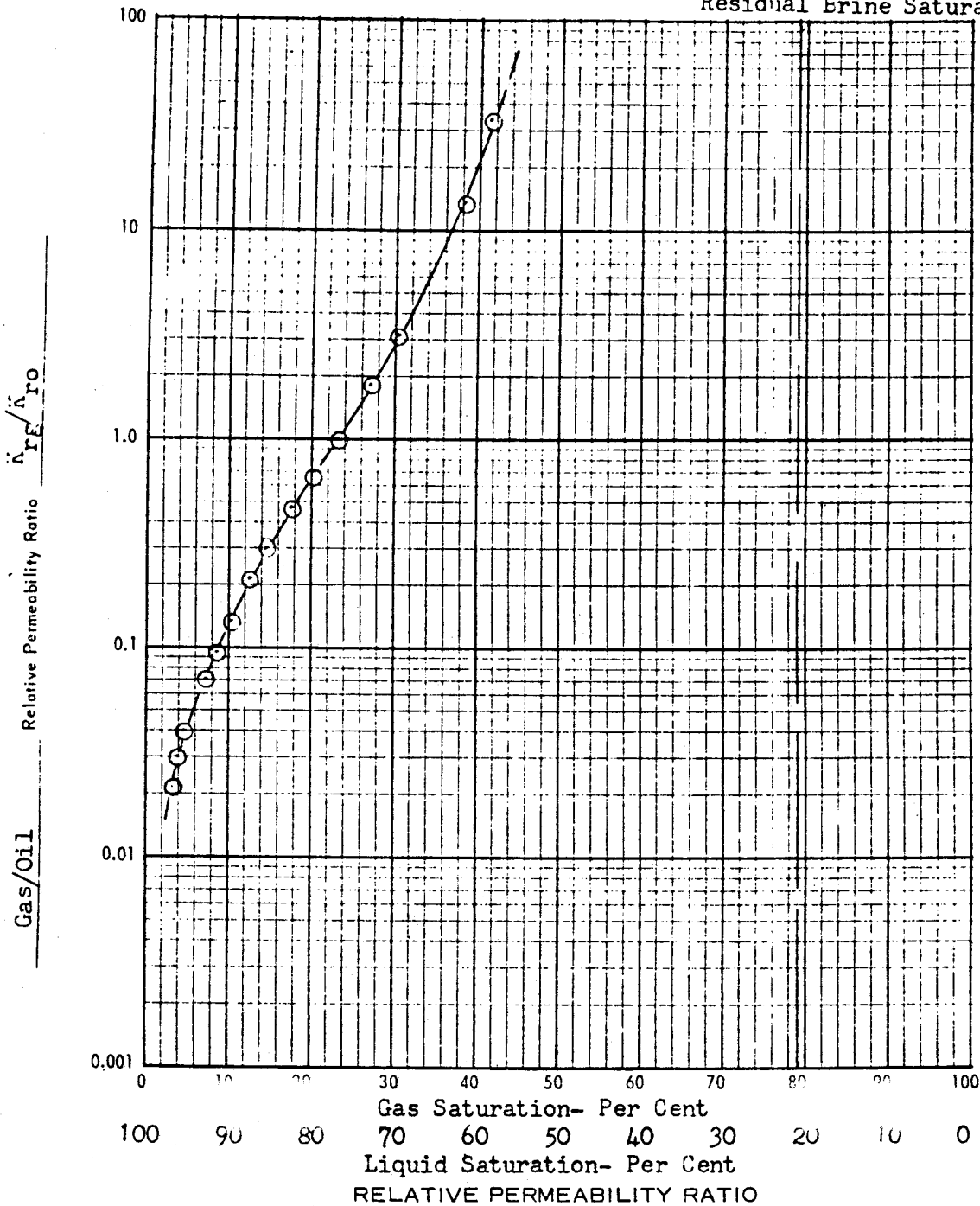
Company Phillips Petroleum Lease Torfelt 2/4 Well No. 2 AX

Field Torfelt County Norway Sector State North Sea

Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
	From	To			
18	10,498.17	10,498.58	0.50*	26.5	Danian

* Effective permeability to oil with indicated residual brine saturation present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.28 and 0.60 md, respectively. The effective permeability to gas with residual brine present was 0.73 md. The viscosities of the gas and oil were 0.0176 and 23.82 centipoises, respectively.

Fig. 11 By Bailey, Buce & Kellogg Date 10-20-72



Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

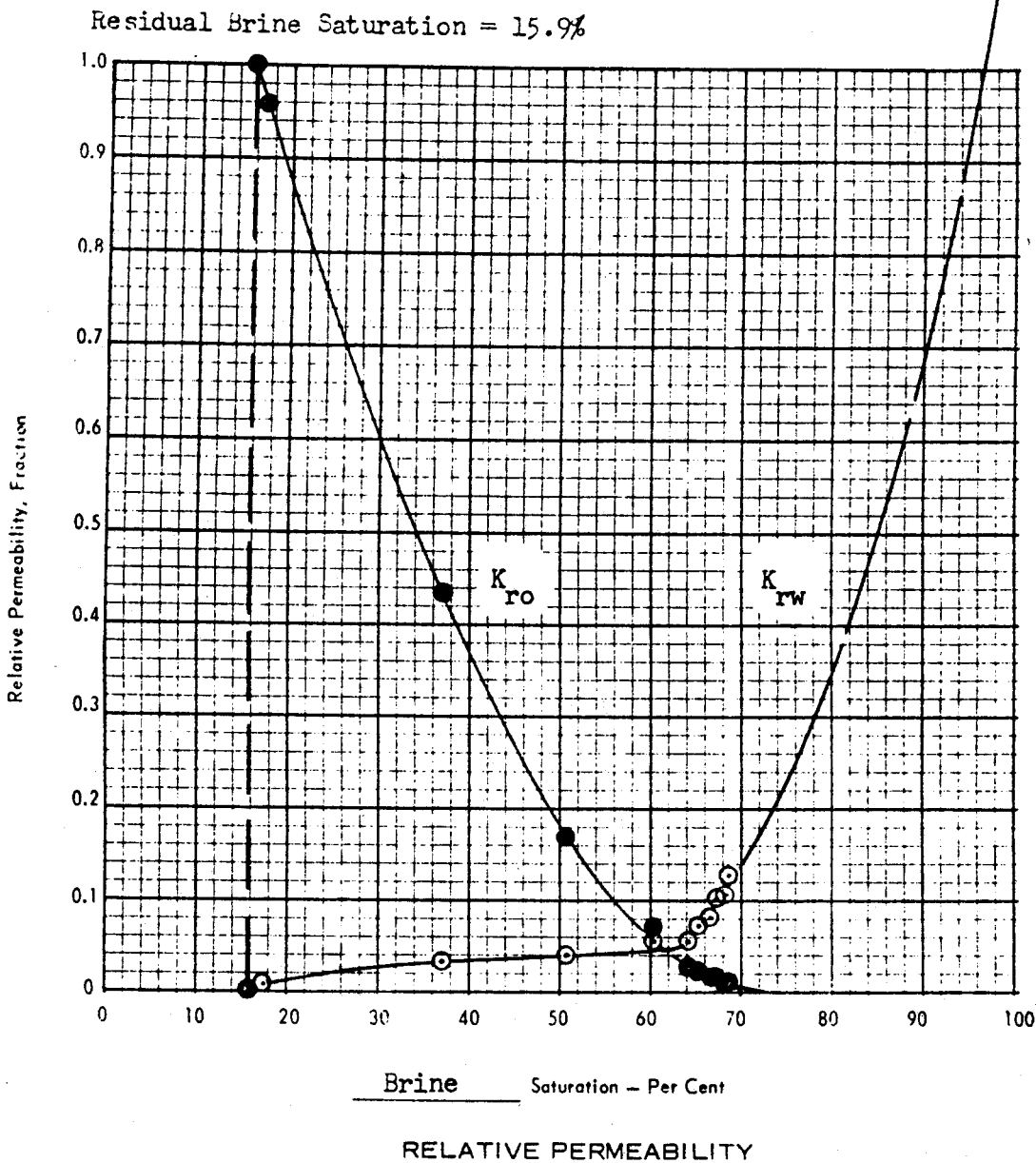
Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	18	10,498.17	10,498.58	0.50 *	26.5	Danian

* Effective permeability to oil with indicated residual brine saturation present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.28 and 0.60 md, respectively. The effective permeability to gas with residual brine present was 0.73 md. The viscosities of the gas and oil were 0.017 and 23.82 centipoises, respectively.

Fig. 12 By Wiley, Bruce and Kellogg Date 10-20-72

To 1.24

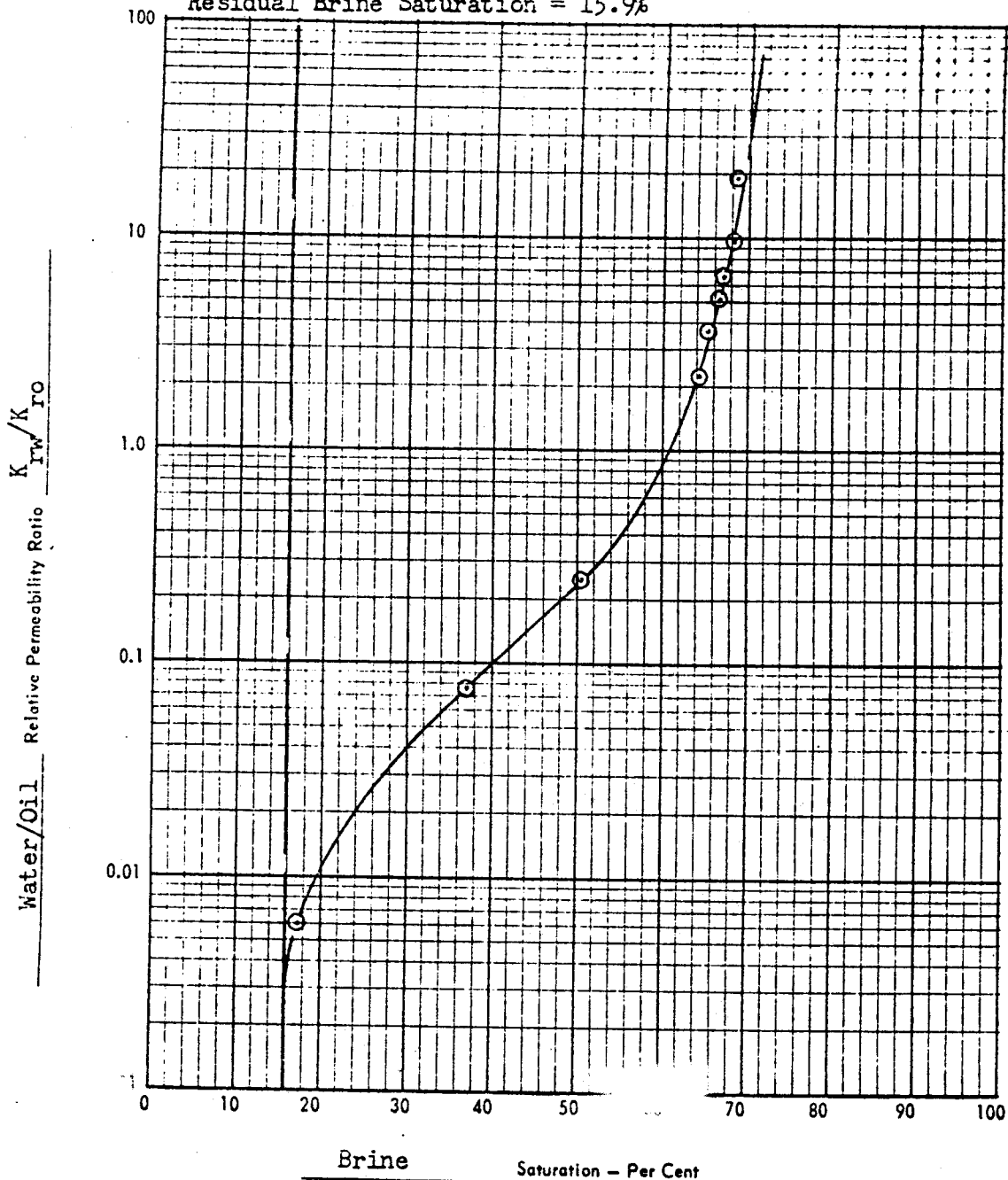


Company	Phillips Petroleum		Lease	Torfelt 2/4		Well No.	8 AX	
Field	Torfelt		County	Norway Sector		State	North Sea	
Symbol	Sample No.	Depth, Feet		Permeability	Porosity	Formation		
		From	To	Millidarcys	Per Cent			
	14	10,261.09	10,261.75	0.71*	27.5	Danian		

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.11 and 0.88 md, respectively. The viscosities of the brine and oil were 1.203 and 23.63 centipoises, respectively.

Fig. 13 By Bailey, Bruce & Kellogg Date 11-10-72

Residual Brine Saturation = 15.9%



RELATIVE PERMEABILITY RATIO

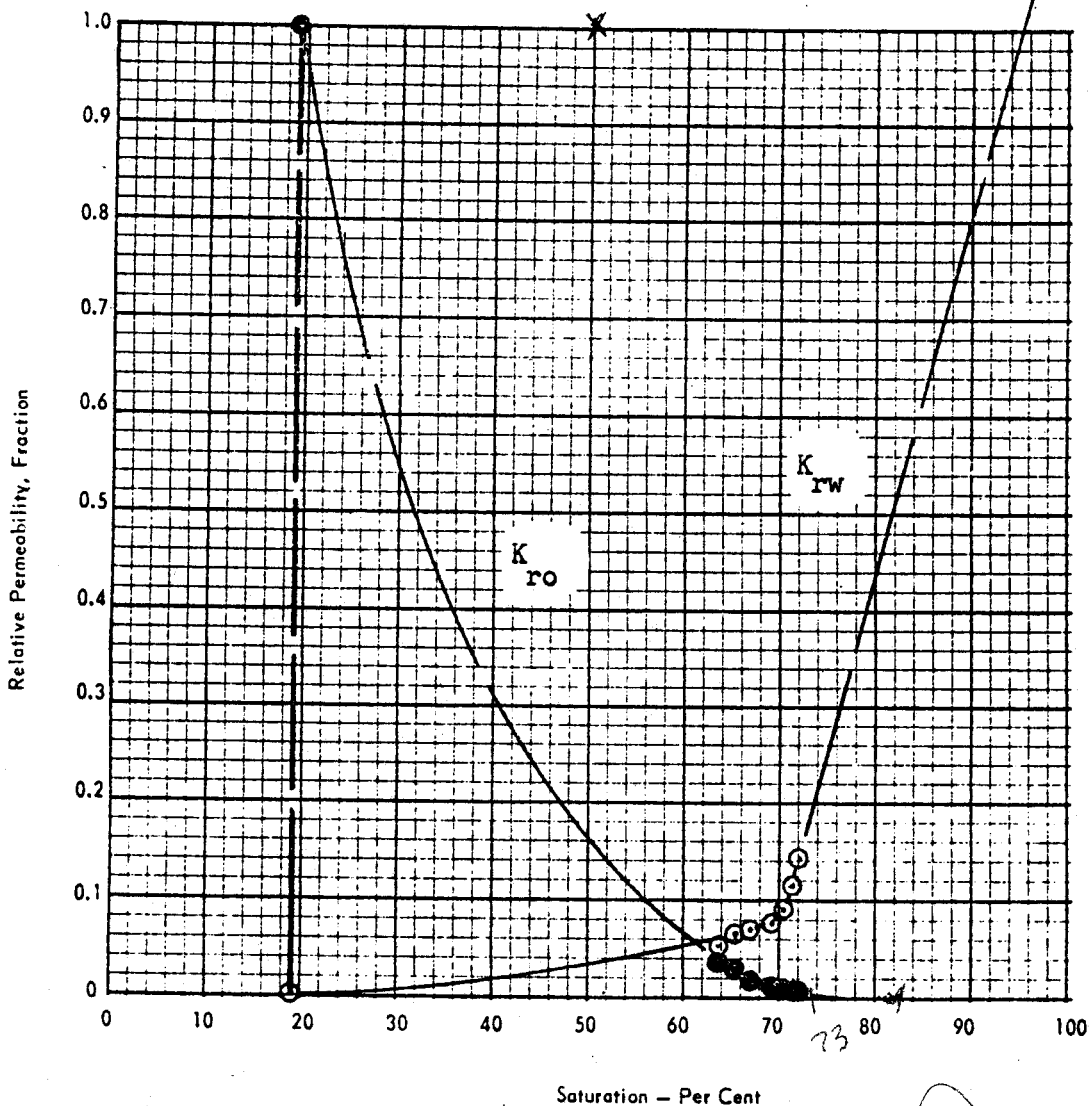
Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX
 Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	14	10,261.09	10,261.75	0.71*	27.5	Danian

* Effective permeability to oil with indicated residual brine present.
 The relative permeability is related to this effective permeability to oil.
 The specific permeabilities to gas and brine were 2.11 and 0.88 md, respectively.
 The viscosities of the brine and oil were 1.203 and 23.63 centipoises, respectively.

Fig. 14 By Bailey, Buce & Kellogg Date 11-10-72

Residual Brine Saturation = 19.3%



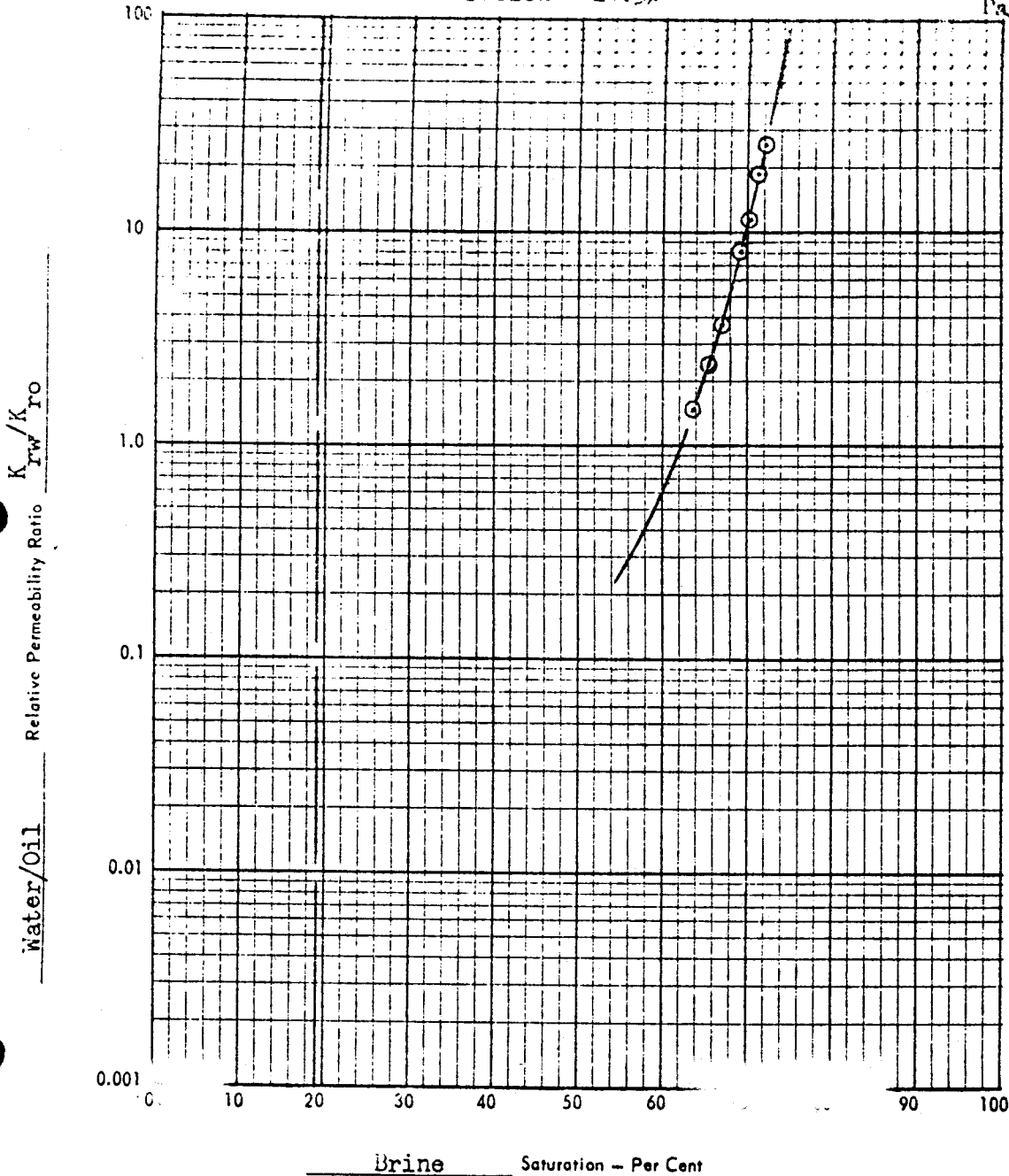
RELATIVE PERMEABILITY



Company	Phillips Petroleum		Lease	Torfelt 2/4		Well No.	8 AX	
Field	Torfelt		County	Norway Sector		State	North Sea	
Symbol	Sample No.	Depth, Feet		Permeability	Porosity	Formation		
		From	To	Millidarcys	Per Cent			
	15	10,294.33	10,295.08	0.30*	24.8	Danian		

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 1.10 and 0.35 md, respectively. The viscosities of the brine and oil were 1.205 and 23.68 centipoises, respectively.

Fig. 15 By Bailey, Buce & Kellogg Date 11-10-72



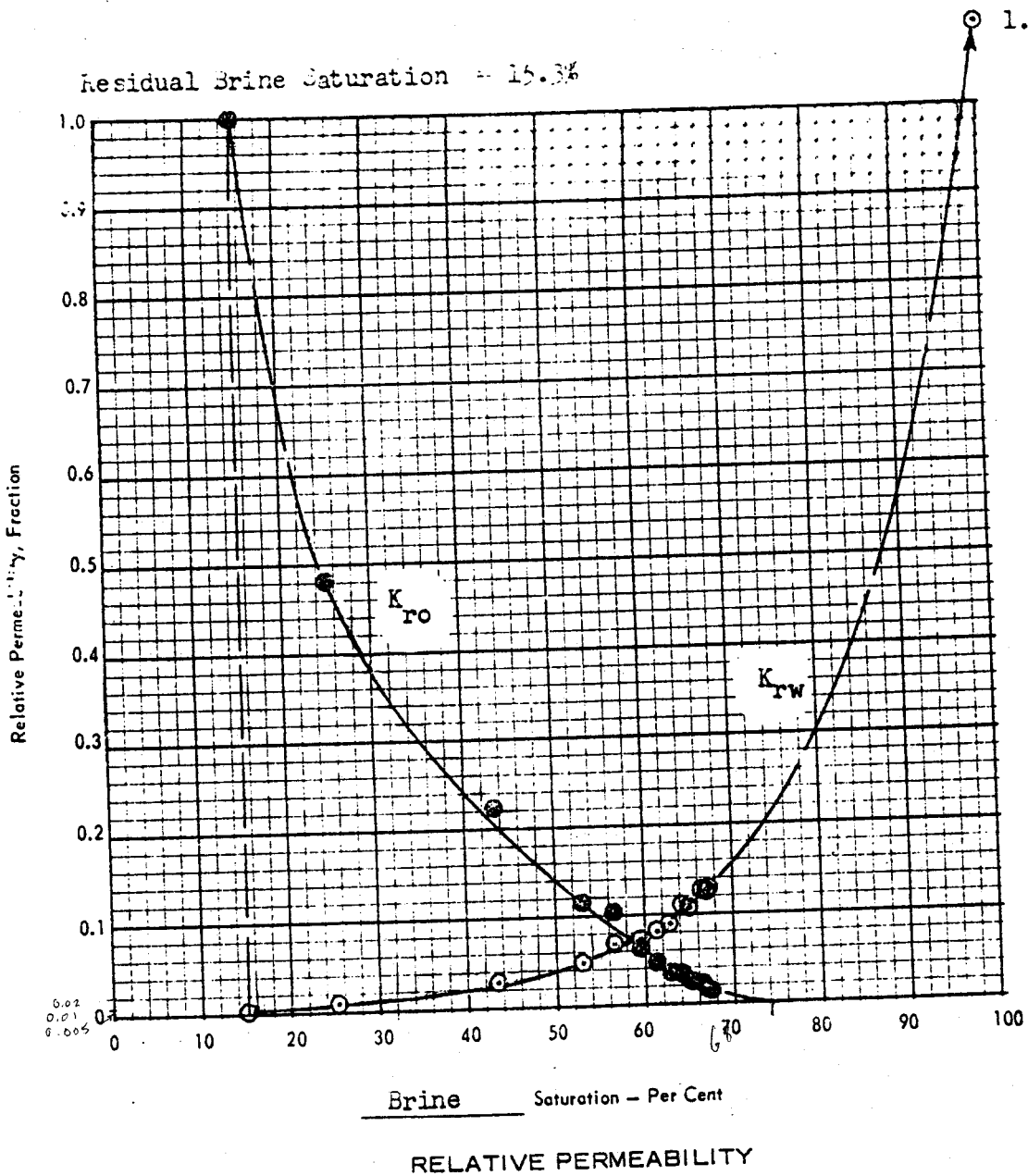
RELATIVE PERMEABILITY RATIO

Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	15	10,294.33	10,295.08	0.30*	24.8	Danian

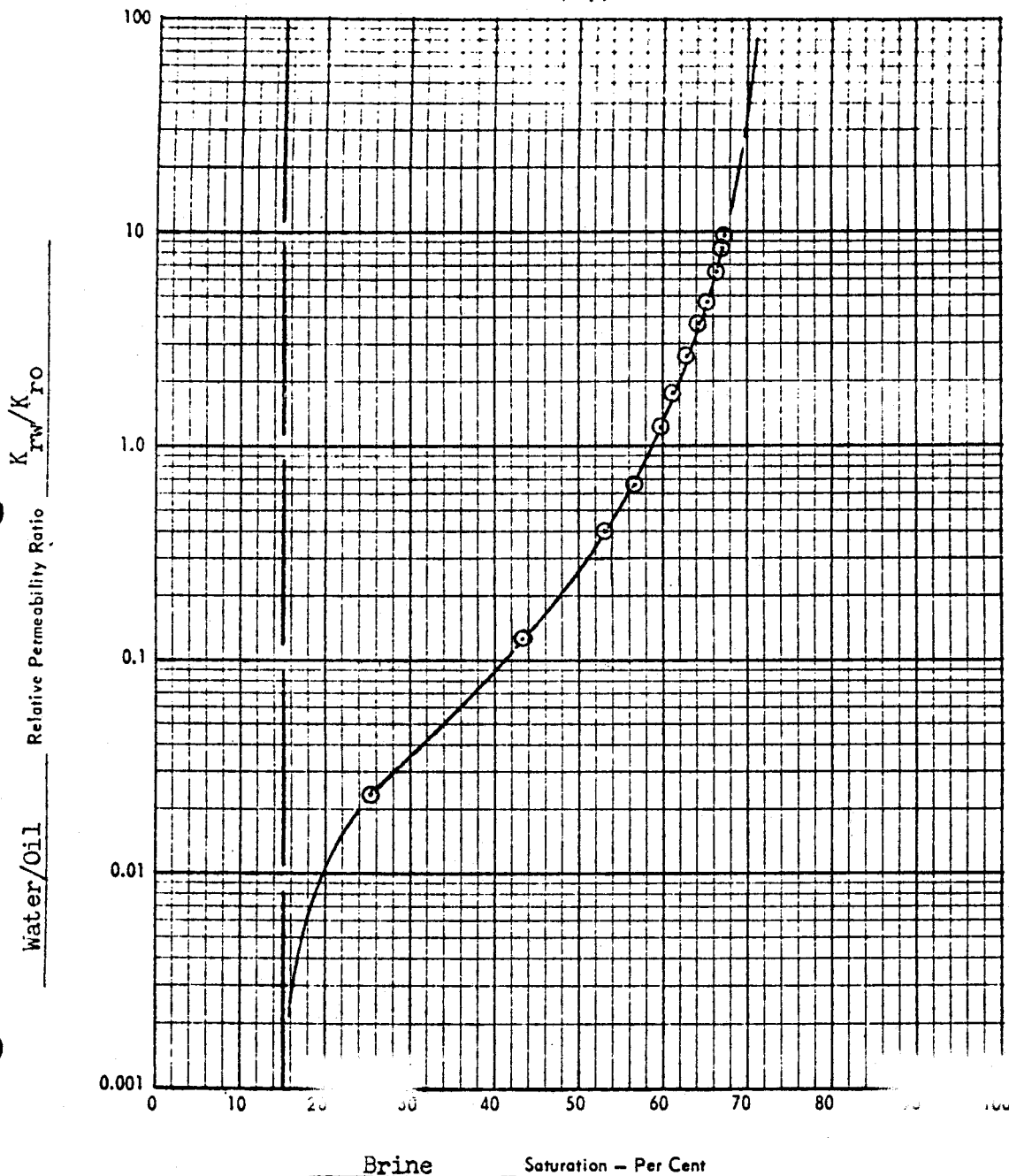
* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 1.10 and 0.35 md, respectively. The viscosities of the brine and oil were 1.205 and 23.68 centipoises, respectively.



Company	Phillips Petroleum		Lease	Torfelt 2/4		Well No.	8 AX	
Field	Torfelt		County	Norway Sector		State	North Sea	
Symbol	Sample No.	Depth, Feet		Permeability	Porosity	Formation		
		From	To	Millidarcys	Per Cent			
	16	10,332.66	10,333.33	0.79*	31.0	Danian		

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.14 and 0.86 md, respectively. The viscosities of the brine and oil were 1.212 and 24.01 centipoises, respectively.

Fig. 17 By Bailey, Buce & Kellogg Date 11-10-72



RELATIVE PERMEABILITY RATIO

Company Phillips Petroleum Lease Torfelt 2/4 Well No. 8 AX

Field Torfelt County Norway Sector State North Sea

Symbol	Sample No.	Depth, Feet		Permeability Millidarcys	Porosity Per Cent	Formation
		From	To			
	16	10,332.66	10,333.33	0.79*	31.0	Danian

* Effective permeability to oil with indicated residual brine present. The relative permeability is related to this effective permeability to oil. The specific permeabilities to gas and brine were 2.14 and 0.86 md, respectively. The viscosities of the brine and oil were 1.212 and 24.01 centipoises, respectively.

Fig. 18 By Sailey, Buce & Kellogg Date 11-10-72