

Denne rapport  
tilhører



L&U DOK.SENTER

L.NR. 30284210018

KODE well 31/2-4 nr. 19

Returneres etter bruk

January 1984

RKER.84.041

SATURATION EXPONENTS, WATER/TOLUENE  
CAPILLARY-PRESSURE CURVES AND RELATED  
PETROPHYSICAL PROPERTIES OF UNCONSOLIDATED  
CORE SAMPLES FROM WELL 31/2-4, NORWAY

by

F. van der Bas

co-authors: J.S. Visser and T.J. Borsboom

Sponsor: Shell Forus

Code: 774.20.160



This CONFIDENTIAL report is made available subject to the condition that the recipient will neither use or disclose the contents except as agreed in writing with the sponsoring party.

Copyright is vested in Shell Internationale Research Mij. B.V., The Hague.

KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM

RIJSWIJK, THE NETHERLANDS

(Shell Research B.V.)

SH01

P5.12.04-01

31/2-4

January 1984

RKER.84.041  
SATURATION EXPONENTS, WATER/TOLUENE  
CAPILLARY-PRESSURE CURVES AND RELATED  
PETROPHYSICAL PROPERTIES OF UNCONSOLIDATED  
CORE SAMPLES FROM WELL 31/2-4, NORWAY

by

F. van der Bas

co-authors: J.S. Visser and T.J. Borsboom  
Sponsor: Shell Forus Code: 774.20.160

Investigation 9.25.162

This **CONFIDENTIAL** report is made available subject to the condition that the recipient will neither use or disclose the contents except as agreed in writing with the sponsoring party.

Neither the whole nor any part of this document may be reproduced, stored in any retrieval system or transmitted in any form or by any means (electronic, mechanical, reprographic, recording or otherwise) without the prior written consent of the copyright owner.

Neither Royal Dutch Petroleum Company nor The "SHELL" Transport and Trading Company p.l.c. nor any company of the Royal Dutch/Shell Group will accept any liability for loss or damage originating from the use of the information contained therein.

Although **SHELL** companies have their own separate identities the expressions "SHELL" and "GROUP" are used for convenience to refer to companies of the Royal Dutch/Shell Group in general, or to one or more such companies as the context may require.

Copyright is vested in Shell Internationale Research Mij. B.V., The Hague.

**KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM**

**RIJSWIJK, THE NETHERLANDS**

(Shell Research B.V.)

CONTENTS

	<u>Page</u>
Summary	III
1. Introduction	1
2. Measurements and results	1
2.1 Saturation exponents	1
2.2 Water/toluene capillary-pressure curves	2
2.3 Related petrophysical properties	2
2.4 Cation exchange capacity	2
 References	
Table 1 Saturation exponents and related properties	
Figures 1-2 Clay-corrected resistivity ratio versus water saturation and water/toluene capillary pressure curve.	
Figure 3 Composite of resistivity index versus water saturation	
Figure 4 Formation resistivity factor versus porosity	
 Data listings of the calculation of saturation exponent and water/toluene capillary curve.	
 Appendix A. Details of various measuring methods	
Figure A1 Lay-out of equipment for establishing saturation exponents, lithological exponents and water/toluene capillary-pressure curves.	
Figure A2 Saturation exponent measuring cell.	

SUMMARY

The saturation exponents, lithological exponents and water/toluene capillary-pressure curves have been determined on four samples from well 31/2-4, Norway.

The average clay-corrected saturation exponent is 1.88 (range 1.79-2.06), and the average clay-corrected lithological exponent is 1.84 (range 1.56-1.95).

KEYWORDS

Norway, well 31/2-4, saturation exponent, lithological exponent, cation-exchange capacity, capillary pressure.

SATURATION EXPONENTS, WATER/TOLUENE  
CAPILLARY-PRESSURE CURVES AND RELATED PETROPHYSICAL  
PROPERTIES OF UNCONSOLIDATED CORE SAMPLES FROM  
WELL 31/2-4, NORWAY

1. INTRODUCTION

At the request of Shell Forus<sup>1</sup> we have determined the saturation exponents, lithological exponents and water/toluene capillary-pressure curves on four samples from well 31/2-4, Norway.

The samples were drilled from the frozen core and mounted in a special core holder. After thawing in the coreholder, the samples were cleaned by flushing with a chloroform/methanol/water mixture. After cleaning, the samples were partly saturated with brackish water, then frozen again before they were taken out of the core holder and mounted in the measuring cell.

2. MEASUREMENTS AND RESULTS

2.1 Saturation exponents

After thawing in the measuring cell the saturation exponent measurements were carried out, as described in Appendix A, at an isostatic stress of 70 bar and a temperature of 21.5°C. The water used contained 73 g NaCl per litre; water resistivity was 0.1 ohm m.

The results, corrected for the contribution of clay to conductivity by applying the Waxman-Smits<sup>2</sup> equation as described by Waxman and Thomas<sup>3</sup>, are presented in Figs. 1-2 as plots of clay-corrected resistivity ratio ( $I^*$ ) versus water saturation ( $S_w$ ). A composite plot of all clay-corrected data points is given in Fig. 3. The clay corrected saturation exponent ( $n^*$ ) for each sample, calculated from the slope of a line, obtained by linear regression of  $\log(I^*)$  versus  $\log(S_w)$  (all data points, including  $I^* = 1, S_w = 1$ ), is given in Table 1. The uncorrected saturation exponents ( $n$ ) are also given.

## 2.2. Water/toluene capillary-pressure curves

The water/toluene capillary-pressure curves were determined together with the saturation exponent as described in Appendix A. Plots of the measured points of the curves are also given in Figs. 1-2.

## 2.3 Related petrophysical properties

Porosity ( $\phi_{70}$ ), clay-corrected formation-resistivity factor ( $F^*$ ) and lithological exponent ( $m^*$ ) were determined under experimental conditions. A plot of  $F^*$  versus  $\phi_{70}$  is given in Fig.4. The results of the above measurements and the grain density (GD) are also presented in Table 1.

## 2.4 Cation exchange capacity

The cation exchange capacity ( $Q_v$ ) given in Table 1 was obtained by the wet-chemistry method.

## REFERENCES

1. Telex for 140822 dated 14-8-81 from Shell Forus, Norway, to KSEPL, Rijswijk.
2. Waxman, M.H. & Smits, L.J.M., Electrical conductivities in oil-bearing shaly sands. SPE Journal, 8 (1968) p.107.
3. Waxman, M.H. & Thomas, E.G., Electrical conductivity in shaly sands.
  - I - The relation between hydrocarbon saturation and resistivity index
  - II - The temperature coefficient of electrical conductivity. SPE 4094, 1972.

KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM  
Saturation Exponent Analysis

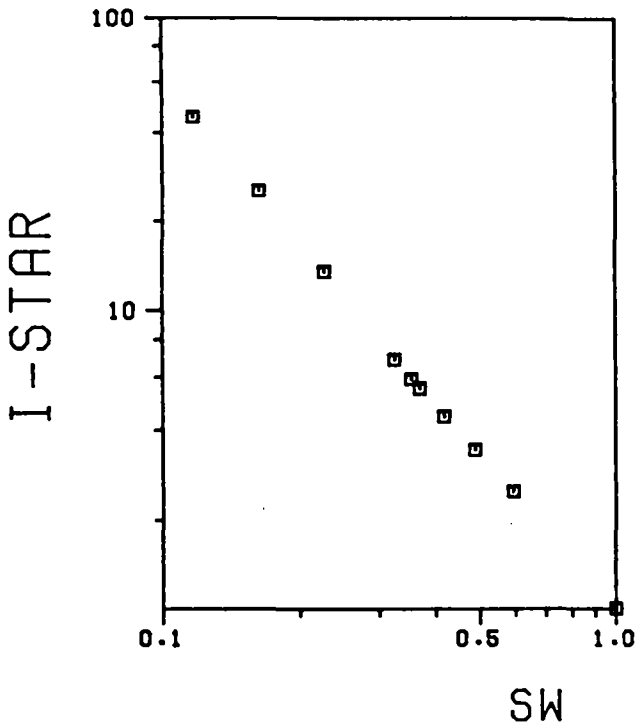
Table 1 - Saturation Exponents and Related Properties

Well Name: 31/2-4

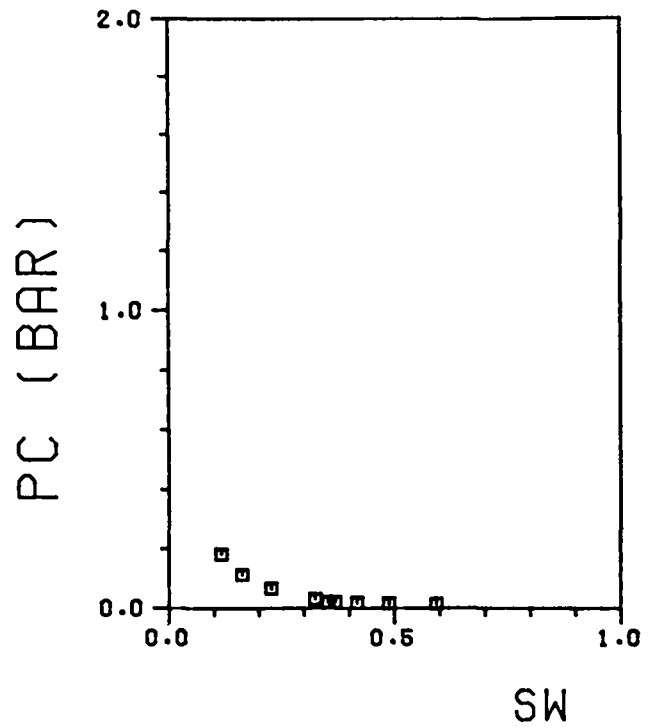
Sample No.	D	Phi (70B)	Phi (1B)	k	GD	Qv	F*	m	m*	n	n*
N1	1451.07	.353	---	---	2.63	0.02	5.1	1.55	1.56	1.77	1.79
N2	1570.40	.259	---	---	2.66	0.14	14.0	1.92	1.95	1.79	1.86
N3	1578.72	.334	---	---	2.66	0.03	7.2	1.79	1.80	2.03	2.06
N4	1624.14	.234	---	---	2.69	0.15	16.6	1.90	1.94	1.76	1.82

where:

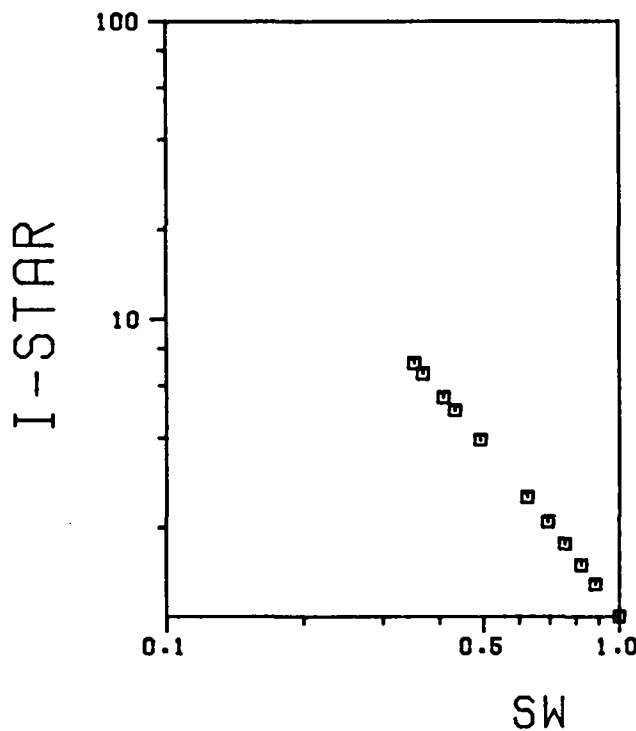
D	=	depth in meters
Phi (70 Bar)	=	porosity under experimental conditions as a fraction of Vb
Phi (1 Bar)	=	porosity under standard conditions as a fraction of Vb
k	=	air permeability in mD
GD	=	grain density in g/ml
Qv	=	cation-exchange capacity in meq/ml
F*	=	clay-corrected formation resistivity factor
m	=	lithological exponent
m*	=	clay-corrected lithological exponent
n	=	saturation exponent
n*	=	clay-corrected saturation exponent



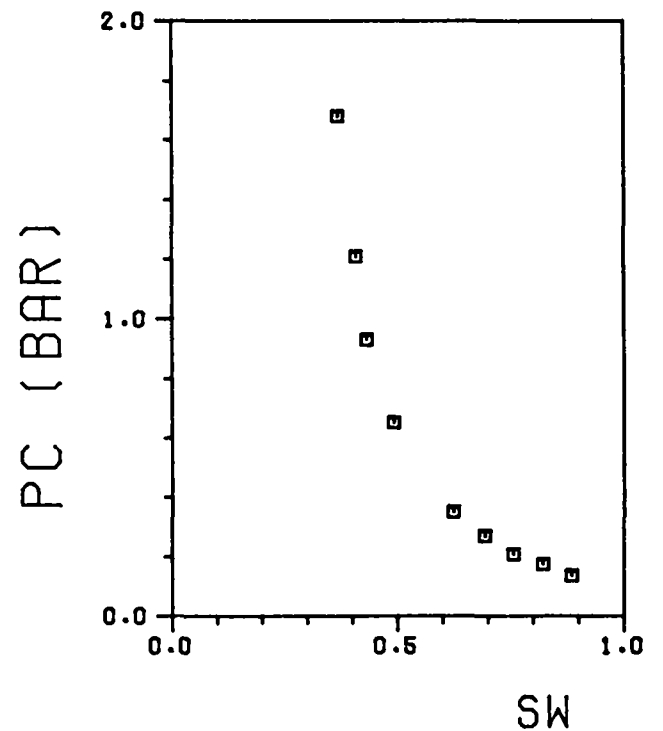
31/2-4  
SAMPLE NO. N1



31/2-4  
SAMPLE NO. N1      POR.=0.35



31/2-4  
SAMPLE NO. N2

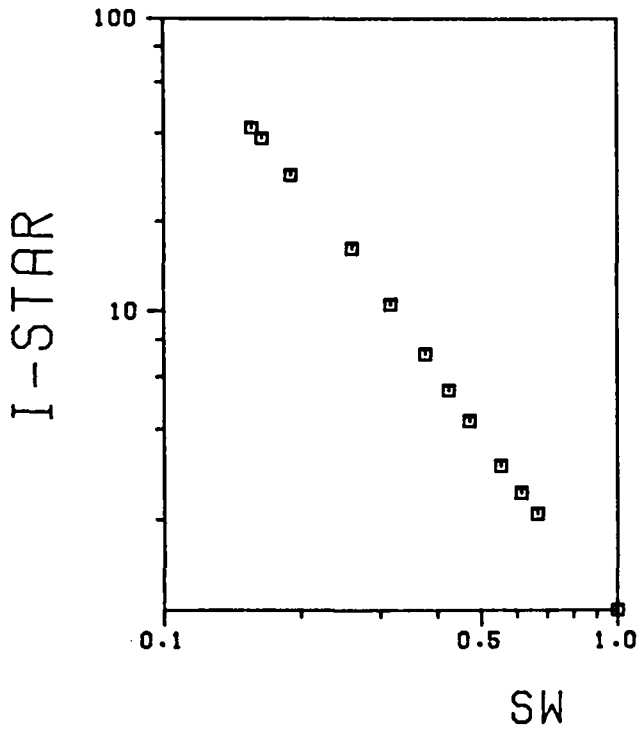


31/2-4  
SAMPLE NO. N2      POR.=0.26

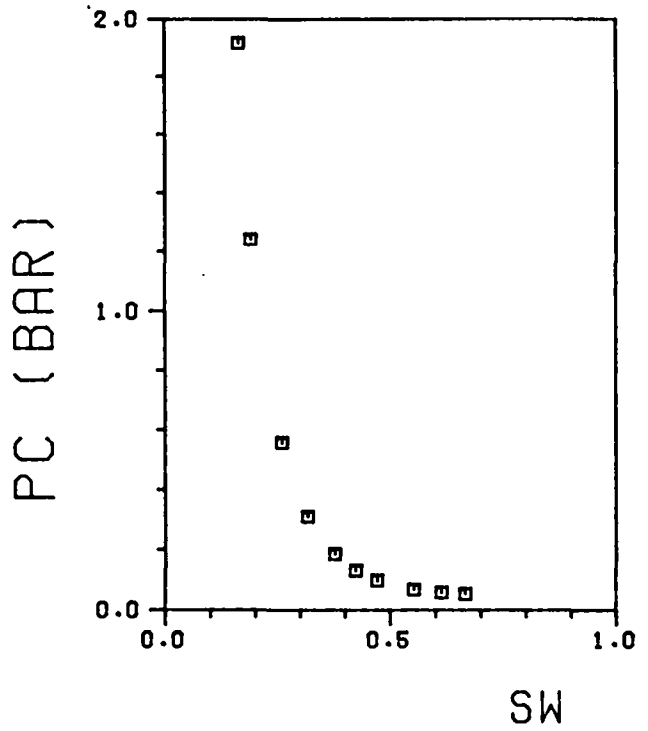
CLAY-CORRECTED RESISTIVITY RATIO VERSUS WATER SATURATION AND  
WATER/TOLUENE CAPILLARY PRESSURE CURVE

FIG. 1

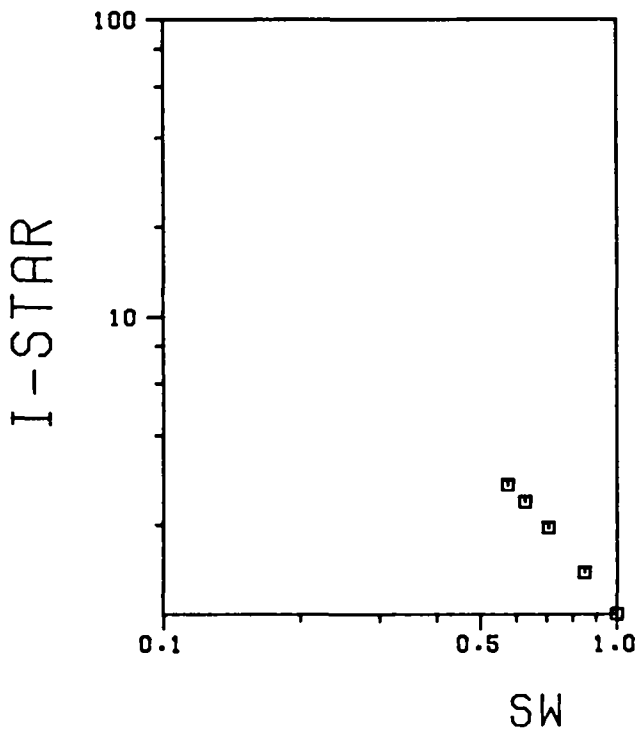




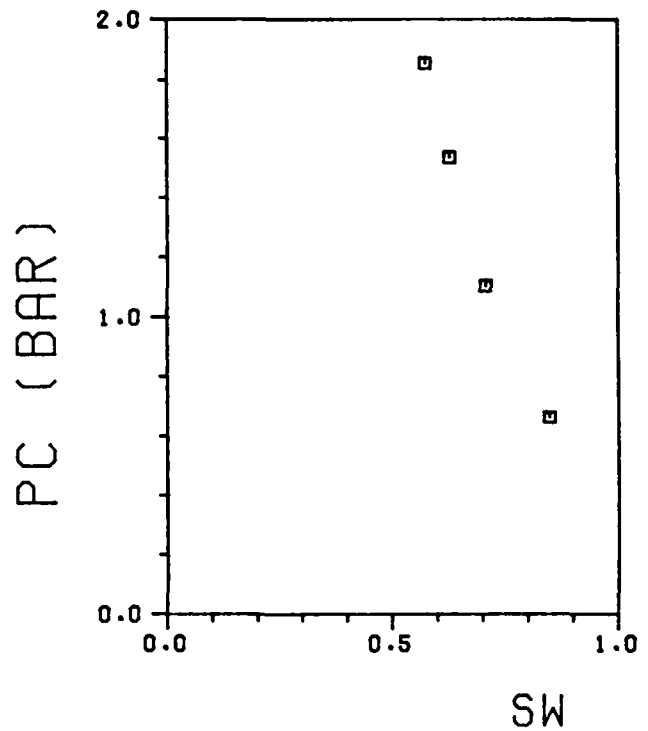
31/2-4  
SAMPLE NO.N3



31/2-4  
SAMPLE NO.N3      POR.=0.33



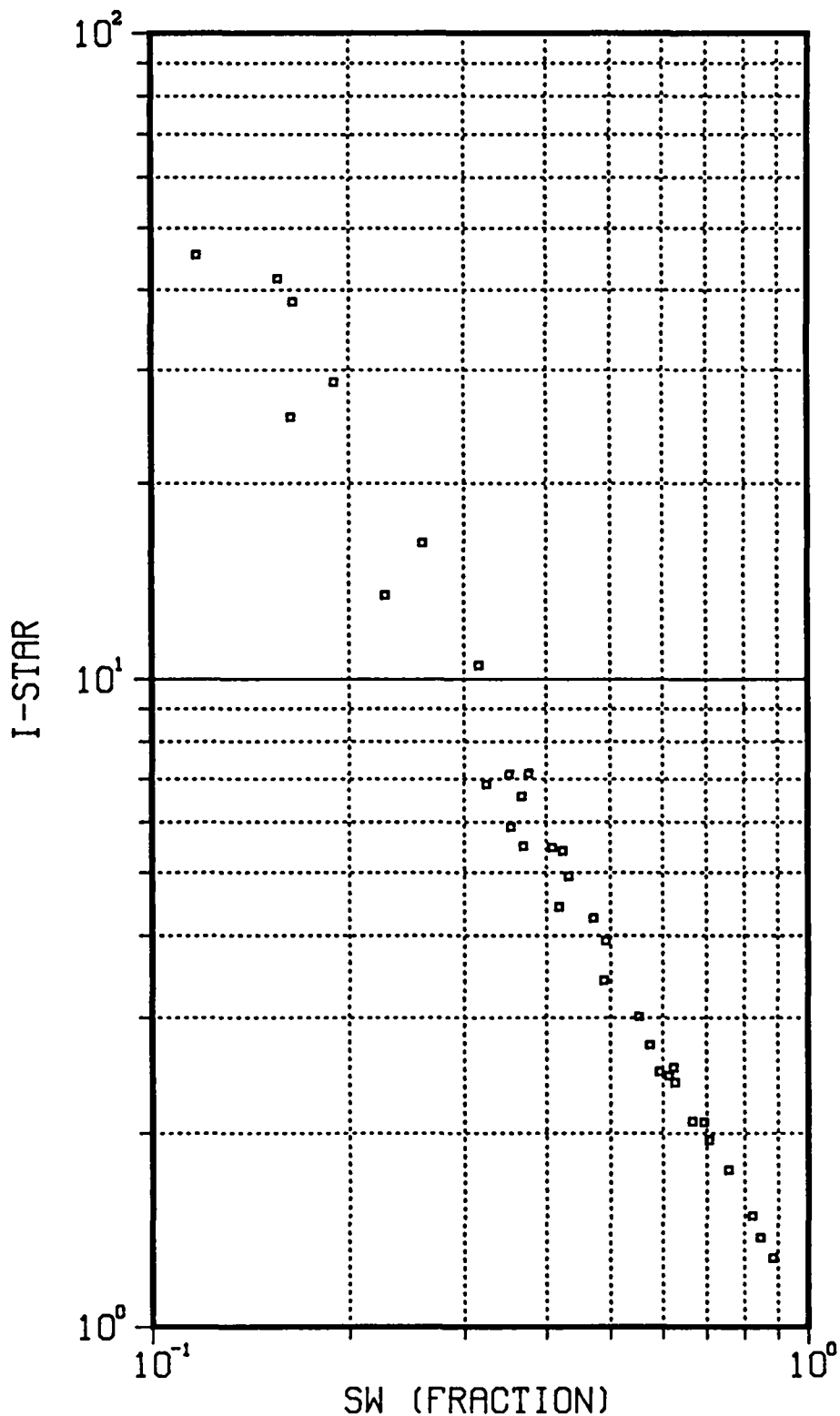
31/2-4  
SAMPLE NO.N4



31/2-4  
SAMPLE NO.N4      POR.=0.23

CLAY-CORRECTED RESISTIVITY RATIO VERSUS WATER SATURATION AND WATER/TOLUENE CAPILLARY PRESSURE CURVE

FIG. 2



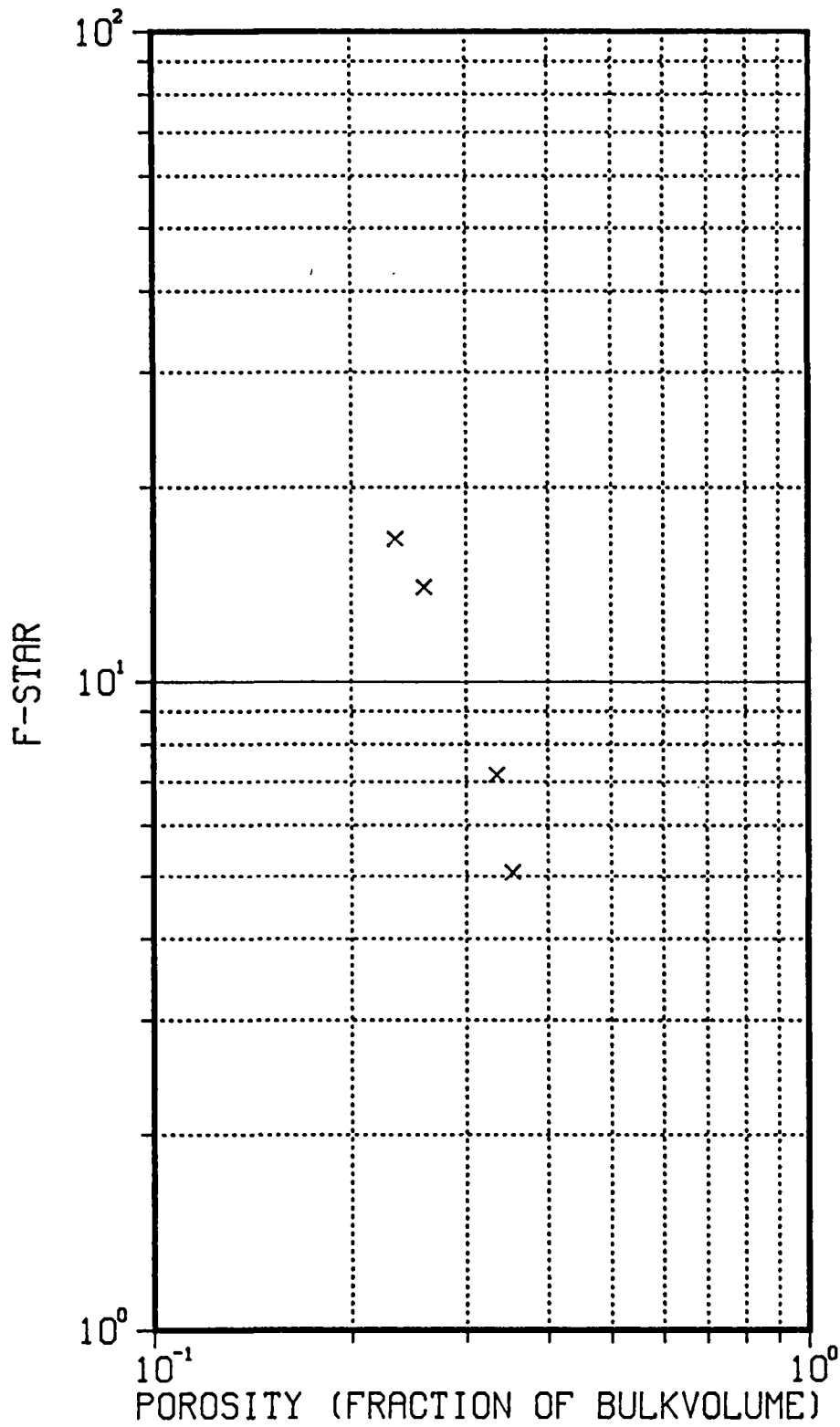
COMPOSITE OF  
RESISTIVITY INDEX VERSUS WATER SATURATION

WELL : 31/2-4

RKER 84.041

AUTHOR:  
DESIGN:

FIG.3



FORMATION RESISTIVITY FACTOR VERSUS POROSITY  
AT AN ISOSTATIC PRESSURE OF 70 BAR

WELL : 31/2-4

AUTHOR:  
DESIGN:

RKER 84.041

FIG. 4

KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM  
 Calculation of Saturation Exponent and Water-Toluene Capillary Curve

-----  
 Drainage Cycle

Well Name: 31/2-4

Sample No: N1

Depth: 1451.07 meters

Qv: .02 meq/ml

R0: 52.7 ohm cm

R0\*: 53.0 ohm cm

Rw: 10.47 ohm cm

Salinity: 73.0 g/ltr

B-factor: 3.23 ml/ohm meq m

No.	Sw	Pc (Bar)	rt (ohm)	I	n	rt* (ohm)	I*	n*
1	1.000	0.000	35.5	1.00	---	35.8	1.00	---
2	0.593	0.014	87.9	2.47	1.73	88.9	2.48	1.74
3	0.488	0.015	120.6	3.39	1.71	122.4	3.42	1.72
4	0.418	0.018	155.8	4.38	1.69	158.4	4.43	1.71
5	0.369	0.020	192.8	5.43	1.70	196.5	5.49	1.71
6	0.353	0.022	206.9	5.82	1.69	211.0	5.90	1.71
7	0.325	0.031	240.4	6.77	1.70	245.6	6.86	1.71
8	0.228	0.066	467.7	13.17	1.74	482.3	13.48	1.76
9	0.163	0.112	868.7	24.45	1.76	906.5	25.33	1.78
10	0.117	0.182	1531.5	43.11	1.76	1624.3	45.40	1.78

Porosity(70 Bar) : .353

F = 5.0      m = 1.55      F\* = 5.1      m\* = 1.56

\*\*\* Equilibrium Points Only \*\*\*

Saturation Exponent

Clay-Corrected Saturation Exponent

n = 1.77    corr.coeff. = .99965

n\* = 1.79    corr.coeff. = .99957

KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM  
 Calculation of Saturation Exponent and Water-Toluene Capillary Curve

-----  
 Drainage Cycle

Well Name: 31/2-4

Sample No: N2

Depth: 1570.40 meters

Qv: .14 meq/ml

R0: 140.2 ohm cm

R0\*: 146.6 ohm cm

Rw: 10.47 ohm cm

Salinity: 73.0 g/ltr

B-factor: 3.23 ml/ohm meq m

No.	Sw	Pc (Bar)	rt (ohm)	I	n	rt* (ohm)	I*	n*
1	1.000	0.000	108.1	1.00	---	113.0	1.00	---
2	0.884	0.137	137.9	1.28	1.99	145.1	1.28	2.03
3	0.822	0.175	159.9	1.48	1.99	168.7	1.49	2.04
4	0.756	0.209	187.4	1.73	1.97	198.8	1.76	2.02
5	0.693	0.270	220.8	2.04	1.95	235.3	2.08	2.00
6	0.624	0.351	265.5	2.46	1.90	284.9	2.52	1.96
7	0.492	0.651	406.4	3.76	1.87	444.1	3.93	1.93
8	0.432	0.930	504.5	4.67	1.84	557.8	4.94	1.90
9	0.408	1.209	555.3	5.14	1.83	617.4	5.46	1.90
10	0.368	1.679	660.8	6.12	1.81	742.8	6.57	1.88
11	0.352	2.059	711.8	6.59	1.80	804.2	7.12	1.88

Porosity(70 Bar) : .259

F = 13.4      m = 1.92      F\* = 14.0      m\* = 1.95

\*\*\* Equilibrium Points Only \*\*\*

Saturation Exponent

Clay-Corrected Saturation Exponent

n = 1.79    corr.coeff.= .99960

n\* = 1.86    corr.coeff.= .99974

KONINKLIJKE/SHELL EXPLORATIE EN PRODUCTIE LABORATORIUM  
 Calculation of Saturation Exponent and Water-Toluene Capillary Curve

-----  
 Drainage Cycle

Well Name: 31/2-4

Sample No: N3

Depth: 1578.72 meters

Qv: .03 meq/ml

R0: 74.4 ohm cm

R0\*: 75.1 ohm cm

Rw: 10.47 ohm cm

Salinity: 73.0 g/ltr

B-factor: 3.23 ml/ohm meq m

No.	Sw	Pc (Bar)	rt (ohm)	I	n	rt* (ohm)	I*	n*
1	1.000	0.000	55.0	1.00	---	55.5	1.00	---
2	0.665	0.052	114.2	2.08	1.79	115.9	2.09	1.81
3	0.613	0.058	133.8	2.43	1.82	135.9	2.45	1.83
4	0.553	0.067	164.5	2.99	1.85	167.4	3.02	1.86
5	0.471	0.098	231.5	4.21	1.91	236.3	4.26	1.92
6	0.423	0.131	293.0	5.33	1.95	299.8	5.40	1.96
7	0.376	0.186	386.2	7.03	1.99	396.3	7.14	2.01
8	0.316	0.310	565.6	10.29	2.02	583.2	10.51	2.04
9	0.259	0.556	866.5	15.77	2.04	899.3	16.20	2.06
10	0.190	1.240	1515.5	27.57	2.00	1593.7	28.72	2.02
11	0.164	1.916	2006.5	36.51	1.99	2126.5	38.32	2.02
12	0.156	2.088	2175.2	39.58	1.98	2312.2	41.66	2.01

Porosity(70 Bar) : .334

F = 7.1      m = 1.79      F\* = 7.2      m\* = 1.80

\*\*\* Equilibrium Points Only \*\*\*

Saturation Exponent

Clay-Corrected Saturation Exponent

n = 2.03    corr.coeff.= .99935

n\* = 2.06    corr.coeff.= .99933

KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM  
 Calculation of Saturation Exponent and Water-Toluene Capillary Curve

-----  
 Drainage Cycle

Well Name: 31/2-4

Sample No: N4

Depth: 1624.14 meters

Qv: .15 meq/ml

R0: 165.3 ohm cm

R0\*: 174.0 ohm cm

Rw: 10.47 ohm cm

Salinity: 73.0 g/ltr

B-factor: 3.23 ml/ohm meq m

No.	Sw	Pc (Bar)	rt (ohm)	I	n	rt* (ohm)	I*	n*
1	1.000	0.000	128.3	1.00	---	135.0	1.00	---
2	0.847	0.663	175.7	1.37	1.89	186.5	1.38	1.94
3	0.706	1.105	245.8	1.92	1.87	263.9	1.96	1.92
4	0.626	1.535	298.0	2.32	1.80	322.8	2.39	1.86
5	0.574	1.854	338.0	2.63	1.74	368.7	2.73	1.81

Porosity(70 Bar) : .234

F = 15.8      m = 1.90      F\* = 16.6      m\* = 1.94

\*\*\* Equilibrium Points Only \*\*\*

Saturation Exponent

Clay-Corrected Saturation Exponent

n = 1.76    corr.coeff.= .99892

n\* = 1.82    corr.coeff.= .99910

APPENDIX ADETAILS OF VARIOUS MEASURING METHODSDetermination of saturation exponent and lithological exponent

Figure A1 shows the lay-out of the equipment in which the saturation exponents are measured. In Fig. A1, 1 is the measuring cell, which will be described later; 2 is a burette containing the brine solution with which a sample is saturated at the beginning of the experiment; 3 is a brine-storage vessel and 4 a vessel which can be evacuated before the brine is introduced to de-aerate the brine solution. The lower part of vessel 5 is filled with oil, the upper part with nitrogen. By means of nitrogen, a pressure up to  $150 \text{ kg/cm}^2$  can be built up in the oil to pressurize the sample. The mercury column (6), which can have a maximum height of 200 cm, is intended to force toluene contained in the upper part of the storage vessel (7) into the sample. Burette 9 collects the salt water expelled from the sample by the toluene.

Figure A2 shows the measuring cell in detail. The sample (15) is surrounded by a rubber sleeve (16), which is pressed against the sample by the oil pressure in the compartment 17. The sample is placed between two platinum electrodes (18 and 19). Between the lower electrode and the sample there is a filter (20), which is permeable to brine and impermeable to toluene. In order to achieve proper capillary contact, several tissue papers are placed between the sample and the electrodes. During the experiment the tissues will always contain some water.

When an experiment is started the capillary (11) is inserted into the capillary insertion point (12) and the sample and compartment 4 are evacuated by a vacuum pump, connected to the system at 13. It takes about four hours to reach a pressure in the sample of less than 0.04 torr. Next, valve 13 is closed and brine de-aerated in compartment 4. The salt water is supplied to burette 2, and then the sample is saturated with water through capillary 11.



The amount of water supplied to the sample and the rest of the system beyond valve 13 can be read from the water level in the burette 2. In a blank run, the volume of water necessary for saturating the system, except for the sample, is measured (approx. 1.50 ml). Subtracting this volume from the total volume measured in a run with the sample gives the pore volume  $V_{\text{pore}}$  (approx. 4 ml).

Subsequently, the capillary 11 is disconnected from 12 and connected to the burette 9. The resistance is then measured; this is the resistance of the 100% water-saturated sample,  $r_0$ . From  $r_0$ , dry weight ( $W$ ), pore volume ( $V_p$ ), grain density ( $GD$ ) and length ( $L$ ) of the sample, the resistivity,  $R_0$ , can be calculated according to  $R_0 = r_0 \left( \frac{W}{GD} + V_p \right) / L^2$ , where  $\left( \frac{W}{GD} + V_p \right)$  is the bulk volume ( $V$ ) under experimental stress conditions. From these data and the porosity (under stress conditions), the lithological exponent ( $m$ ) can be calculated according to Archie's equation:

$F = \phi^{-m}$ , where the formation resistivity factor ( $F$ ) is given by:

$$F = R_0 / R_W \quad (R_W \text{ is the resistivity of the brine})$$

Subsequently, the water is expelled from the sample by the toluene, which is forced through capillary 10 into the sample by the mercury column 6. The latter is increased step by step. The water produced at each step ( $V_{\text{prod}}$ ) is collected in the burette 9. At each step, resistance of the sample now saturated partly with brine and partly with toluene,  $V_{\text{prod}}$ , and the height of the mercury column are measured.

These values are corrected for the resistance and the production of the tissues, as measured in the blank run. From the relationship between resistivity ratio  $I (= R_t / R_0)$  and water saturation  $S_W (= (V_{\text{pore}} - V_{\text{prod}}) / V_{\text{pore}})$  the saturation exponent,  $n$ , is determined according to  $I = S_W^{-n}$ .

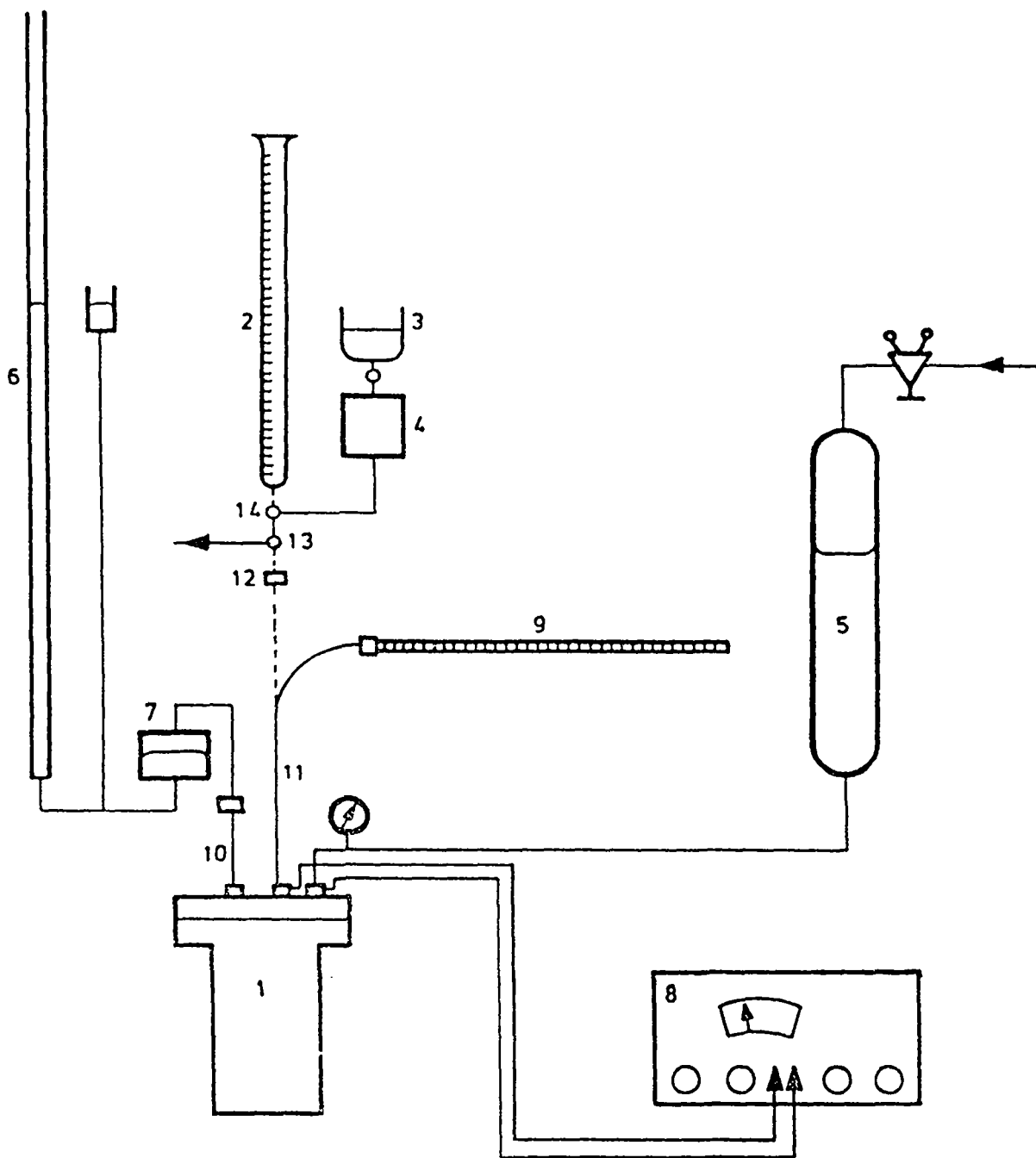


Fig. A-1 LAY-OUT OF EQUIPMENT FOR ESTABLISHING SATURATION EXPONENTS, LITHOLOGICAL EXPONENTS AND WATER / TOLUENE CAPILLARY - PRESSURE CURVES.

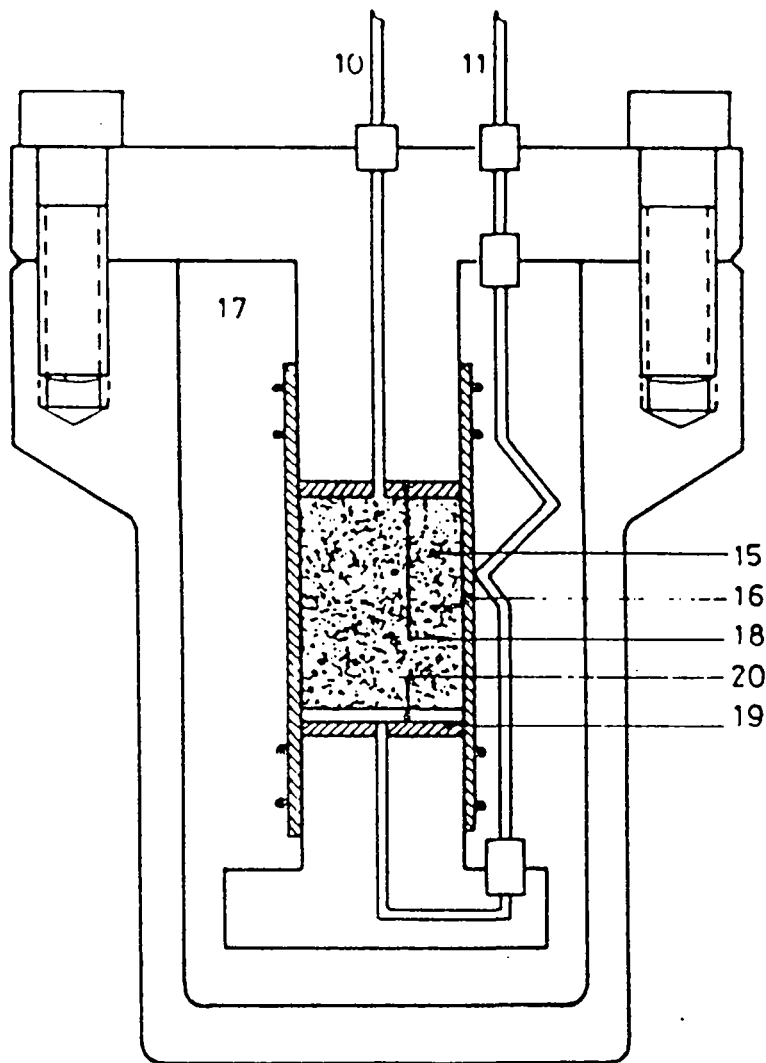


Fig. A-2 SATURATION EXPONENT MEASURING CELL

Author vBa  
Drawn

Di.nr. 35672<sup>F</sup>

FIG. A-2

RKER 84.041

LEGEND TO FIGURES A1 AND A2

1. Saturation-exponent measuring cell
2. Burette
3. Brine-storage vessel
4. Compartment for de-aeration of brine
5. Oil vessel
6. Mercury column
7. Mercury/toluene storage vessel
8. Device for measuring resistance
9. Burette
10. Capillary
11. Capillary
12. Capillary insertion point
13. Connection to vacuum pump
14. Valve
15. Sample
16. Sleeve
17. Oil pressure compartment
18. Electrode
19. Electrode
20. Semi-permeable filter

INITIAL DISTRIBUTION

14 copies

SIPM the Hague