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ONE WELL STUDY ON

31/2-5

AUGUST 1981

LARS RØSSLAND

Den norske stats oljeselskap a.s

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LIST OF TABLES

INTRODUCTION

This is a preliminary report on a one well study performed on the geological/petrophysical model for the 31/2-5 well.
The main object has been to study the short time behaviour (well-test time) and to evaluate what variables that are important for the well/field performance. The first part of this work was a study of the pressure respons expected for a thin oil zone between a gas cap and aquifer. The pressure respons for this three phase system has been compared to

a) Partially penetrated well in a thin oil zone
b) Partially penetrated well in a thin oil zone in pressure communication with an aquifer
c) Partially penetrated well in a thin oil zone in pressure communication with the gas cap

Few data existed at the time this study was performed and a number of sensitivity cases were run to look upon the effect of the different variables and how important these were for the short and long time reservoir behaviour. Sensitivities were run on the following parameters.

a) Relative permeability
b) Horisontal permeability
c) Vertical permeability
d) Drainage radius
e) Location of perforation interval
f) Barriers

The zone that contain the oil column is unconsolidated and it was therefore difficult to obtain conventional core plugs. With this background it was therefore choosen to look carefully upon the importance of the data obtained from core plugs. This is reflected in sensitivity cases a, b and c.
The sensitivity case on drainage radius was to give an indication of the recovery that can be expected for the 31/2-5 geometry (geologi) as a function of number of wells.
Three locations within the oil column was used for case e. In addition a case was run with the perforation in the water zone and one with a double completion where both the oil and gas zone were produced.

The well log indicate that there are a number of vertical permeability "barriers". There are no final geological interpretation that tell that these calcite cemented regions are local or extencive barriers. In the base case model these regions were neglected but som cases were run with limited barriers to see their effect upon the reservoir/well performance.

1. MODELDESCRIPTION

1.1 Geological model.

The 31/2-5 well was divided into two zones for use in this study. The upper zone (see Fig. 1) has some mica sand intervals interbedded in loose sand. (1530 - 1564 m RKB). The lower zone (1564 - 1616 m RKB) is a homogeneous loose sand that contain a number of calcite cemented "regions" of unknown areal extent. The calcite cemented zone located at 1616 m RKB (see log Fig. 1) was assumed as a continous barrier. The top of the hydrocarbon column is at 1536 m with GOC at 1578 m and OWC at 1601 m RKB.

1.2 Petrophysical data.

The zonation that was described in the previous chapter was used. Only a very limited number of plugs were taken in the interval of interest. Therefor a correlation between the different wells[(1)] were used and data from the comparabel zones in the different wells were used for comparison. The data obtained are given in Table 1.

Table 1 Average Permeability from Well 1, 2, 3, 5 for Zone 1 and 2.

Well	Permeability				kv/kh	
	Zone 1	Zone 2	1	2	1	2
5	2400	9900*	1545-1565.5	1565-1614.74	1.16/0.60**	0.51
3		6200		1448-1480		.72
2		6000***		1631-1642		.30
1		11500		1477-1488		.59

* Excluded data in the interval 1601 - 1603 m RKB (see log Fig. 1). These were assumed not to be representative for the interval. Also excluded data near and within the calcite cemented nodules(?)

** There was one core plug with a very high vertical permeability. If this measurement is excluded the lower value is the average value.

*** Excluded data near and within the calcite cemented area.

Zone 1 has limited influence on the reservoir performance when the production is from the oil zone, such that the data from zone 2 are the more important.
Table 2 give the average petrophysical data used in the model.

Table 2. Average Petrophysical Data for the 31/2-5 Model.

Zone	$\overline{K}$ (md)	$\overline{Ø}$	$\overline{N/G}$	$\overline{Sw}$
1	2500	.306	0.76	.064
2	9000	.310	0.90	.031*

* Sw from the interval 1580 - 1585 m RKB

1.3 PVT-data.

At the time this study was performed, only the oil density from one RFT sample was available. A fluid analysis program[2] by correlation techniques was used to estimate the PVT data.

Input data:

Solids in water	:	70000 PPM	
Reservoir temperature	:	125^{o}F	
Reservoir pressure	:	2291 psig	
Separator gas gravity	:	.610	(from 31/2-3)
Separator pressure	:	270 psig	"
Separator temperature	:	60^{o}F (assumed)	

Composition of gas from 31/2-3

The results are given in Tables 3 to 5.

31/2-5
PVT CORRELATION
GAS DATA RFT 14.1 31/2-1

DATE: 01/29/81
TIME: 07:20CST
FILE: LRPVT

O I L   P V T   P R O P E R T I E S

CORRELATION TECHNIQUE

PO PSIG	FVF RVB/STB	RS SCF/STB	DENSITY LBS/CF	FVF-T RVB/STB	VISO CP
15.	1.027	0.	52.98	38.802	6.407
290.	1.039	41.	52.71	4.245	5.599
580.	1.058	96.	52.20	2.393	4.629
870.	1.076	142.	51.68	1.809	3.929
1160.	1.099	195.	50.96	1.520	3.216
1450.	1.119	245.	50.44	1.361	2.890
1740.	1.137	293.	50.01	1.266	2.624
2030.	1.155	341.	49.57	1.207	2.378
2291.	1.171	384.	49.17	1.171	2.171
2610.	1.170	384.	49.17	1.170	2.221
2900.	1.168	384.	49.17	1.168	2.266
2291.	1.171	384.	49.17	1.171	2.171

GAS GRAVITY	:	0.610	(AIR=1.0)
OIL GRAVITY	:	30.5	DEG. API
SEPARATOR PRESSURE	:	270.	PSIG
TEMPERATURE	:	60.	DEG. F.
RESERVOIR TEMPERATURE	:	125.	DEG. F.
SEPARATOR SOLUTION GAS	:	43.	SCF/STB
BUBBLE-POINT PRESSURE	:	2291.	PSIG
GAS-OIL RATIO	:	384.	SCF/STB
OIL COMP.	:	9.0	B/MMB/PSI
GAS FVF	:	1.077	RVB/MSCF

Table 3. Oil PVT Properties for 31/2-5

31/2-5
PVT CORRELATION
GAS DATA RFT 14.1 31/2-1

DATE: 01/29/81
TIME: 07:20CST
FILE: LRPVT

G A S P V T P R O P E R T I E S

CORRELATION TECHNIQUE

PRESSURE PSIG	Z-FACTOR	VISCOSITY CP	GASFAC SCF/RCF	FVF RVB/MSCF	CG B/MMB/PSI
15.	0.9925	0.0122	1.8	98.4303	33670.0
290.	0.9669	0.0124	19.1	9.3466	3390.8
580.	0.9374	0.0128	38.4	4.6426	1785.9
870.	0.9105	0.0133	58.8	3.0311	1227.0
1160.	0.8867	0.0139	80.2	2.2233	936.6
1450.	0.8670	0.0146	102.2	1.7433	752.8
1740.	0.8518	0.0154	124.7	1.4299	621.2
2030.	0.8419	0.0162	147.0	1.2128	519.0
2291.	0.8377	0.0171	166.6	1.0700	443.5
2610.	0.8383	0.0182	189.5	0.9408	367.2
2900.	0.8442	0.0192	209.0	0.8530	310.3
2291.	0.8377	0.0171	166.6	1.0700	443.5

WELL-STREAM GAS GRAVITY : 0.610 (AIR=1.0)
STOCK-TANK LIQUID GRAVITY : 31. DEG. API
MEASUREMENT PRESSURE BASE : 14.70 PSIA
RESERVOIR TEMPERATURE : 125. DEG. F.

BUBBLE-POINT(OR INITIAL) PRESSURE : 2291. PSIG
GOR : 384. SCF/STB
DENSITY : 7.698 LBS/CF

Table 4. Gas PVT Properties for 31/2-5

31/2-5
PVT CORRELATION
GAS DATA RFT 14.1 31/2-1

DATE: 01/29/81
TIME: 07:20CST
FILE: LRPVT

W A T E R   P V T   P R O P E R T I E S

CORRELATION TECHNIQUE

P PSIG	DENS LBS/CF	FVF RVB/STB	FVF+GAS RVB/STB	SOL.GAS SCF/STB	LIB.GAS SCF/STB	CP B/MMB/PSI	%14CW+G
15.	64.621	1.012	1.066	0.2	9.6	2.91	37.26
290.	64.647	1.011	1.040	2.0	7.7	3.00	56.67
580.	64.676	1.011	1.029	3.8	6.0	3.09	24.92
870.	64.708	1.010	1.022	5.1	4.7	3.18	24.14
1160.	64.735	1.010	1.017	6.3	3.5	3.23	13.47
1450.	64.759	1.009	1.013	7.4	2.4	3.25	9.53
1740.	64.785	1.009	1.011	8.3	1.5	3.27	6.62
2030.	64.812	1.009	1.009	9.1	0.6	3.28	4.77
2291.	64.838	1.008	1.008	9.8	0.	3.29	3.29
2610.	64.906	1.007	1.007	9.8	0.	3.28	3.28
2900.	64.968	1.006	1.006	9.8	0.	3.28	3.28
2291.	64.838	1.008	1.008	9.8	0.	3.29	3.29

TOTAL DISSOLVED SOLIDS	:	70000.	PPM
RESERVOIR TEMPERATURE	:	125.	DEG. F.
RESERVOIR POROSITY	:	30.6	PERCENT
BUBBLE-POINT	:	2291.	PSIG
BRINE VISCOSITY	:	0.653	CP.
ROCK COMPRESSIBILITY	:	3.150	B/MMB/PSI

Table 5. Water PVT Properties for 31/2-5

2. PRESSURE RESPONS FOR A THREE PHASE CONING SYSTEM

2.1 Introduction

The system that is present in the well 31/2-5 is very complicated when it comes to test analysis (analysis by standard techniques). This is because a number of complicating factors are present. The standard pressure (rate) respons analysis is based on a slightly compressibel fluid in an infinite reservoir with a constant thickness were the whole interval is perforated. The factors that have to be taken into consideration in this case are:

a) Partial penetration
b) Free gas in the oil zone
c) Pressure support from the aquifer
d) Pressure support from the gas zone
e) Coning (multiphase production)

In addition will the drawdown during the production periods be small since the formation has a high permeability.

2.2 Model used

Beta II with the radial option and american units was used in this study. The model had the following dimensions. (see also Fig. 2)

Z-direction : 13 layers
r-direction : 16 columns
Radial symmetry

The first radial column was used to define the perforation interval by giving a high permeability for the perforated interval and zero permeability for the layers above and below the perforations. Layer 13 and column 16 were given a high permeability to avoid boundary effects.

The well was produced for 5 hrs and then shut in for another 5 hrs. Small timesteps were used both for the early part of the drawdown and the buildup such that a complete pressure profile could be calculated.

Other data used:

K = 1000 md

$\emptyset$ = .306

$K_v = K_H$

Capillary pressure from log Sw

S_{wc} = 10%

$K_{rw} (S_{or}) = 0.20$

$(S_{or})_{ow}$ = 22%

$(S_{or})_{go}$ = 40% Trapped gas

$K_{rg} (S_{or})_{go} = 0.70$

2.3 Results obtained

Four different cases were runned to analyse the effect of the aquifer, effect of the gas zone and the combined effect of aquifer and gas zone.

a) The oil zone isolated from the aquifer and the gas zone.

The results are plotted as a Horner plot in Fig. 3, curve a. The first part of the Horner plot shows a continous decreasing slope. The curvature is probably due to gas that goes into solution. The late part of the test has been analysed with the following results.

m = 7.9 psi/logcycle
k = 1090 md

This is close to the input permeability such that the straight line choosen should be the correct straight line.

b) Oil zone in pressure communication with the aquifer.

Fig. 3, Case b indicate that one have close to the same performance as for case a. The pressure support from the aquifer can be seen from the fact that case b has a higher pressure than case a, and at late times converge towards the initial reservoir pressure. A portion of the buildup data seem to have the same straight line as case a.

c) Gas zone in pressure communication with the oil zone.

This is shown in Fig. 3 as case c. The pressure support from the gas cap is more efficient than the pressure support from the aquifer. The straight line that could be seen in case a and partially in case b, can not be seen since the pressure converge to the initial reservoir pressure at times about equal to the start of the straight line for case a and b.

d) Gas, oil and water zone in pressure communication.

This is case d in Fig. 3. Here one have pressure support both from the aquifer and the gas cap. After about 3 min of the buildup, dominate the pressure support from the gas and water zone and it is not possible to make a standard Horner analysis of the pressure respons.

3. SENSITIVITIES ON VARIABLES THAT INFLUENCE THE WELL BEHAVIOUR

3.1 Introduction/Well Model

This model was used to investigate both long time and short time behaviour. A number of sensitivity cases were run to see the effect on the results and to look upon the relative importance of the variables that were runned sensitivities on.
The model used had the same configuration as given in Fig. 2 but with the following dimensions (see also Fig. 1).

Block size (ft)	:	
Radial direction	:	4.6, 8., 14., 25., 43., 75., 130., 400., 700., 1225., 2140.
Vertical direction	:	95.1, 29.5, 10.1, 6.14, 7*10.78, 6.28, 10.1, 32.8.

The model used the PVT data given i Tables 3 - 5 and with the following other data:

K = 2500 md layer 1, 9000 md layer 2 -14

K_V = $.6*K_H$

Ø = .30

Q = 8000 bbl/day

The production rate Q is a three phase flowrate measured at reservoir pressure.
The number of blocks in the radial direction was decreased when the drainage radius was changed. For the sensitivity cases on vertical barriers were the simulator blocks that contained the barrier given zero permeability.

3.2 Relative permeability

At the time of the start of this study three measurements on oil water relative permeability and two on gas-oil relative permeability were available. These data were from well 31/2-1A [3]. The core plugs that were used were from zones that were different from the zone that contain oil in the 31/2-5 well and with a considerable lower permeability.

The relative permeability data were normalized by the following equations:

$$Sw^* = \frac{S_w - S_{wc}}{1-S_{or}-S_{wc}} \quad (1)$$

$$K_{rw}^* = \frac{K_{rw}(S_w)}{K_{rw}(S_{or})} \quad (2)$$

$$Sg^* = \frac{S_g}{1-S_{or}-S_{wc}} \quad (3)$$

$$K_{rg}^* = \frac{K_{rg}\ (S_g)}{K_{rg}(S_{wc}+S_{or})} \quad (4)$$

The normalized relative permeability curves are given in Figs. 4 and 5. These curves were compared with data from 34/10. The normalized water oil relative permeability curves were close to identical while the normalized gas-oil relative permeability curves showed a considerably difference.

The normalized curves given in Figs. 4 and 5 were used througout this study. To get the actual relative permeability curves, four variables had to be known, namly S_{or} for oil water and "S_{or}" for gas-oil system (trapped gas) and $k_{rw}\ (S_{or})_{ow}$ and $k_{rg}(S_{or})_{go}$.

The effective permeability to oil at S_{wc} saturation is close to the effective permeability at reservoir pressure for gas at the same S_{wc}. The unknowns are by this reduced to S_{or} for oil-water system, $K_{rw}\ (S_{or})$ and S_{or} for gas oil system.

With three variables and three levels on each we get 27 possible combinations. To reduce the number of cases a latin square([4]) was used. This is shown in Fig. 6. The effective end point for the gas relative permeability curve was calculated by the following procedure.

1. The normalized gas relative permeability curve given in Fig. 5 was denormalized with respect to S_{wc}. This gave a curve where $K_{rg} = 1$ at $S_g = 1-S_{wc}$, i.e the effective gas permeability at $S_g = 1-S_{wc}$ was equal to the effective oil permeability at $S_o = 1-S_{wc}$.

2. The effective end point for the gas relative permeability curve was then given at $S_g = 1-S_{wc}-S_{or}$ on the denormalized curve described above.

$(S_{or})_{ow}$ \ $(S_{or})_{go}$	.20	.30	.50
.20	a) .10	b) .20	c) .50
.30	d) .50	e) .10	f) .20
.50	g) .20	h) .50	i) .10

Fig 6 Latin Square with Choosen Values of the three Variables.

The numbers on the x-axis are the values choosen for the residual oil saturation for a gas-oil system, while the values on the y-axis are for the residual oil for the oil-water system. The parameter in the squares are the $k_{rw}(S_{or})$ values. A more general picture of the latin square is shown in Fig. 7 where variables A_1 A_2 and A_3 correspond to $(S_{or})_{go}$, $(S_{or})_{ow}$ and $K_{rw}(S_{or})$

Parameter: A_3

A_2 \ A_1	1	2	3
1	1	2	3
2	3	1	2
3	2	3	1

Fig. 7 Latin Square Used.

From the latin square in Fig. 6 with the corresponding values of $(S_{or})_{ow}$, $(S_{or})_{go}$, $K_{rw}(S_{or})$ and the normalized curves given in Figs 4 and 5 can the actual relative permeabilities be calculated by regrouping Eqs. 1 to 3 for case - a - to - i - ; i.e for case e) we have

$$(S_{or})_{go} = .30$$
$$(S_{or})_{ow} = .30$$
$$K_{rw}(S_{or}) = .10$$

Summary of the results obtained are given in Table 6.

The second column in Table 6 is an over all aritmetic mean of the results obtained at a given time (final simulation time). Standard deviation is a measure of variability obtained within the results and 1 standard deviation include 68% of the values obtained, i.w. for E_R is 68% of the results within the range 7.625 + .386 to 7.625 - .386 i.e. a narrow range.

The dimensionless coeffisient of variation can more easily be used to compare the degree of variation for the parameters used. From the third column it can be observed that N_w/N_o has a much higher value for the y..(.) parameter, i.e N_w/N_o has a much higher relative variation than any of the other parameters.

The variables are given in decreasing order of importance in columns 5 to 7 and the importance of the variables or combination of variables are given in the columns for the regression coeffisient, i.e for N_g/N_o, $K_{ro}(S_{or})$ are the most important parameter and 55% of the variation of the results can be explained by this parameter. By including the second most important parameter $(S_{or})_{go}$, one can explain 80% of the variation.

The conclusion drawn from Table 6 are as follows.

1. Recovery has a low variation with respect to the end points of relative permeability with $K_{rw}(S_{or})$ and $(S_{or})_{go}$ ~~are~~ as the two most important parameters.

Table 6. Main Results from Realtive Permeability Sensitivities.

Variable	Over all mean $\bar{y}..(.)$	Standard deviation	Coeffisient of variation $\sigma/\bar{y}..(.)$	The most important variables			Regression Coeffisient R^2		
				1	2	3	1	1+2	1+2+3
E_R (%)	7.625	.386	.051	$k_{rw}(S_{or})$	$(S_{or})_{go}$	$(S_{or})_{ow}$	.49	.83	.83
N_w/N_o	.541	.341	.630	$k_{rw}(S_{or})$	$(S_{or})_{go}$	$(S_{or})_{ow}$	.996		
N_g/N_o	2727	200	.074	$k_{rw}(S_{or})$	$(S_{or})_{go}$	$(S_{or})_{ow}$	.55	.80	.85
Q_o	1431	237	.166	$(S_{or})_{go}$	$k_{rw}(S_{or})$	$(S_{or})_{ow}$	.45	.80	.80

2. The cumulative water oil ratio has a high variation and with $K_{rw}(S_{or})$ as the controlling factor.

3. The cumulative gas-oil ratio has a low variation, with $K_{rw}(S_{or})$ and $(S_{or})_{go}$ as the two most important factors.

4. The oil production has a moderate variation with $(S_{or})_{go}$ and $K_{rw}(S_{or})$ as the two most important factors.

Since the variation of the results for N_w/N_o is the most important, the results will be analysed further. Fig. 8 gives the latin square with the cumulative water-oil ratio produced included, i.e for case g) the input values are $(S_{or})_{ow}=.50$, $(S_{or})_{go} = .20$, $K_{rw}(S_{or}) = .20$ and the resulting $N_w/N_o = .404$. The column on the right is the average value over the first and third variable (y.n(.), n = 1, 2, 3) for the second variable $(S_{or})_{ow}$. This give that for $(S_{or})_{ow} = .30$ the average result is $N_w/N_o = .537$. The line below the latin square is the average value over the second and third variables for given values of the first variable $(S_{or})_{go}$, i.e for $(S_{or})_{go} = .50$ we get $N_w/N_o = .564$. From this we can deduce that the result is close to independent of $(S_{or})_{ow}$ and $(S_{or})_{go}$ since all the average values mentioned are close to the overall mean y..(.) = .541. The average value over the first and second variables for given values of the third variable $K_{rw}(S_{or})$ are given as y..(n), n = 1, 2, 3 and it can readily be seen that the results depend heavily on the $K_{rw}(S_{or})$ value. At the bottom is given the linear regression equation for this case which can be used to predict the N_w/N_o value for a given $K_{rw}(S_{or})$ value.

In the appendix are the results given in Figs. 9 and 10 for oil production Figs. 11 and 12 for WOR, and Figs. 13 and 14 for gas oil ratio as a function of time for cases a to i.

Case b was choosen as the base case since it gave close to average results for all the results analysed and without having any extreme values.

3.3 Permeability

The zone from 1564 m RKB down to 1616 m RKB see Fig. 1 was defined as a homogeneous zone in the model. A major part of this zone consist of unconsolidated material such that very few core results exists. The plugs from which petrophysical properties have been measured, are located in intervals which are consolidated such that the representativness of the results are questionable. Therefor two sensitivity cases to case B were run, with respectivly 6D and 12D horisontal permeability.

The results are given in table 7 in dimensionless form with respect to case B and graphed in Figs 15 to 17.

Table 7. Result from Sensitivity on Permeability.

	Case J k = 6000 md	Case b k = 9000 md	Case k k = 12000 md
E_R	.75	1.0	1.26
N_w/N_o	1.00	1.0	.97
N_g/N_o	1.46	1.0	.72
Q_o	.72	1.0	1.06

Table 7 shows that recovery, cumulative gas oil production and oil production rate at a given time are all dependent upon the permeability of the formation while the cumulative WOR seem to be independent of the permeability. This applies directly only for the geometry choosen for the base case. A change of location of perforation interval could change the results for WOR and GOR. It can be seen that case K has 1.7 times the recovery of case j which again has twice the cumulative produced gas - oil ratio compared to case K. Such that case K is more favourable than case j. This implies that it is important to measure the permeability accuratly though the permeability is high.

3.4 Vertical permeability

There have to be flow in the vertical direction to build up a cone. This implies that the flow conductivity in the vertical direction is important for the well behaviour. Two sensitivity cases on K_v/K_h were run with K_v/K_h equal to respectively 1. and .1. The results are given in Table 8 in dimensionless form and in Figs. 18 to 20.

Table 8. Sensitivity on Vertical to Horizontal Permeability

	Case m $K_V/K_H = 1$	Case b $K_V/K_H = .6$	Case n $K_V/K_H = .1$
E_R	.98	1.	1.18
N_w/N_o	1.0	1.	.86
N_g/N_o	1.02	1.	.80
Q_o	.97	1.	1.15

Fig. 18 shows that the difference in oil production decreases with time, so also the difference in WOR (Fig. 19) while the difference in GOR (Fig. 20) seem to be close to constant. This behaviour differ from the sensitivity on permeability cases where the difference in oil production was about constant, the difference in GOR increased while there was no difference in WOR as a function of time. This can be seen in Figs. 15 to 17.

From Table 8 it can be seen that we need a variation in K_v/K_h on the order of at least 10 to see any significant difference in well performance. This should indicate that the results are more dependent upon the horisontal permeability than the vertical permeability.

3.5 Drainage Radius

The recovery from a thin oil zone between a gas and water zone will depend heavily on the well spacing. This is because the recovery is dependent upon near well phenomena. Case O and P shows the effect of decreasing the drainage radius. The results obtained are given in Table 9 and Fig. 21 to 25.

Table 9. Sensitivity on Drainage Radius.

	Case B re = 5000 ft	Case P** re = 1700 ft	Case O* re = 1000 ft
E_R	1.	2.59	2.96
N_w/N_o	1.	.83	.67
N_g/N_o	1.	1.25	1.10
Q_o	1.	.33	.27
Number of wells	1	8.65	25

* Results after 1460 days of production

** Results after 4380 days of production

From Table 9 one can see that the recovery increase with decreasing drainage radius. (But at the same time, the number of well increase considerably). The cut off value for case O and P were 500 STB/day of oil while for case B was the cut off the final simulation time of 30 years. Figs. 21 to 25 shows that the early time behaviour is independent of the drainage radius. Fig. 23 which is GOR vs time shows that case P and O have close to the same behaviour but the performance is shifted with respect to time. This can also be seen on Figs. 21 and 22. Figs 25 shows that for a given average reservoir pressure, the recovery increase with decreasing drainage radius. This should indicate that the closer the well spacing is, the more efficient is the driving energy in the system utilized.

3.6 Location of Perforation Interval.

The base case had a perforation interval located in layer 9. (See fig. 1). Layer 9 was approximately 3 m thick and the lower limit of layer 9 was located 6 m above the water oil contact. Two sensitivity cases were run with respectively perforation interval 3 m above the WOC (layer 10) and 12 m above the contact layer 7. Results are given in Table 10 and Figs. 26, 27 and 28.

Table 10. Results for Variation of Location of the Perforated Interval.

	Case Q 3 m above WOC	Case b 6 m above WOC	Case R 12 m above WOC
E_R	1.27	1	.56
N_w/N_o	1.26	1	.10
N_g/N_o	.67	1	2.21
Q_o	.98	1	.54

Table 10 shows that case Q gives a higher recovery and water production than the base case. While case R gives a lower recovery and WOR and a higher GOR than the base case. This implies that an optimasation on the location of the perforated interval have to be performed to estimate the optimum economical recovery. There is no increase in WOR for case R and no increase in GOR for case Q during well test time (less than 2 weeks.) That should implie that to see any increase in WOR and GOR the perforated interval for the test ought to be as for the base case.

Two other locations of perforation intervals were tested. One was a perforation interval in the water zone (layer 13) and the other was a double completion where the oil zone was perforated as for the base case while the gas zone was perforated just above the GOC. The idea with case one was to create an oil cone down into the water zone and produce the oil phase through this cone. The results for this case are given in Table 11 and Figs. 29 to 33.

Table 11. Alternative Completions Methods.

	Case S perforation in the water zone	Case b base case
E_R	1.78	1
N_w/N_o	1.79	1
N_g/N_o	.29	1

Q_o 1.49 1.

Table 11 shows that the oil production is higher when the oil is produced from the water zone as in case S. This can also be seen in Fig. 29 where case S has a higher oil production than the base case for times greater than 10 days. During the first 10 days there is a rapidly decreaseing WOR as can be seen in Fig. 30. (This is the time needed to create a fairly stabel oil cone). Case S has higher WOR than the base case during the whole production periode. This can also be seen in Table 11 where case S has a factor of 1.79 on cumulative WOR. Since the perforation is located "far" from the gas zone it takes a considerable longer time for case S before the gas cone has any influence on the results as shown in Fig. 31. This results in a higher recovery (a factor of 1.78) as shown in Fig. 32. Since less gas is produced the driving energy that is stored in the gas cap is utilized more effectiv as indicated in Fig. 33.

Case T was a double completion where the gas zone was perforated just above the GOC while the oil zone was perforated as in the base case. The idea was to introduce a pressure drop near the GOC such that gas did not cone down into the oil zone. The gas flow rate was 100 x 10^6 SCF/day. This gave a slightly higher oil production (Fig. 34) then for the base case. The ultimate recovery was however low because by producing from the gas phase the driving energy was produced. This is reflcted in Fig. 35 where recovery is plotted vs average reservoir pressure (compare with Fig. 25, case B)

3.7 Barriers

Barriers that may exist in or near the oil zone, or artifical barriers can have an effect on the well performance. It is possible to introduce cylindrical and horisontal barriers by different treatments. In this study 3 different cases have been studied. These are horisontal barriers and are located as:

case U : GOC, radius 12 ft
case V : GOC, radius 170 ft
case w : 26 ft below GOC, radius 52 ft

Table 12. Effect of Barriers.

	Case U	Case V	Case W	Case b base case
E_R	1.01	1.03	1.43	1.
N_w/N_o	.97	.99	1.30	1.
N_g/N_o	.99	.96	.54	1.
Q_o	1.	1.01	.87	1.

Table 12 and Figs. 36 - 38 shows that a horisontal barrier located in the GOC has a very limited effect on the well behaviour. But the barrier located in the oil zone, above the perforation as in case w will have influence on the results. The recovery is increased by close to 50% with half the cumulative produced gas-oil ratio compared to the base case. This ~~should~~ implies that the driving energy is utilized more effectivly than for the base case. Other location of the barrier would give different results and an optimasation ought to be performed.

4. CONCLUSION

1. The end point of the water-oil relative permeability curve is more important than the residual oil saturation and trapped gas saturation when the performance of the well is going to be predicted.

2. The cumulative water oil ratio produced is the most sensitive parameter to relative permeability among those parameters studied.

3. The horisontal reservoir permeability is important for the well performance though the permeability is high.

4. The vertical permeability has a considerably lower effect on the results than the horisontal permeability.

5. The recovery was increased by a factor of about 3 by reducing the drainage radius by a factor of 5. Less increase in recovery was gained by decreasing the drainage radius by a factor less than 5.

6. The well performance depends heavily on the location of the perforation interval in the oil zone.

7. The recovery can be increased by perforating the well below the OWC.

8. Barriers in or near the GOC have limited effect on the performance of the well. If the barrier is located in the oil zone above the perforation interval, the effect is higher.

9. The pressure respons from a thin oil column between a gas and water zone where the rock permeability is high will be difficult to analyse due to the pressure support from the gas cap.

5. RECOMMENDATIONS

1. One should get accurate estimates of the relative permeability data for the formation that contain the oil zone with the highest priority in measuring the end value of the water oil relative permeability curve.

2. The horisontal permeability should be measured accuratly though the permeability has a high value.

3. Further studies ought to be performed on well completion to optimize the recovery. This include location of perforation interval within the oil zone and in the water zone.

4. The possibility for introducing artificial permeability barriers in the reservoir and the effects of these ought to be studied. This would also include a study of natural permeability barriers and their effect on the well performance.

5. When some of the variables, at which it has been runned sensitivity cases on in this study is measured within a tolerable accuracy the combined effect of other variables ought to be studied such that the effect of the important variables can be mapped.

6. Using actual test results from 31/2-5 improved prediction of the well performance should be obtained.

7. Mapping of the oil accumulation over the field ought to be done such that one can consider the effect of geometry (gas, water and oil zone thickness), rock properties barriers etc.

NOMENCLATURE

E_R	:	Recovery
GOC	:	Gas oil contact
k	:	Average permeability
K_v	:	Vertical permeability
K_H	:	Horisontal permeability
$K_{rw}(S_{or})$	:	Relative water permeability at S_{or}
$K_{rg}(S_{or})$	:	Relative gas permeability at trapped gas saturation
K_{rw}^*	:	Normalized water saturation
K_{rg}	:	Normalized gas saturation
N_g	:	Cumulative gas production
N_o	:	Cumulative oil production
N_w	:	Cumulative water production
Q_o	:	Oil production
R	:	Regression coefficient
S_g^*	:	Normalized gas saturation
S_{or}	:	Residual oil saturation
S_w^*	:	Normalized water saturation
S_{wc}	:	Connate water saturation
WOC	:	Water oil contact
$y_{..}(.)$	:	Over all mean
ϕ	:	Porosity
σ	:	Standard deviation

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1. "Stratigraphic Correlation for Block 31/2", by B. Rasmussen.

2. "Fluid Analysis by Correlation Technique (FACT)", Garrett Computing Systems.

3. "Special Core Ananlysis study for A/S Norske Shell Exploration & Production, Well: 31/2-1A" Corelab, June 1980.

4. "Statistical Analysis a Computer Oriented Approach", A.A. Afifi, S.P. Azen.

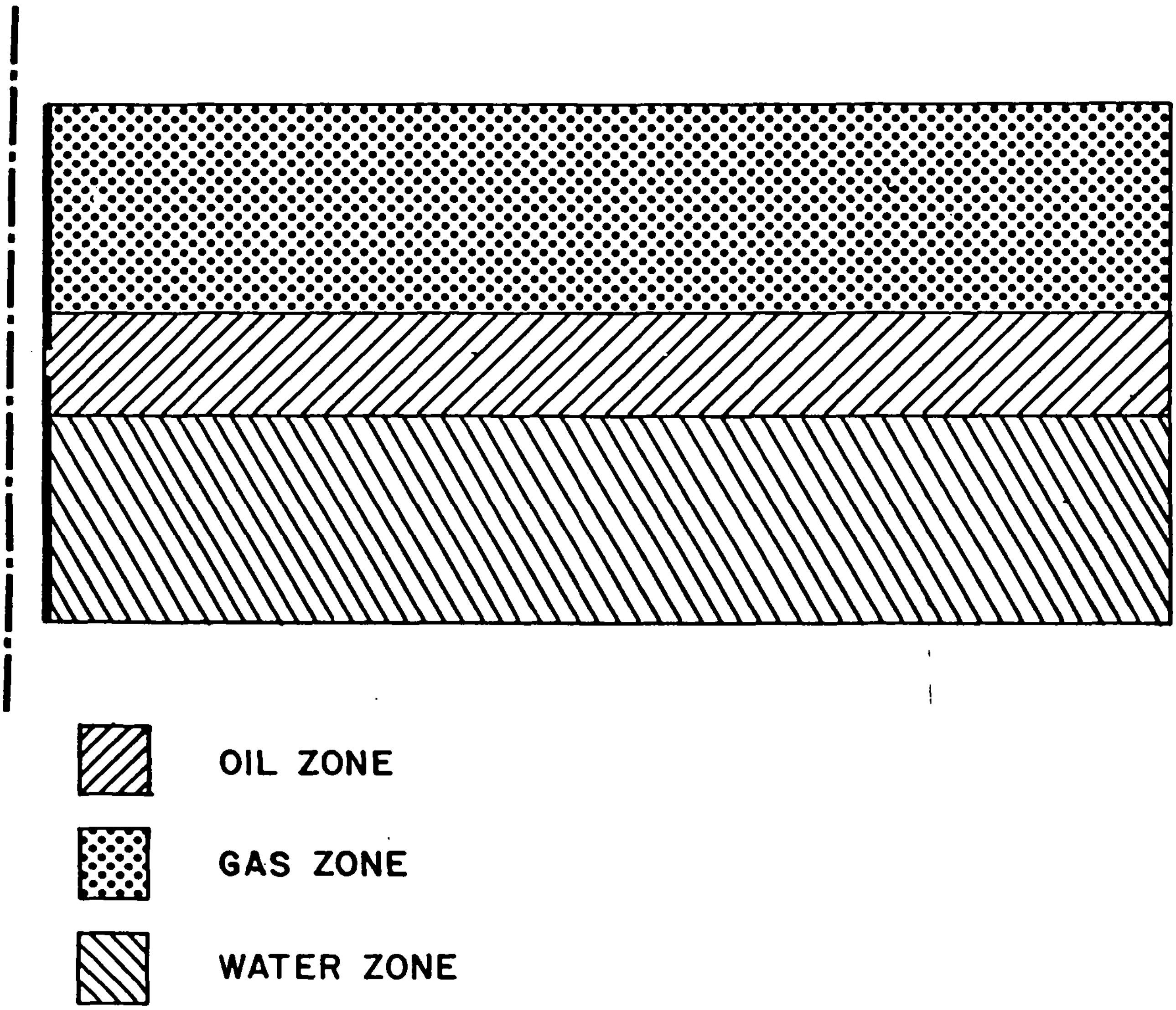
APPENDIX

31/2-5, SIMULATOR MODEL

4 Layers in gas zone

5 Layers in oil zone

4 Layers in water zone



Block size:

Radial direction : .328, .666, 1.348, 2.732, 5.53, 11.22
22.7, 46.1, 93.3, 189., 778., 1576,
3194., 6473., 13120.

Vertical direction : 36.1, 32.8, 29.5, 16.4, 2*13.1, 3*16.4,
32.8, 65.6, 98.4, 328.

Fig. 2 31/2-5 Simulator Model, Pressure Respons Analysis.

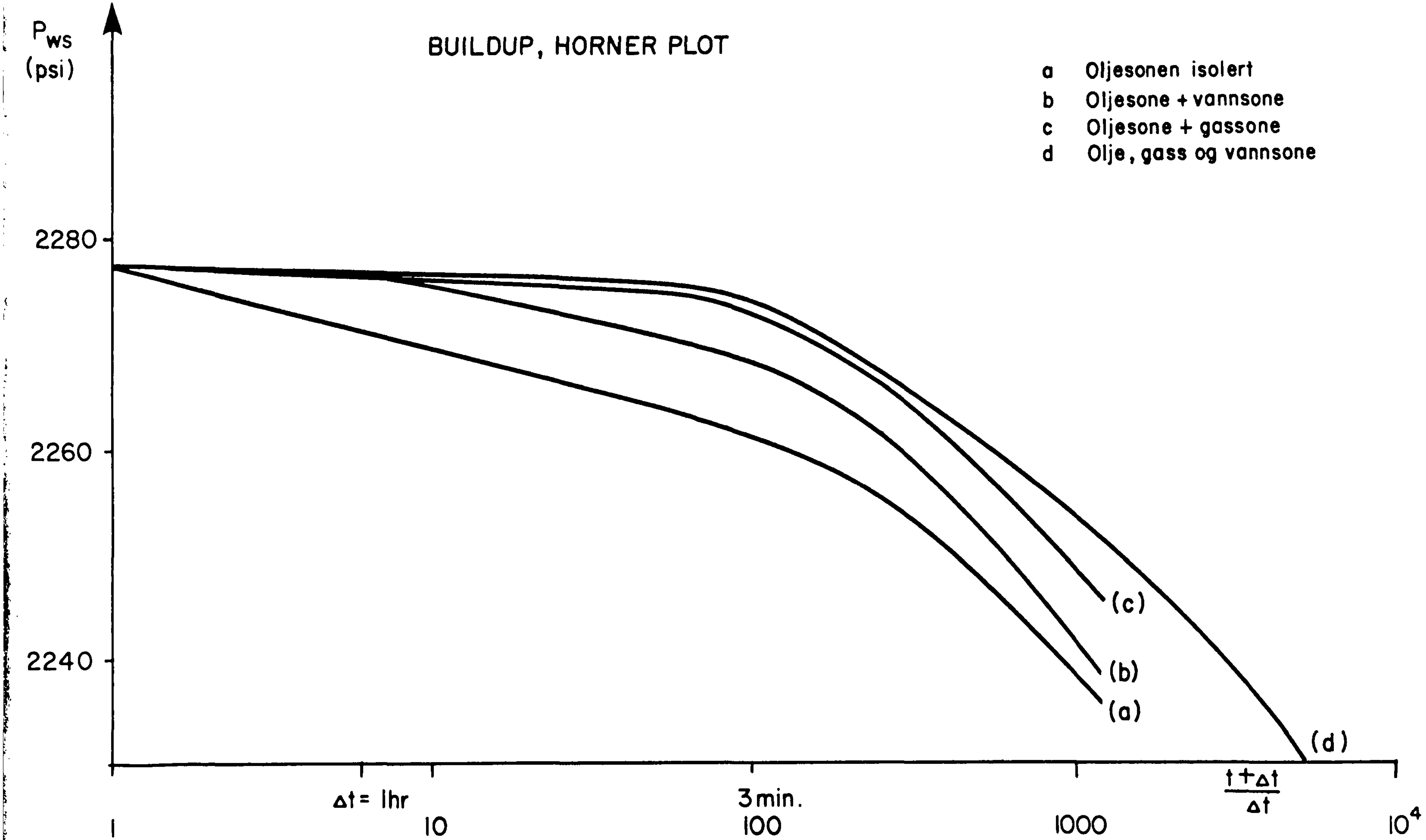


Fig. 3. Horner Plot for Buildup Data for Case a to d.

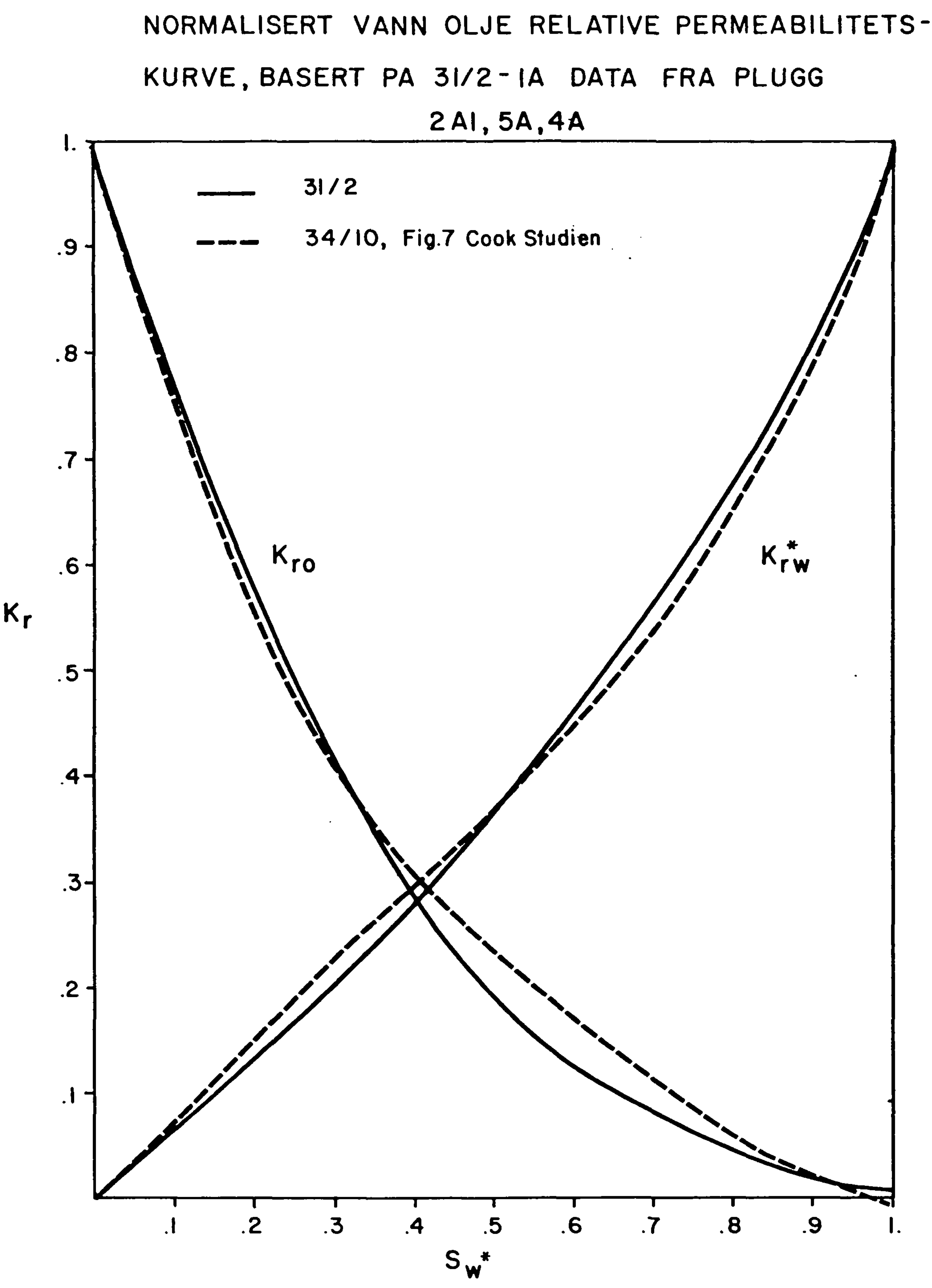


Fig. 4. Normalized Water-Oil Relative Permeability Data

NORMALISERT GASS OLJE RELATIVE PERMEABILITETS-KURVE BASERT PÅ 31/2-1A, PLUGG 2A1, 5A

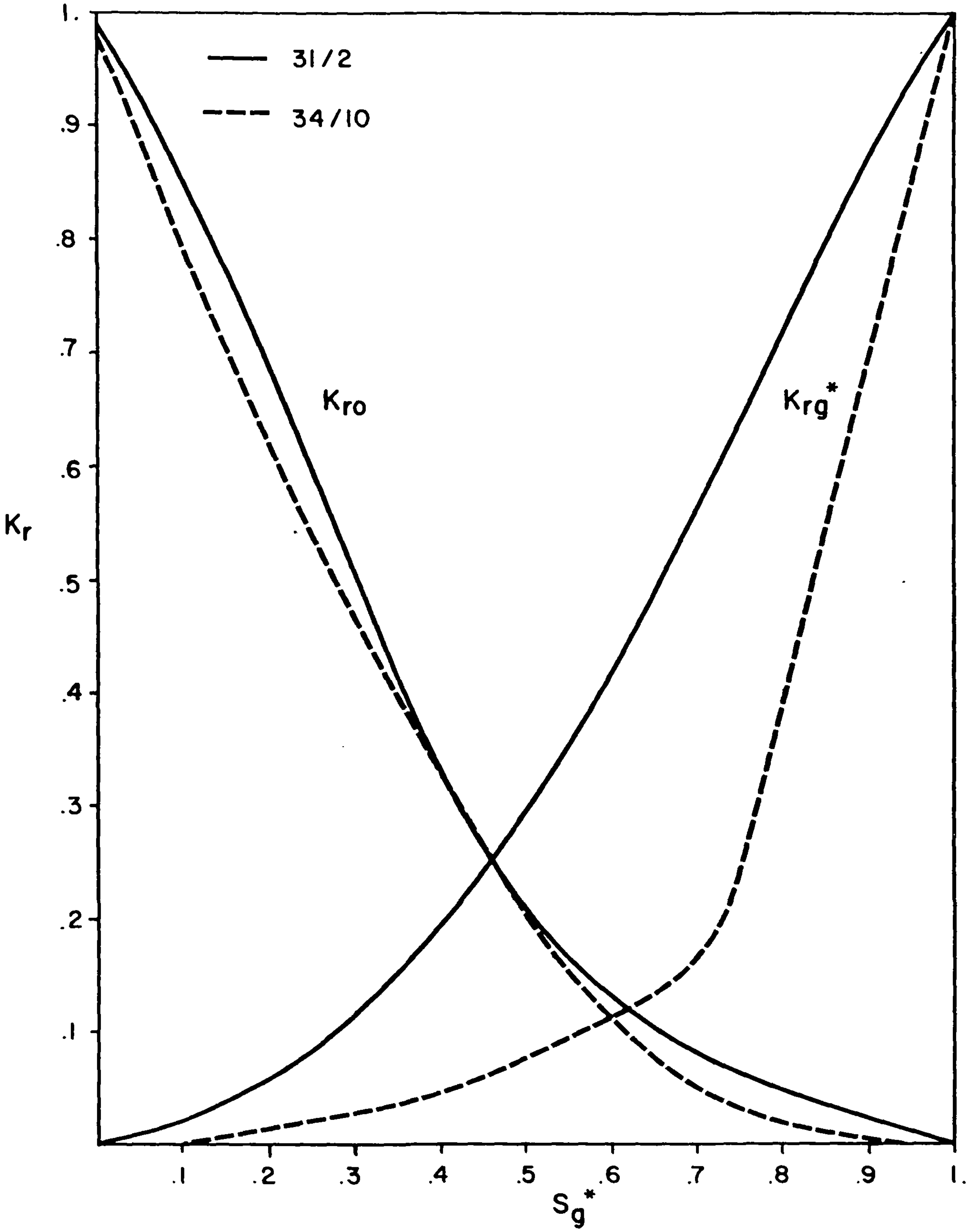


Fig. 5. Normalized Gas-Oil Relative Permeability Data

$(Sor)_{ow}$ \ $(Sor)_{Go}$	.20	.30	.50		
.20	a) .10 .208	b) .20 .419	c) .50 1.010	.546	$\bar{y}.1(.)$
.30	d) .50 .948	e) .10 .217	f) .20 .447	.537	$\bar{y}$ .1(.)
.50	g) .20 .404	h) .50 .978	i) .10 .236	.539	$\bar{y}.3(.)$
	.520	.538	.564		
	$\bar{y}1(.)$	$\bar{y}2(.)$	$\bar{y}3(.)$		

$\bar{y}..(1)$ = .220 $\bar{y}..(2)$ = .423 $\bar{y}..(3)$ = .979 $\bar{y}..(.)$ = .541

$N_w/N_o = .038 + 1.886 \cdot Krw(Sor)$ $R^2 = .9961$

Fig. 8. N_w/N_o Results and Analysis.

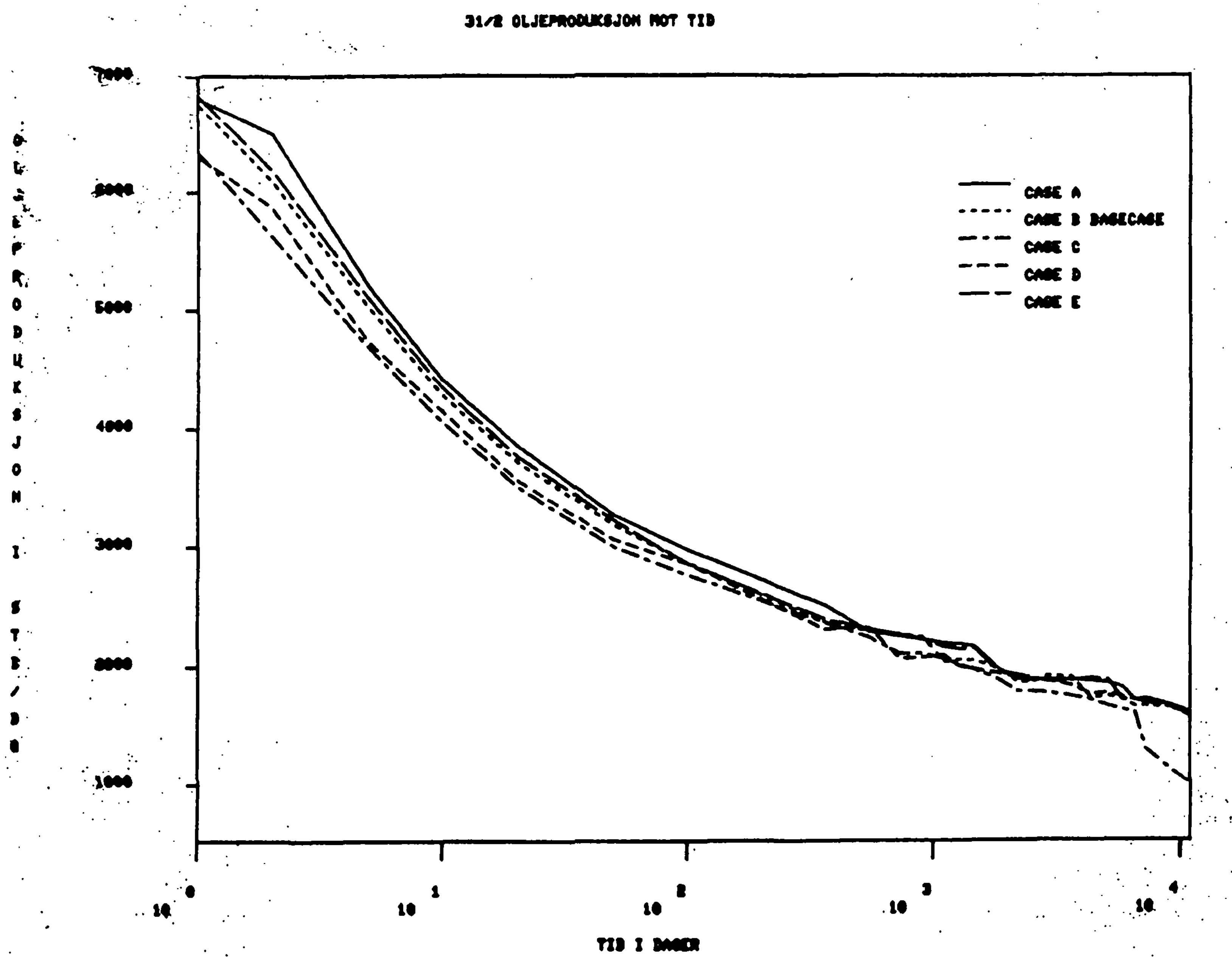


Fig. 9 Oil Production vs Time for Sensitivity on Relative Permeability for Case A-E.

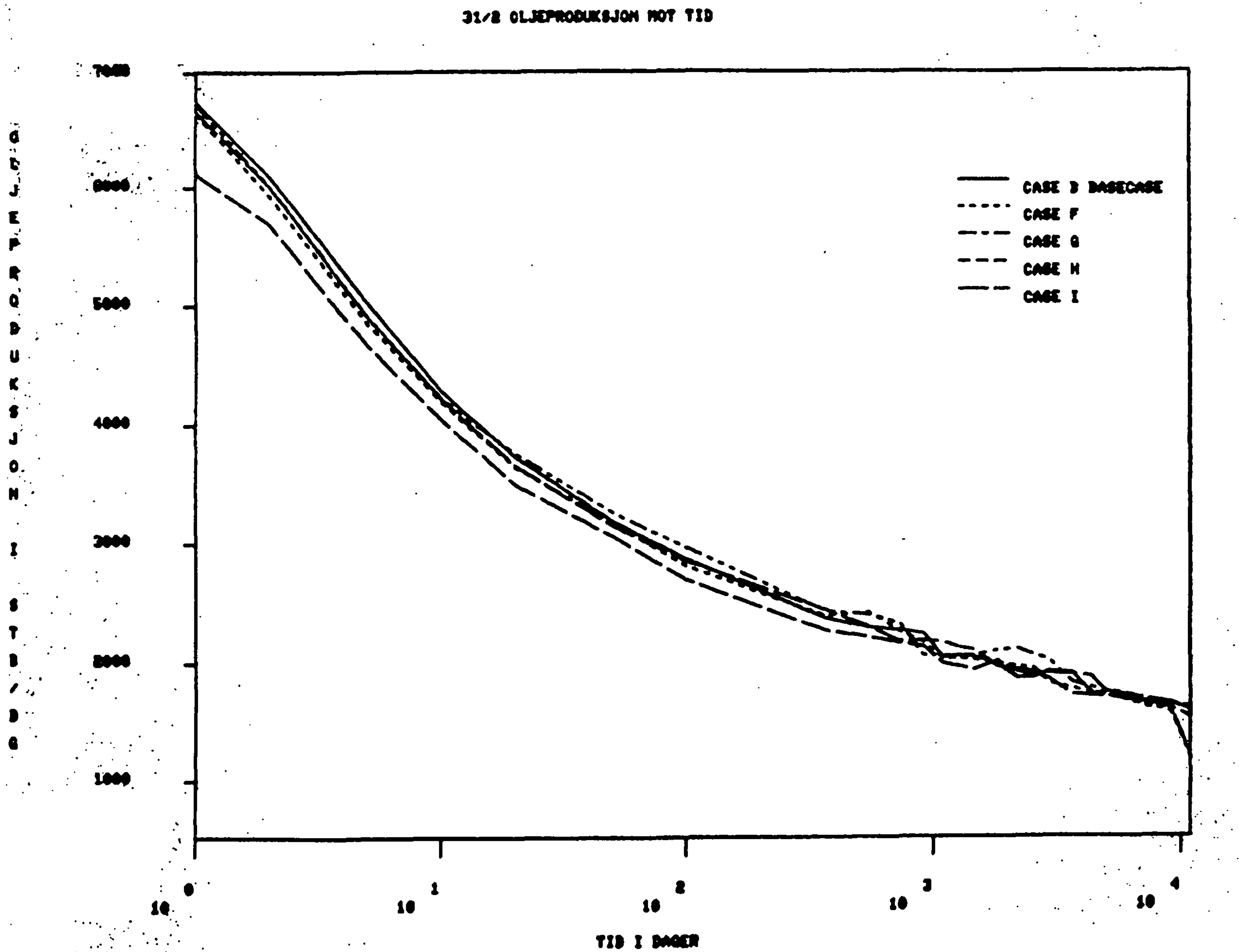


Fig. 10 Oil Production vs Time for Sensitivity on Relative Permaebility for Case B, F-I.

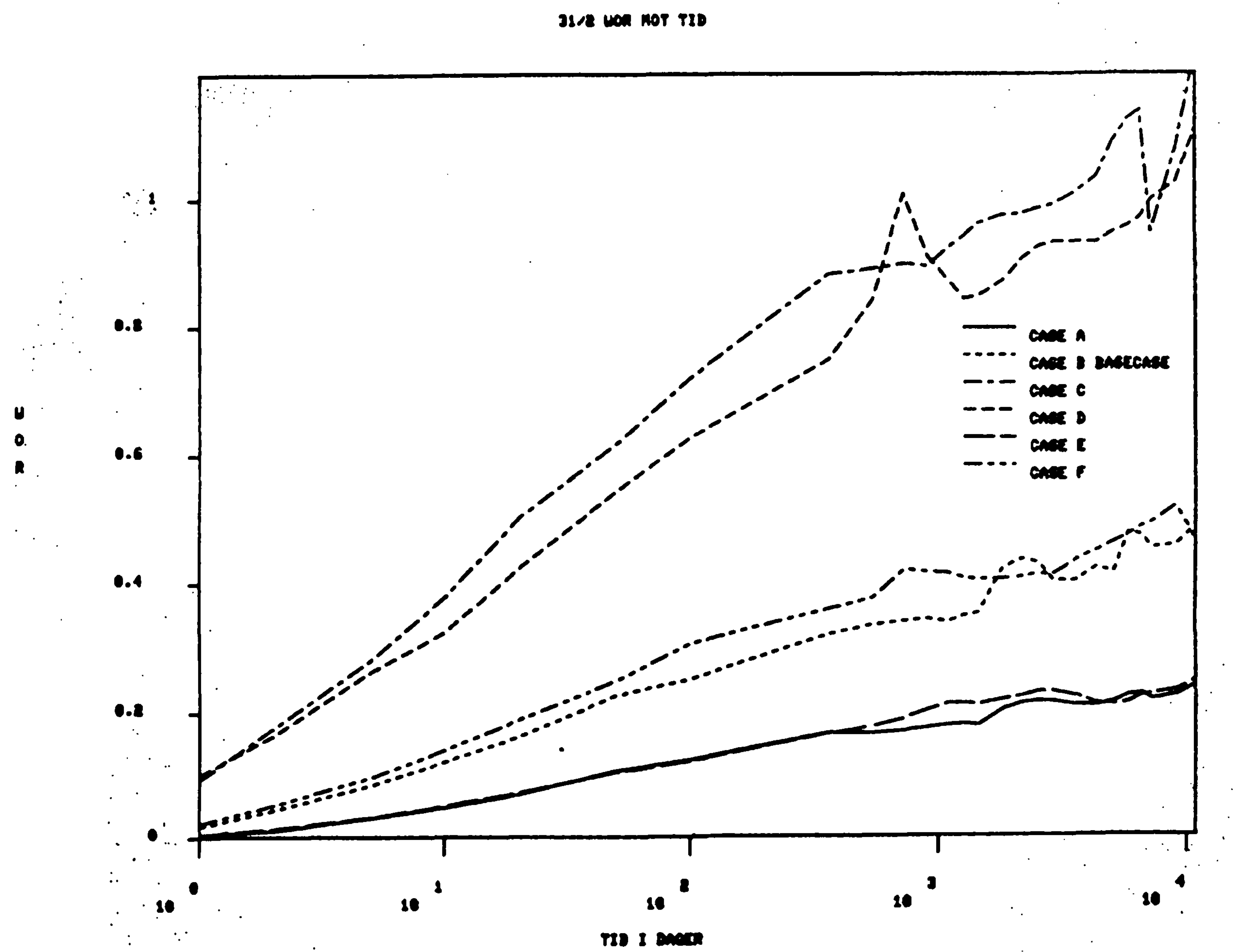


Fig. 11 WOR vs Time for Sensitivity on Relative Permeability for Case A-F.

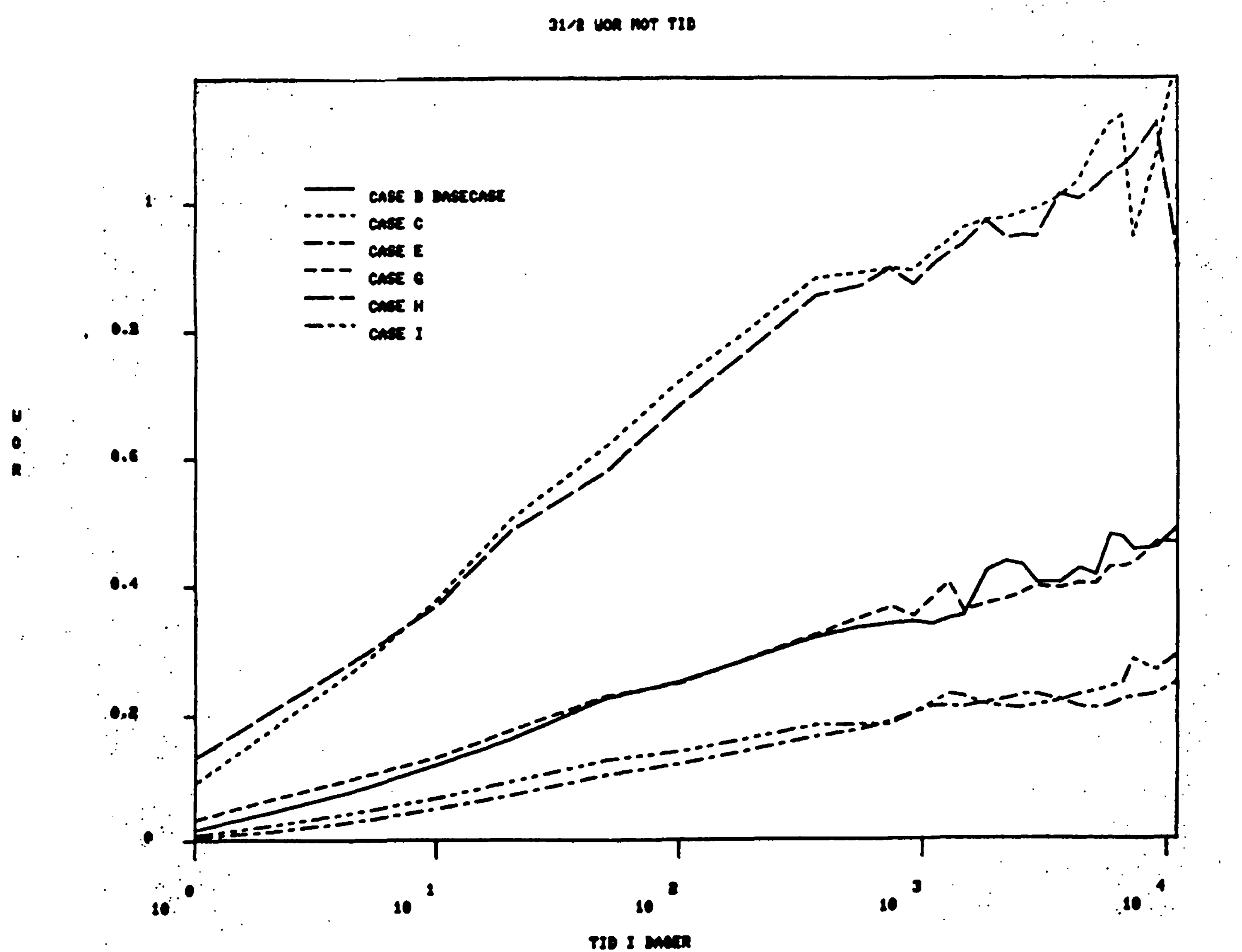


Fig. 12 WOR vs Time for Sensitivity on Relative Permeability for Case B, C, E-I.

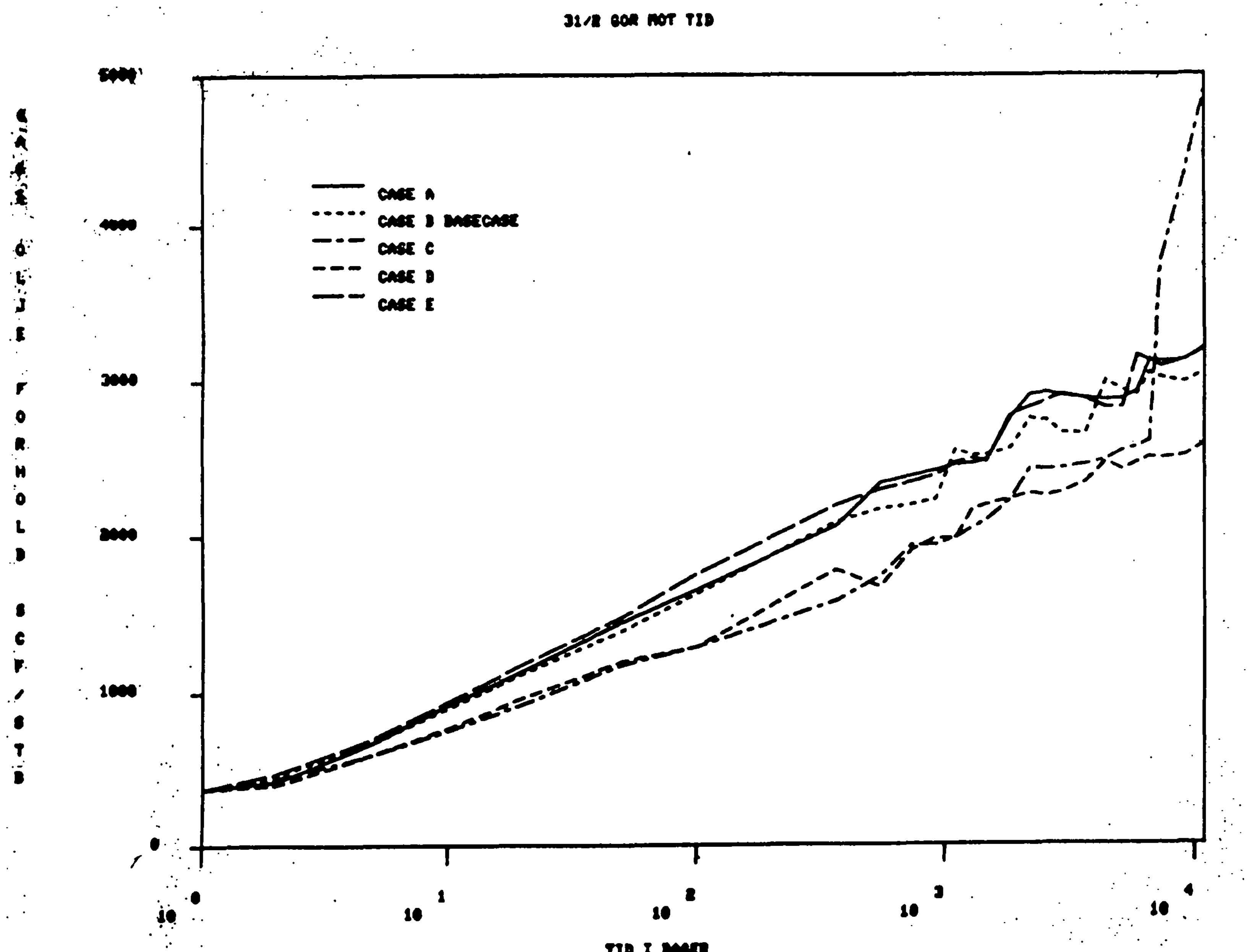


Fig. 13 GOR vs time for Sensitivity on Relative Permeability for Case A-e.

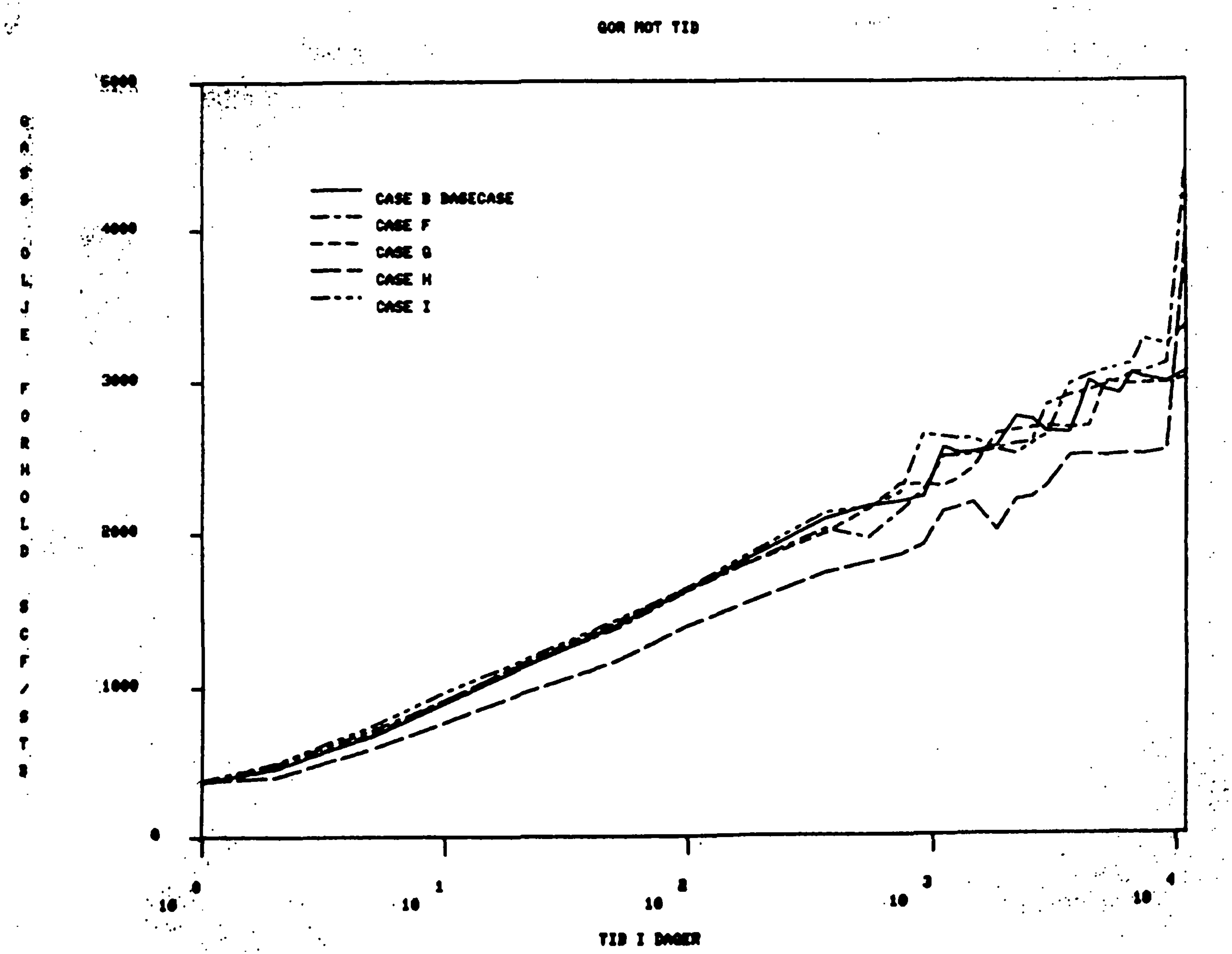


Fig. 14 GOR vs Time for Sensitivity on Relative Permeability for Case B, F-I.

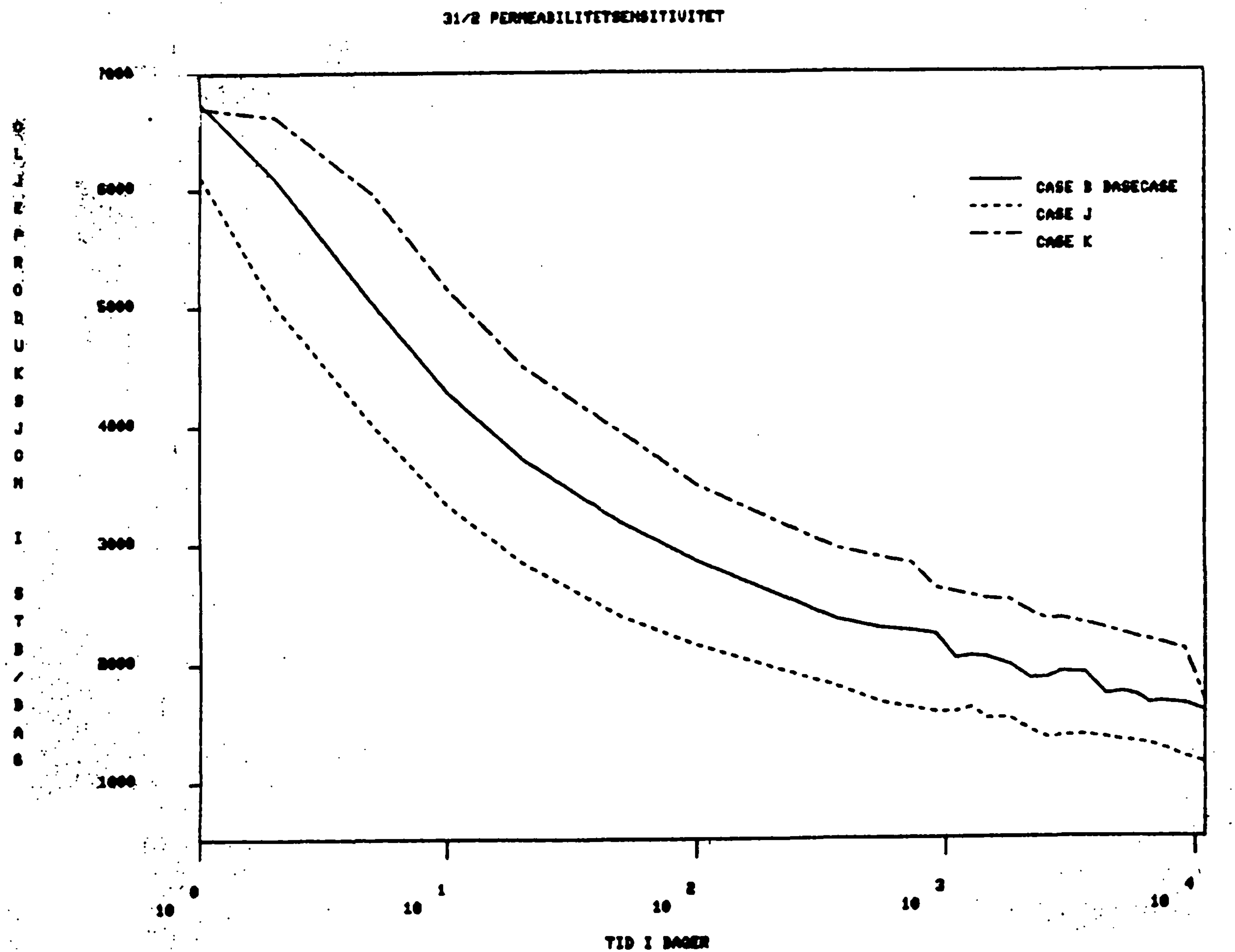


Fig. 15 Oil Production vs Time for Sensitivity on Permeability for Case B, J, K.

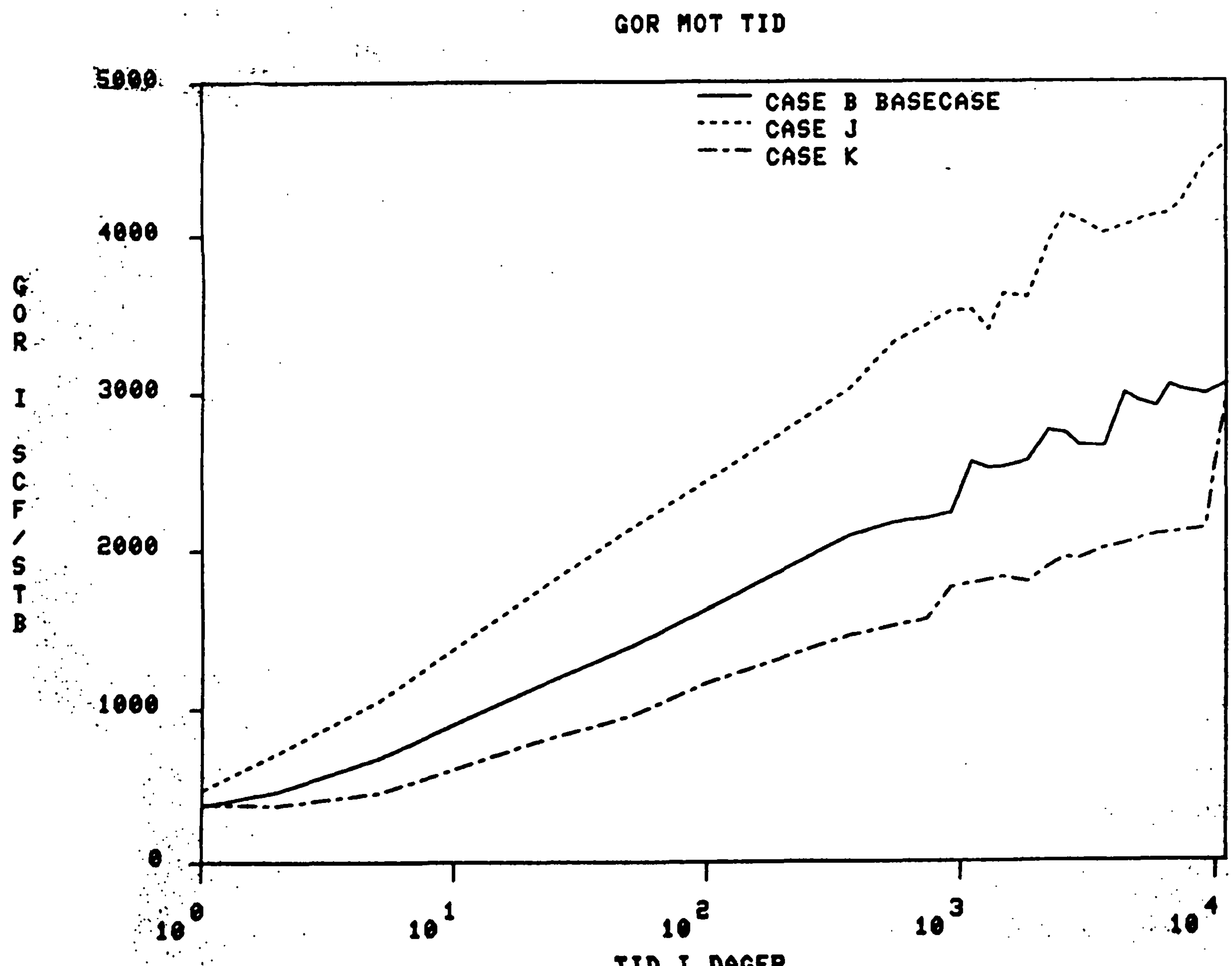


Fig. 16 Gor vs Time for Sensitivity on Permeability for Case B, J, K.

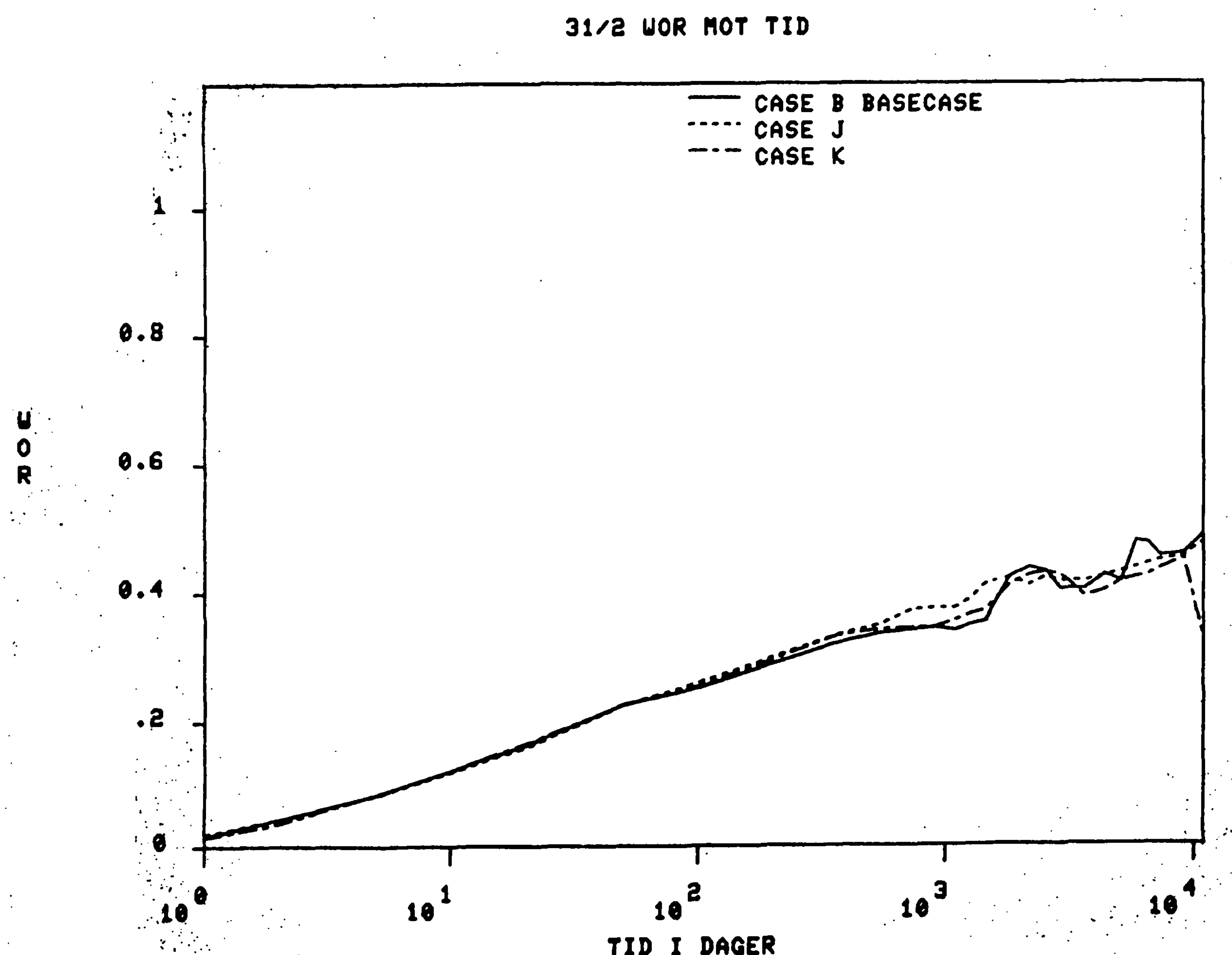


Fig. 17 WOR vs Time for Sensitivity on Permeability for Case B, J, K.

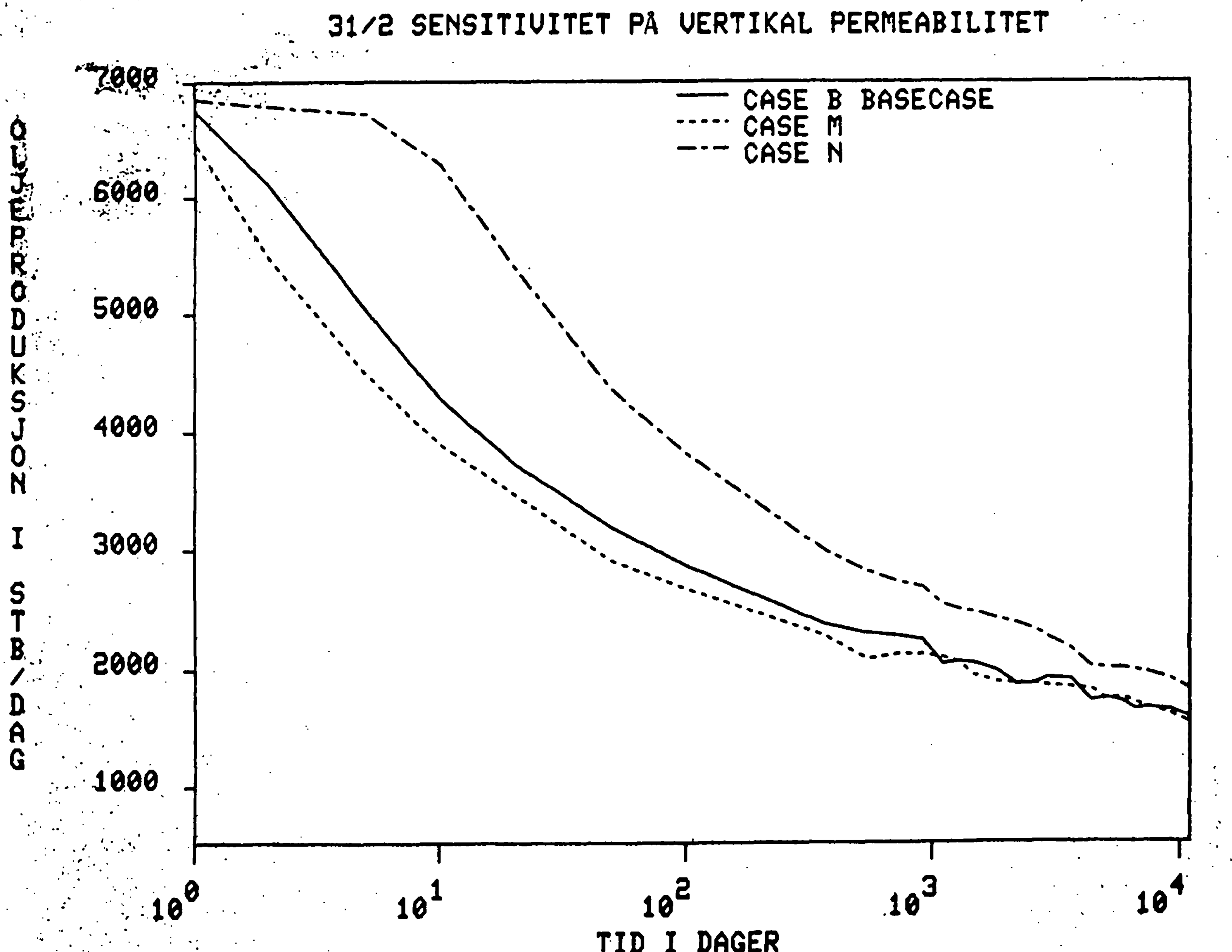


Fig. 18 Oil Production vs Time for Sensitivity on Vertical Permeability, Case B, M, N.

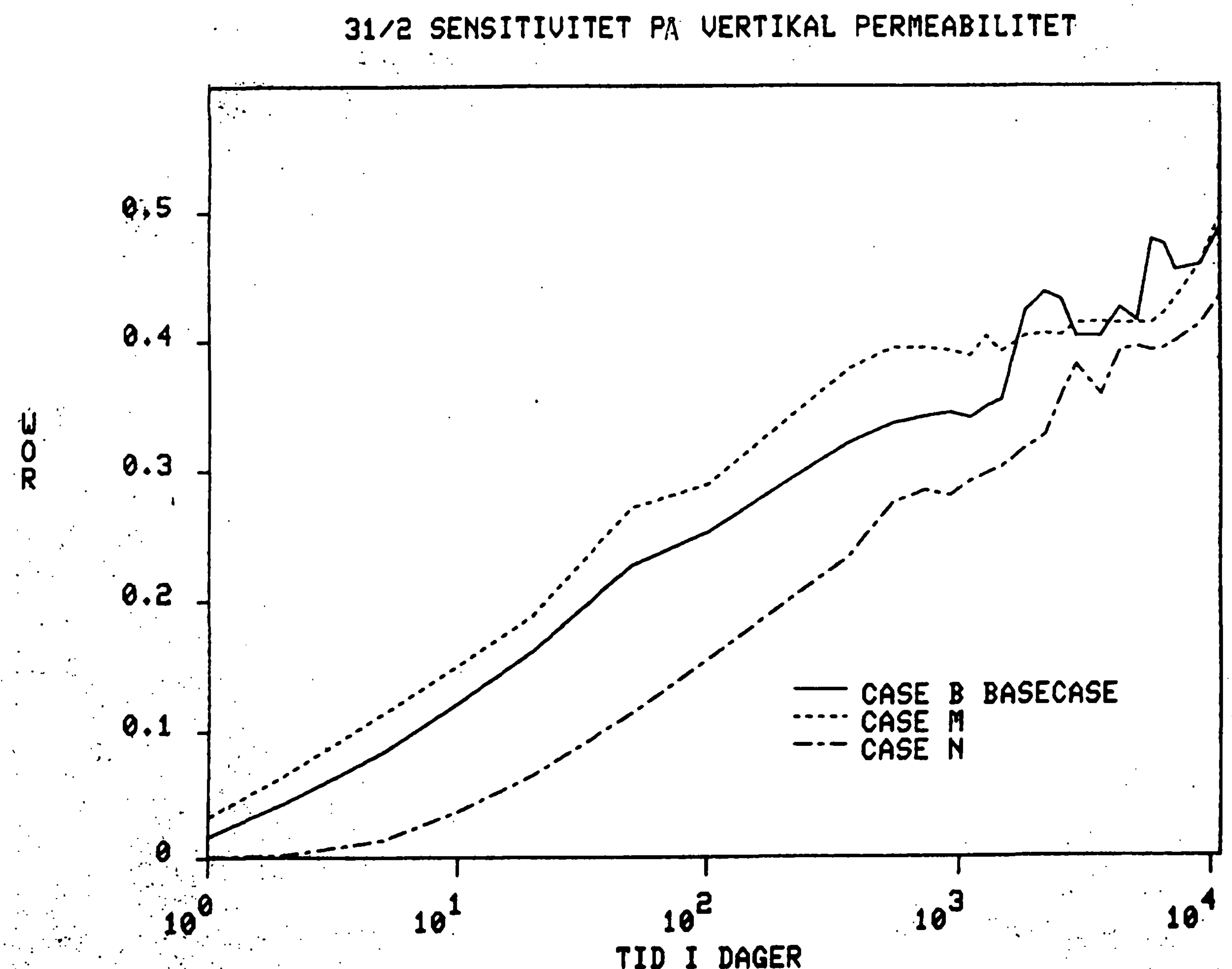


Fig. 19 WOR vs Time for Sensitivity on Vertical Permeability, Case B, M, N.

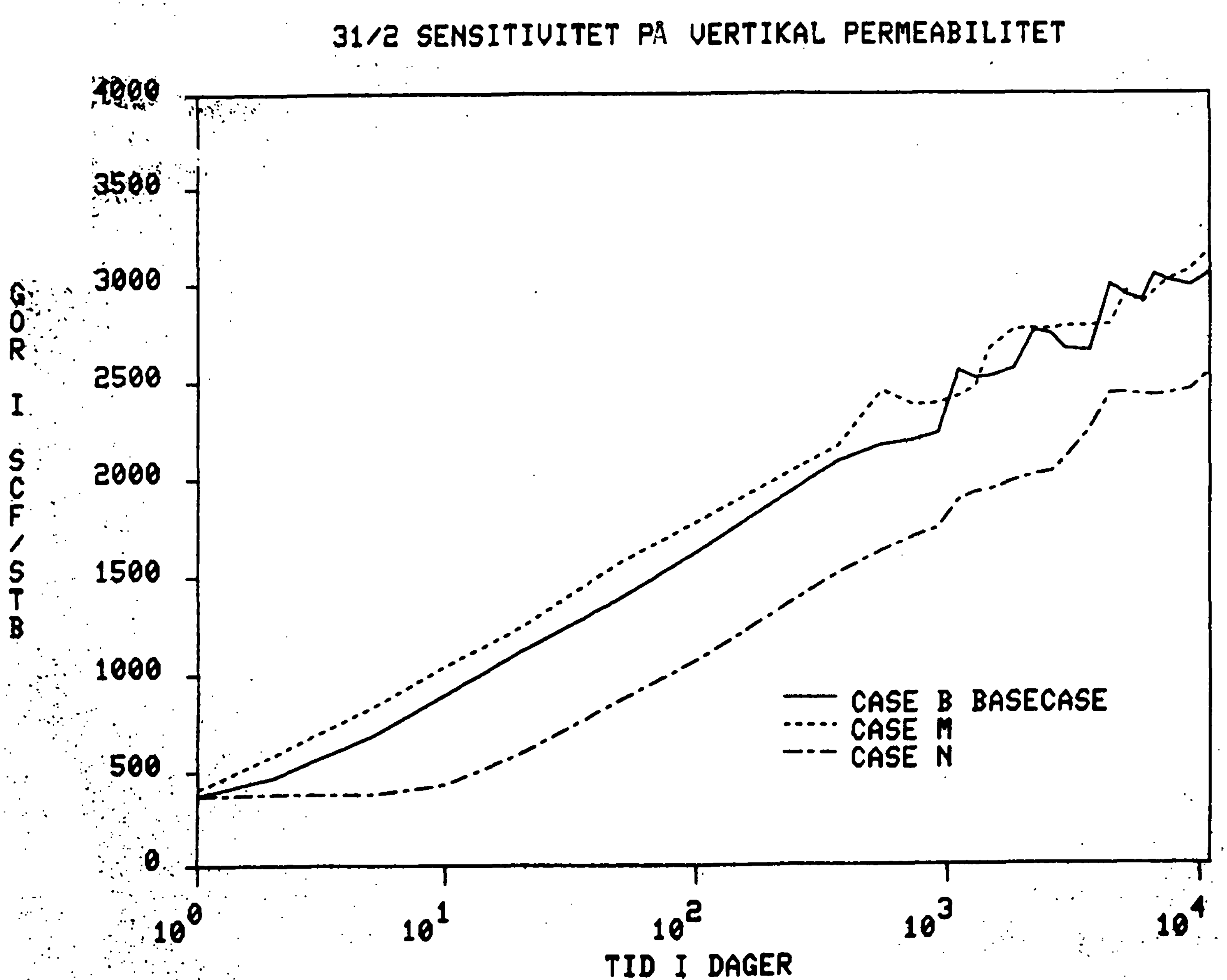


Fig. 20 GOR vs Time for Sensitivity on Vertical Permeability, Case B, M, N.

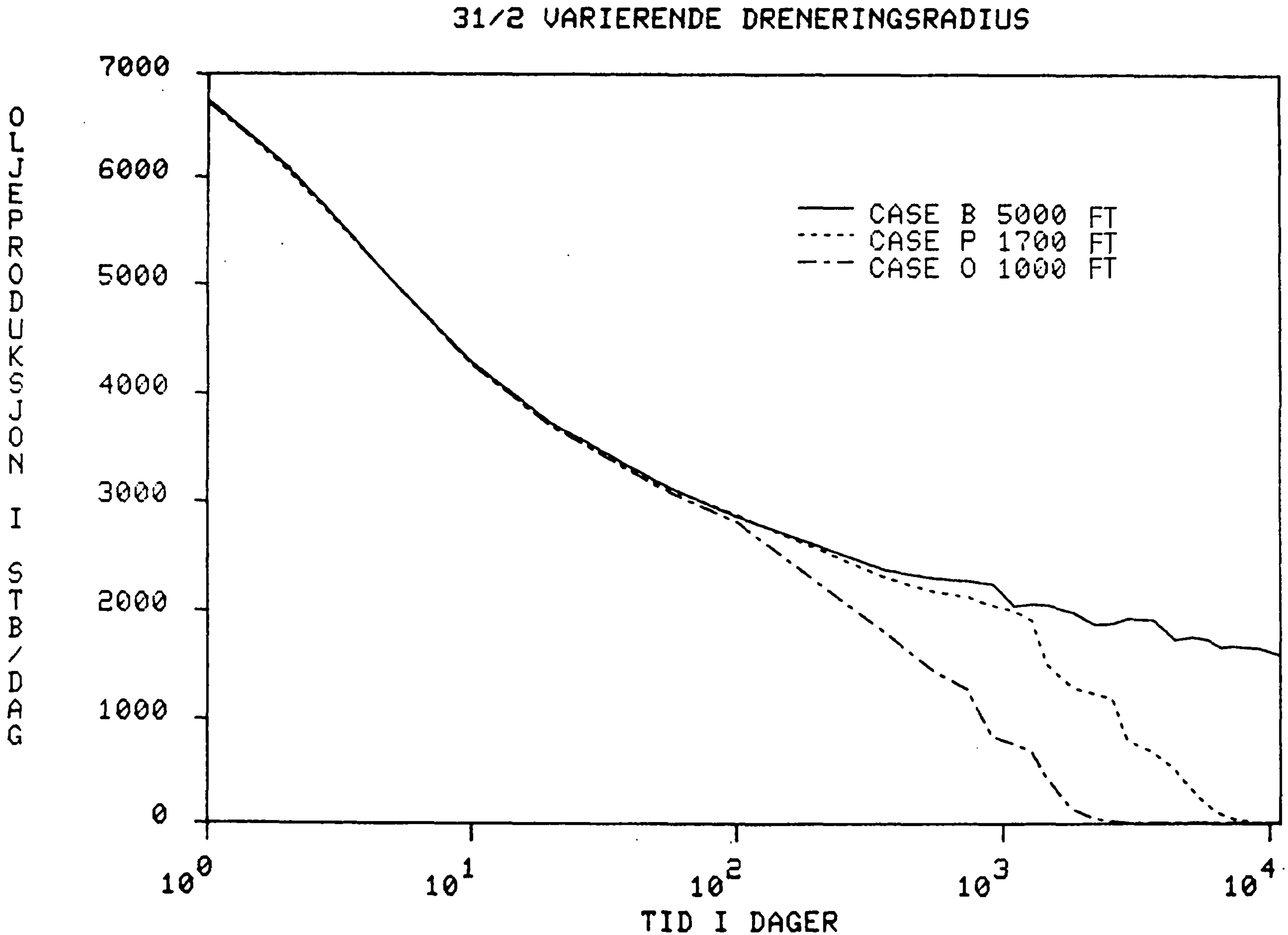


Fig. 21 Oil Production vs Time for Variable Drainage Radius, Case B, P, O.

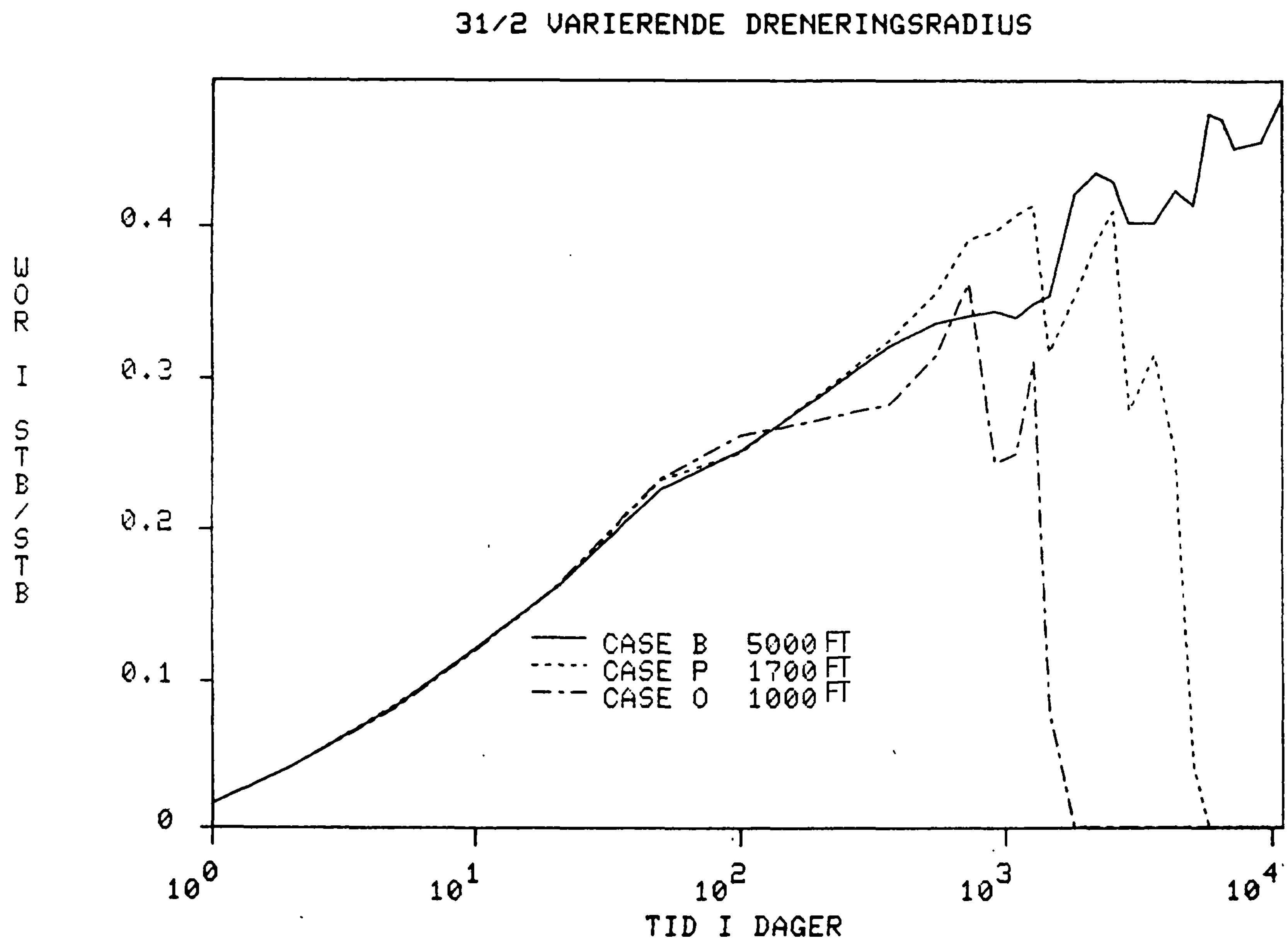


Fig. 22 WOR vs Time for Variable Drainage Radius, Case B, P, O.

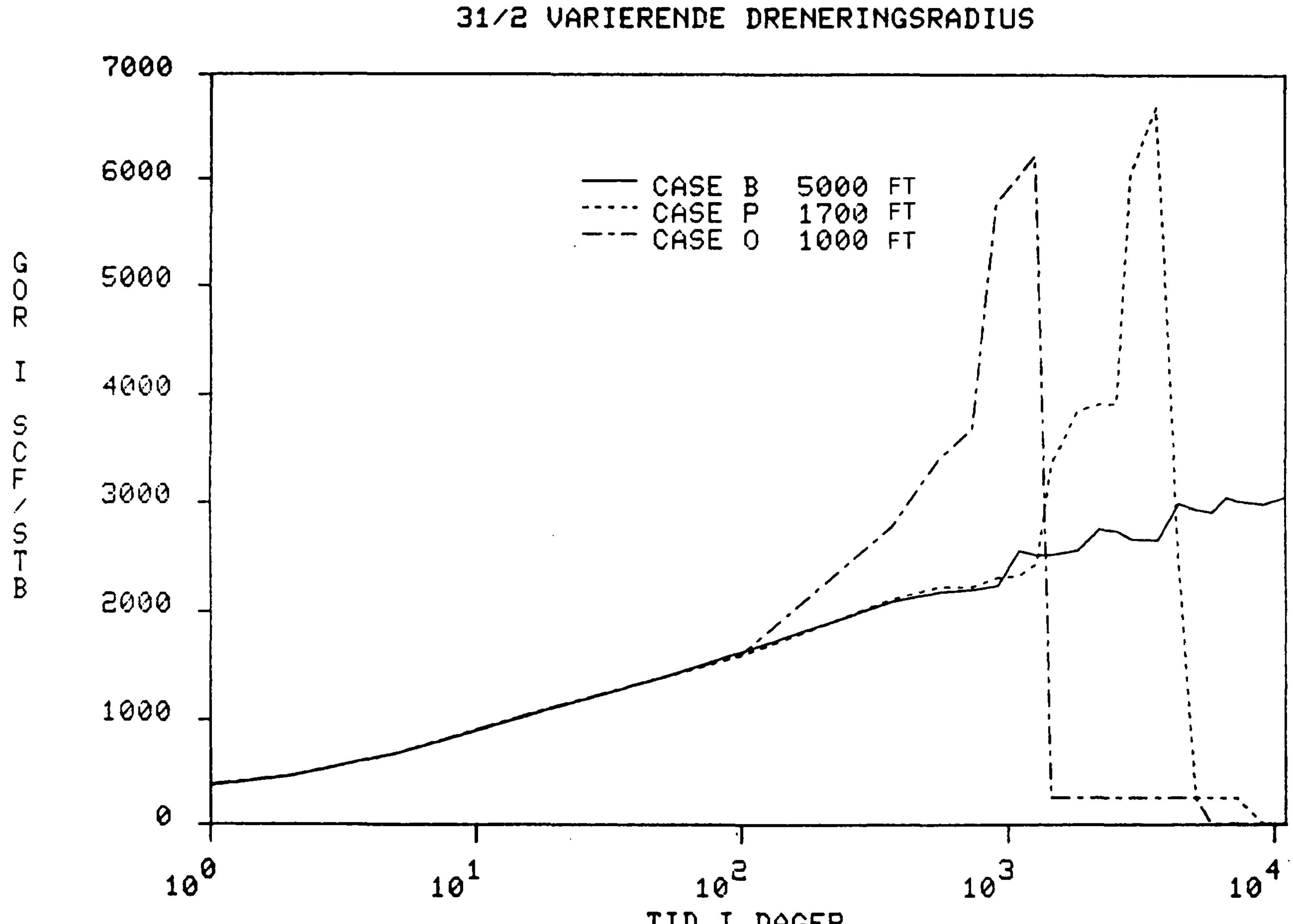


Fig. 23 Gor vs Time for Variable Drainage Radius, Case B, P, O.

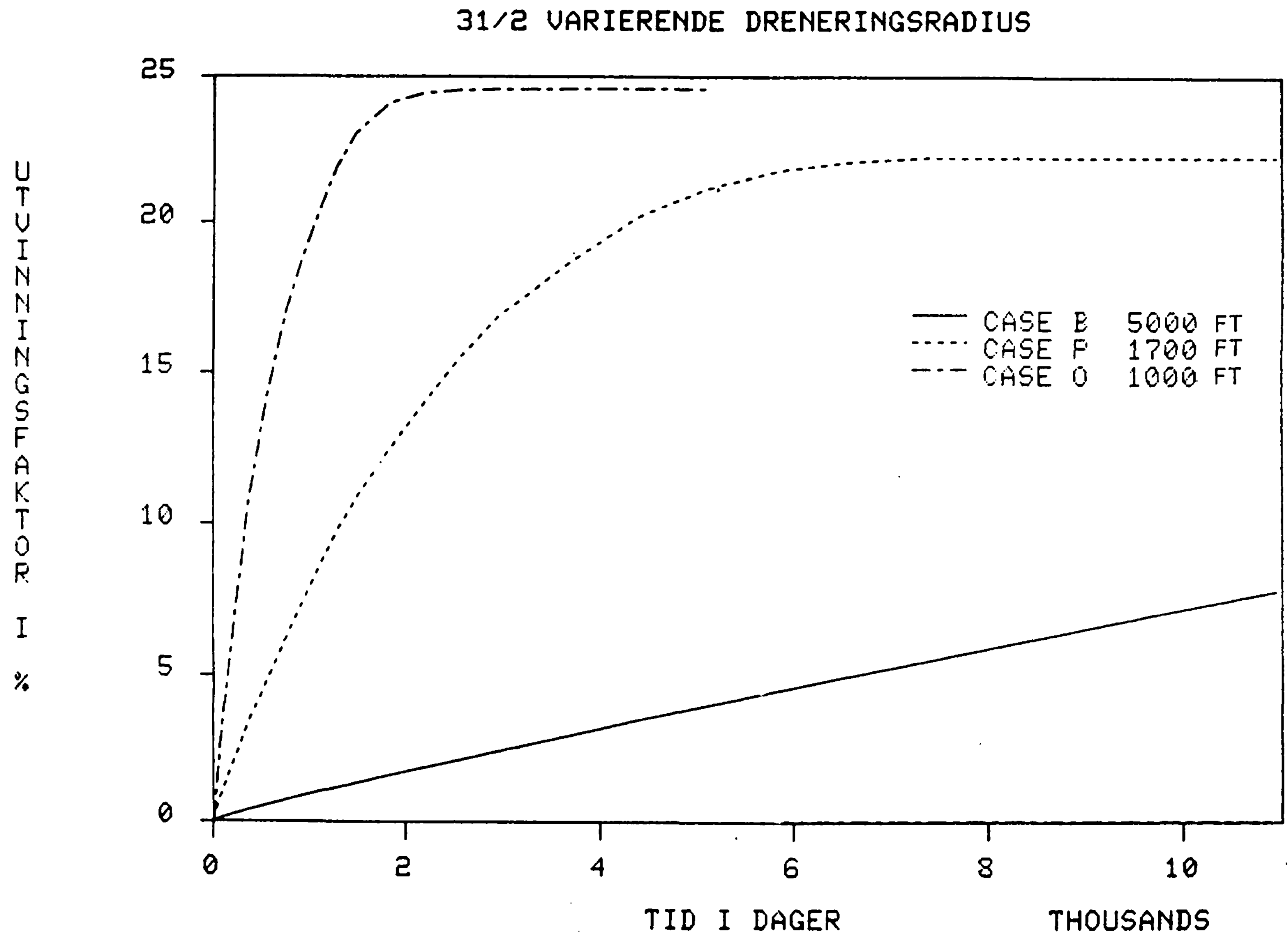


Fig. 24 Recovery vs Time for Variable Drainage Radius, Case B, P, O.

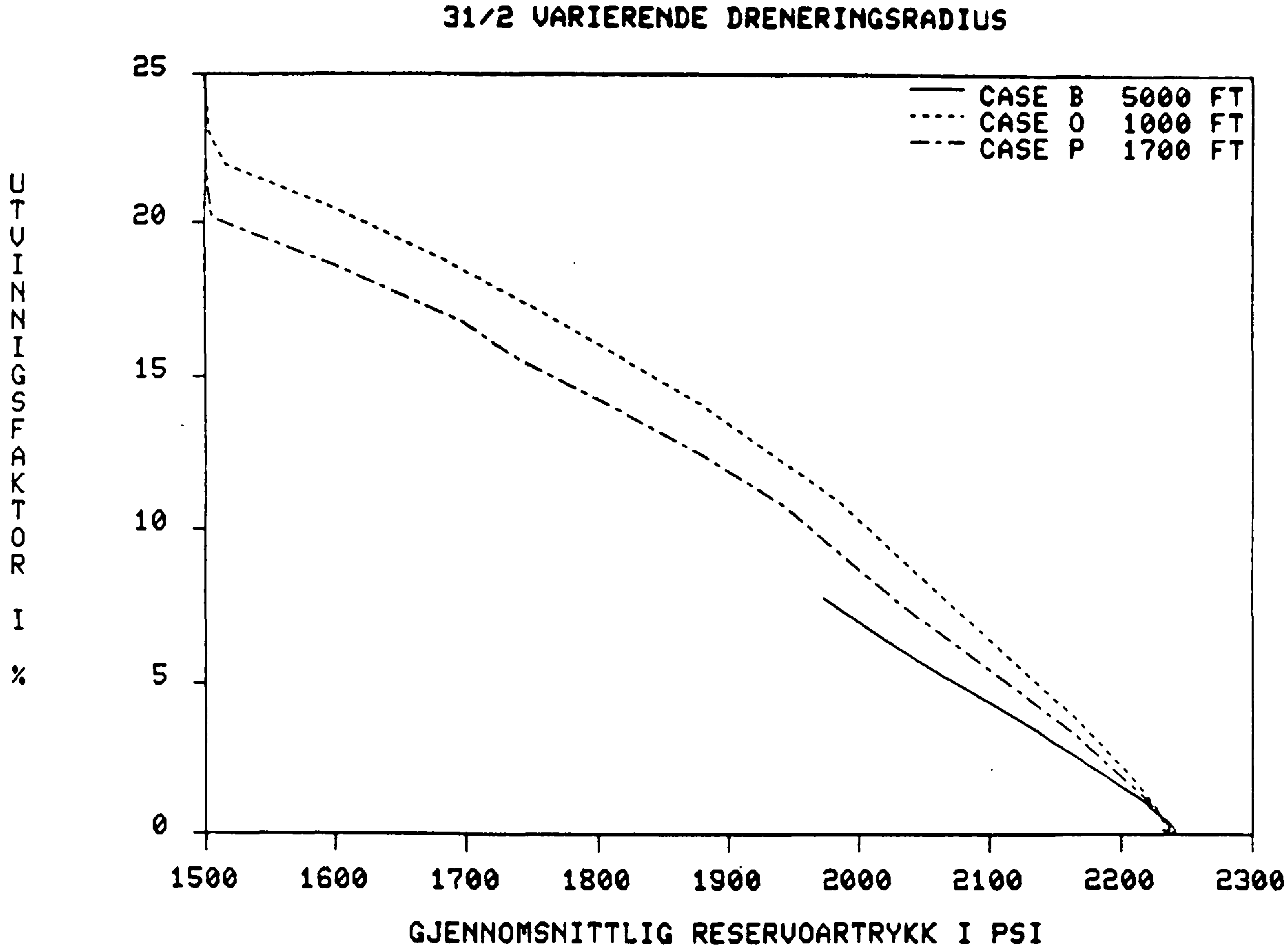


Fig. 25 Recovery vs Average Reservoir Pressure for Variable Drainage Radius, Case B, P, O.

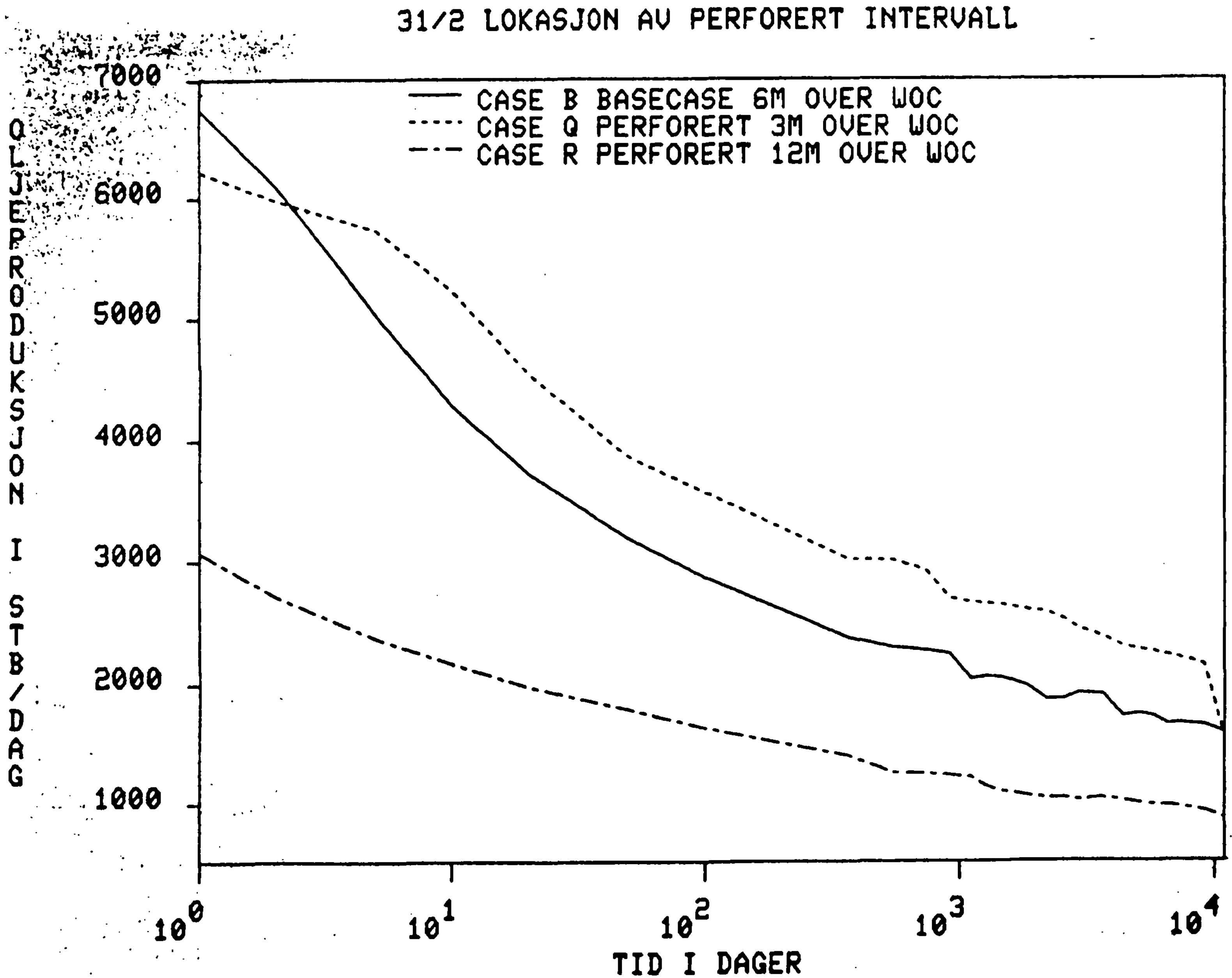


Fig. 26 Oil Production vs Time for Variable Location of the Perforated Interval, Case B, Q, R.

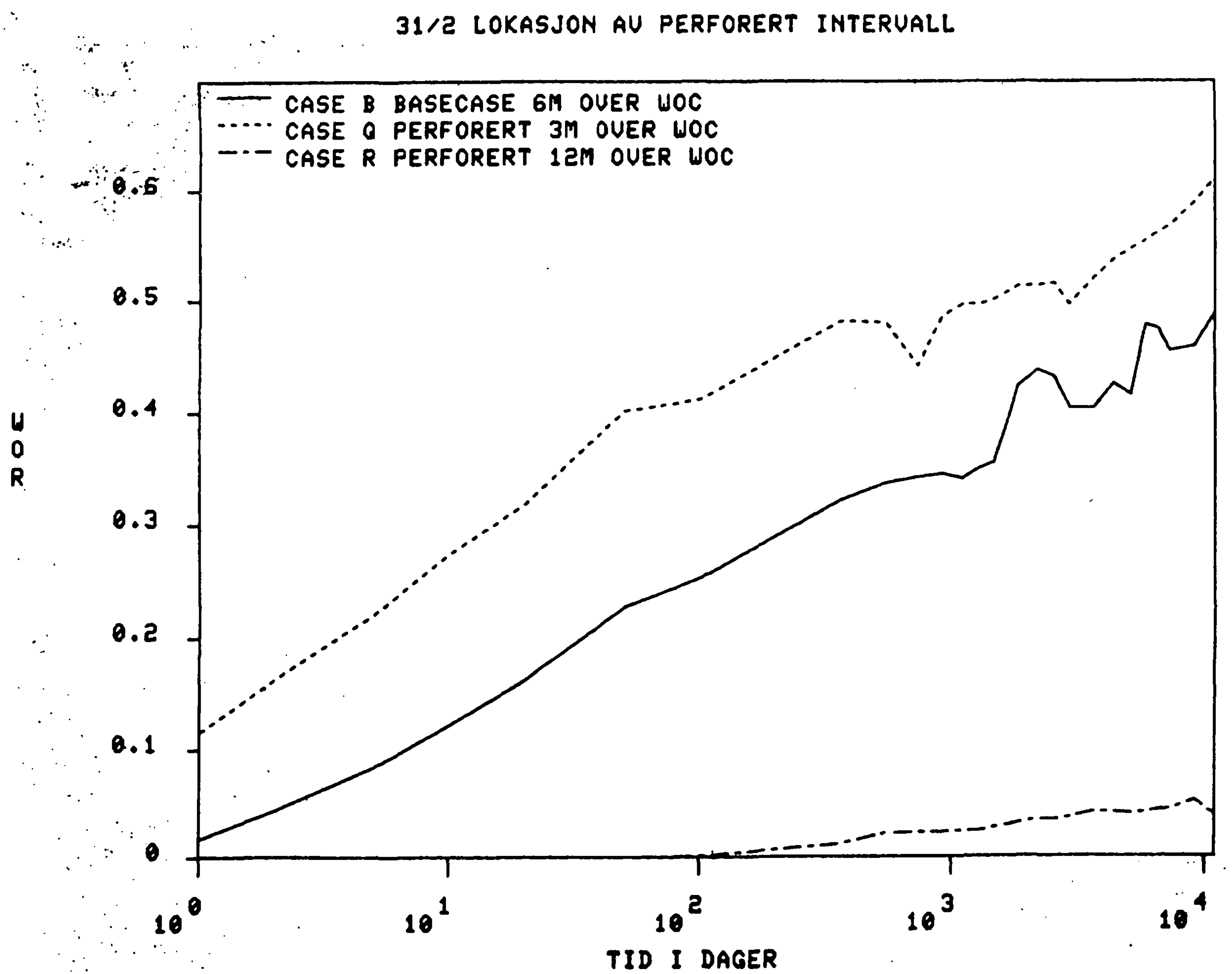


Fig. 27 WOR vs Time for Variable Location of the Perforated Interval, Case B, Q, R.

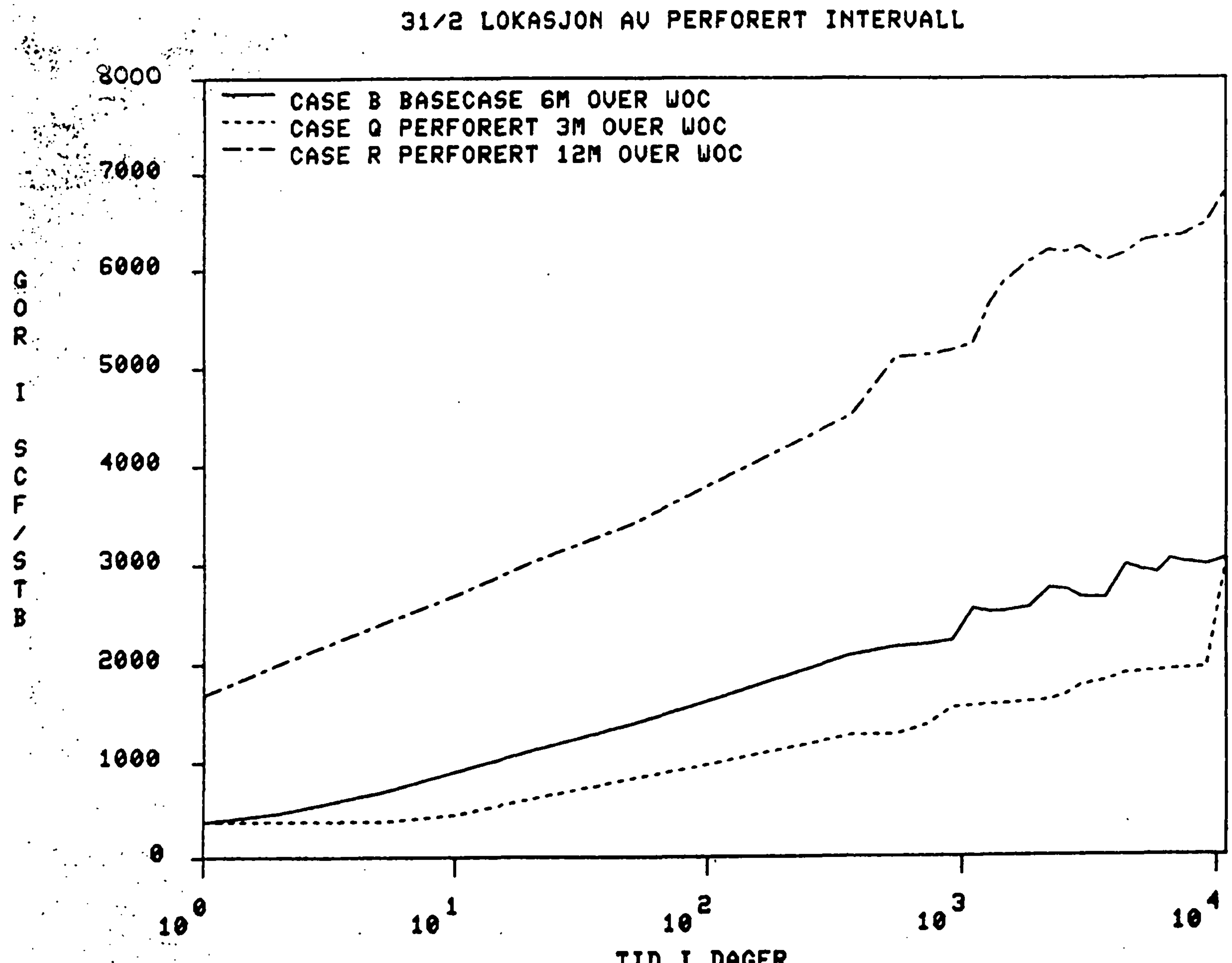


Fig. 28 GOR vs Time for Variable Location of the Perforated Interval, Case B, Q, R.

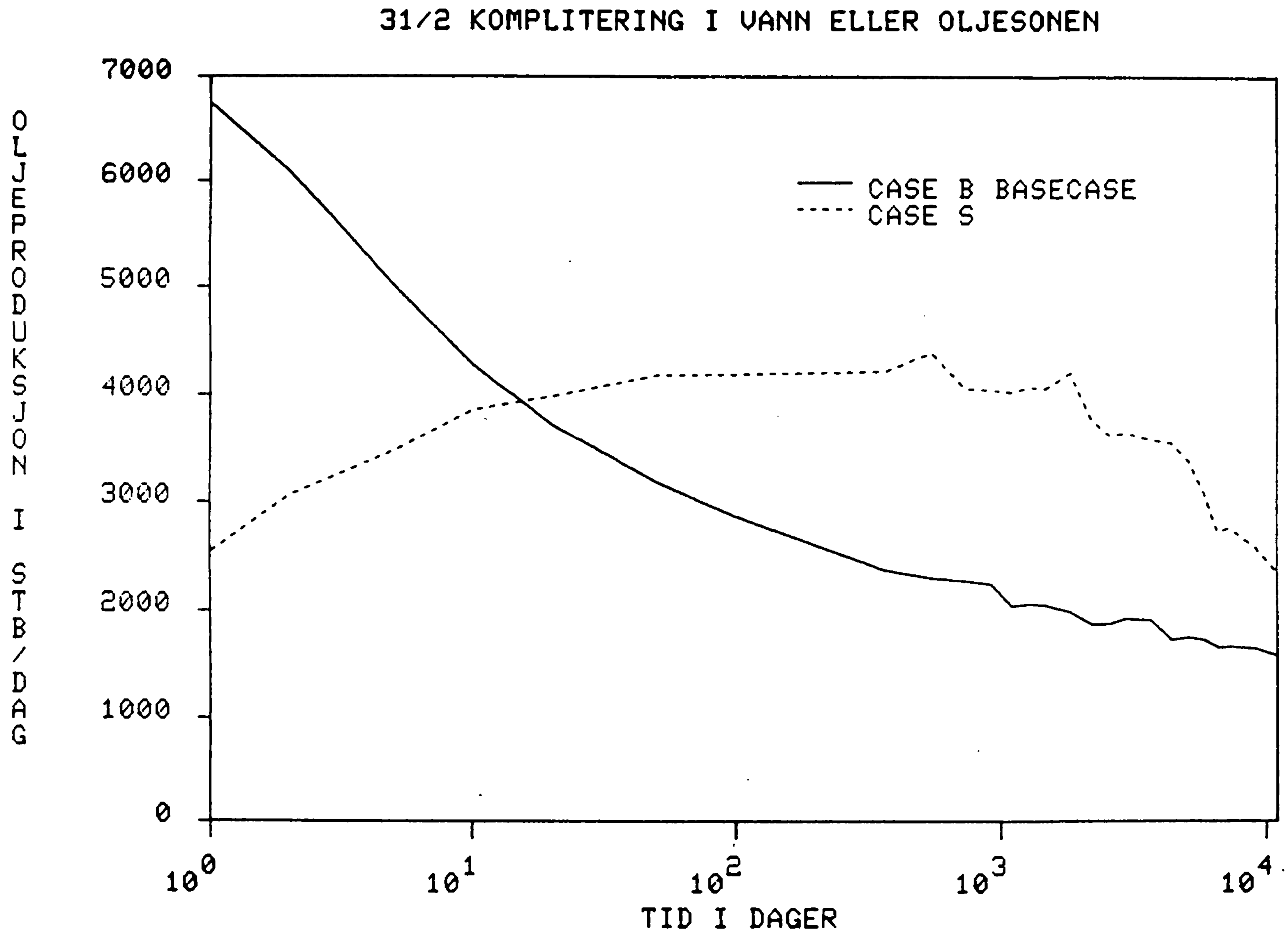


Fig. 29 Oil Production vs Time for Perforation Located in the Water Zone, Case Sand B.

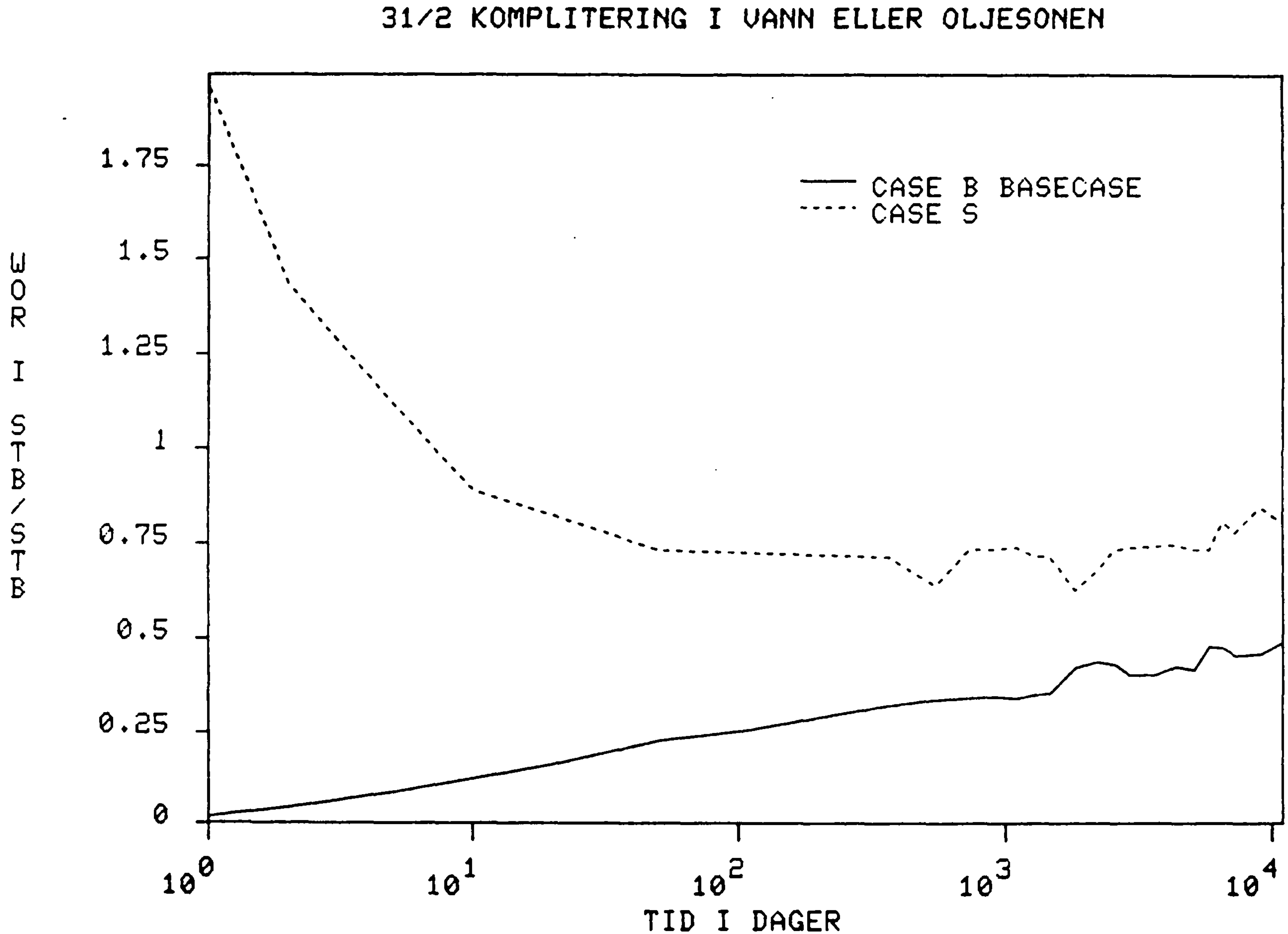


Fig. 30 WOR vs Time for Perforation Located in the Water Zone, Case Sand B.

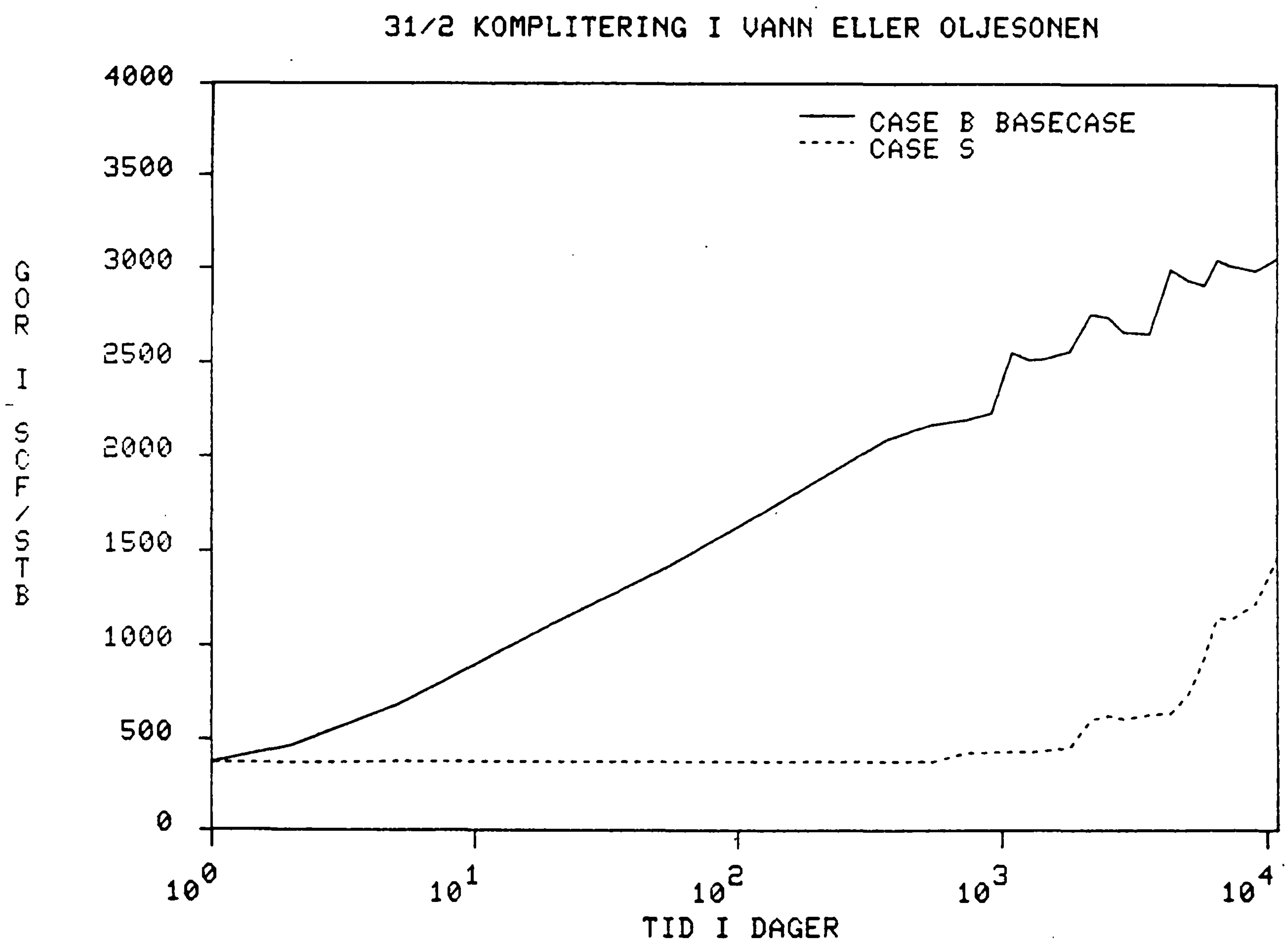


Fig. 31 GOR vs Time for Perforation Located in the Water Zone, Case Sand B.

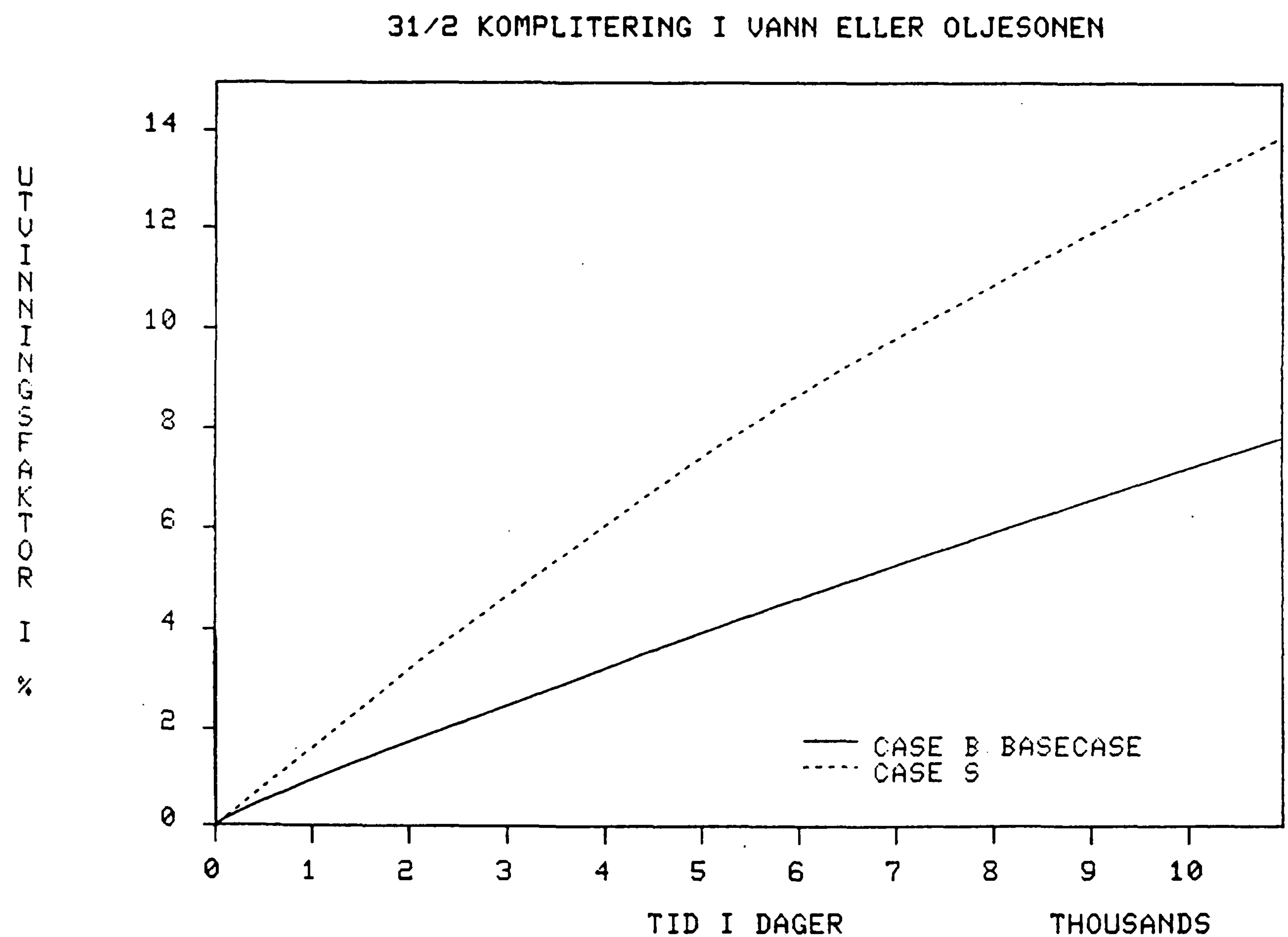


Fig. 32 Recovery vs Time for Perforation Located in the Water Zone, Case Sand B.

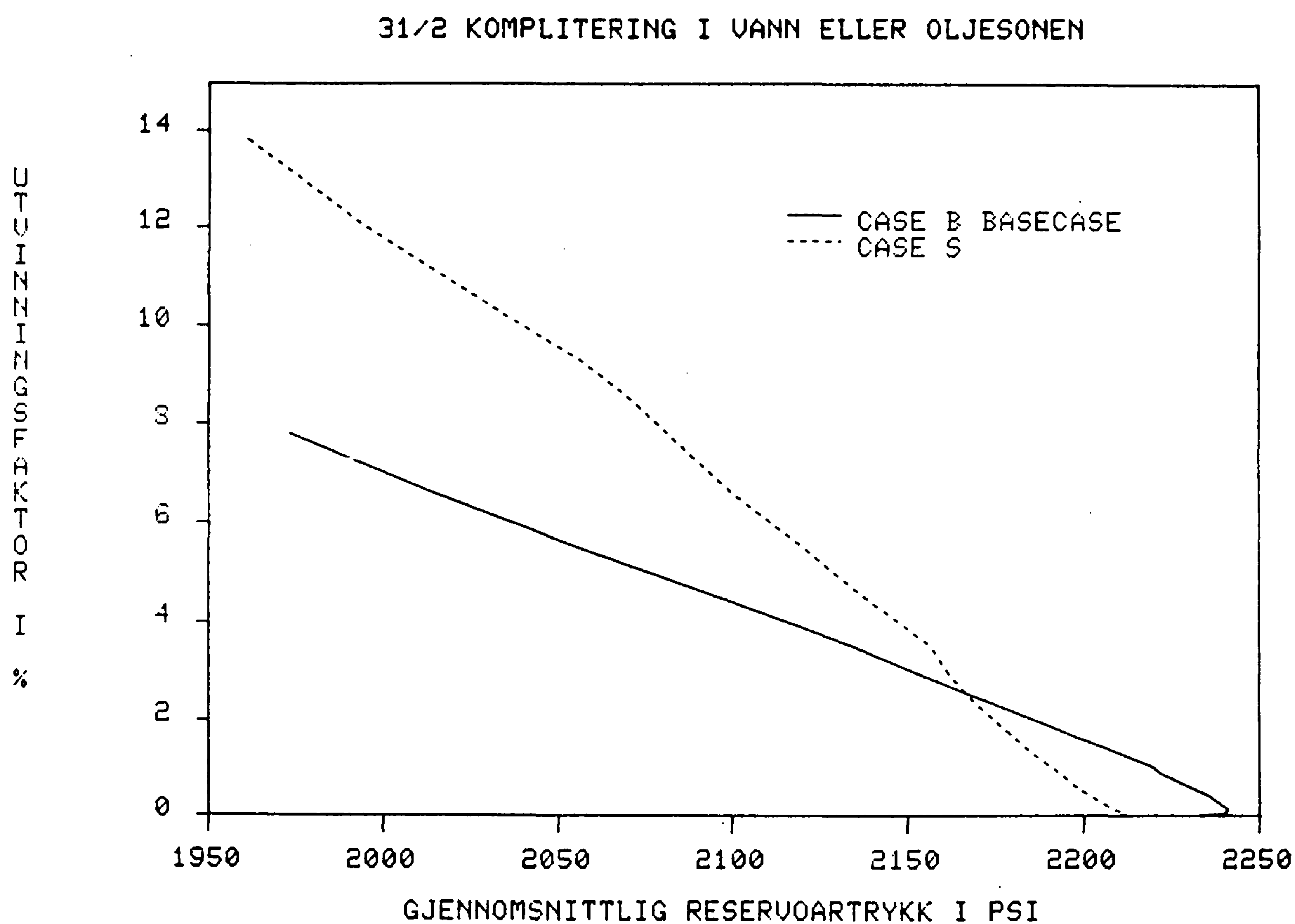


Fig. 33 Recovery vs Average Reservoir Pressure for Perforation Located in the Water Zone, Case Sand B.

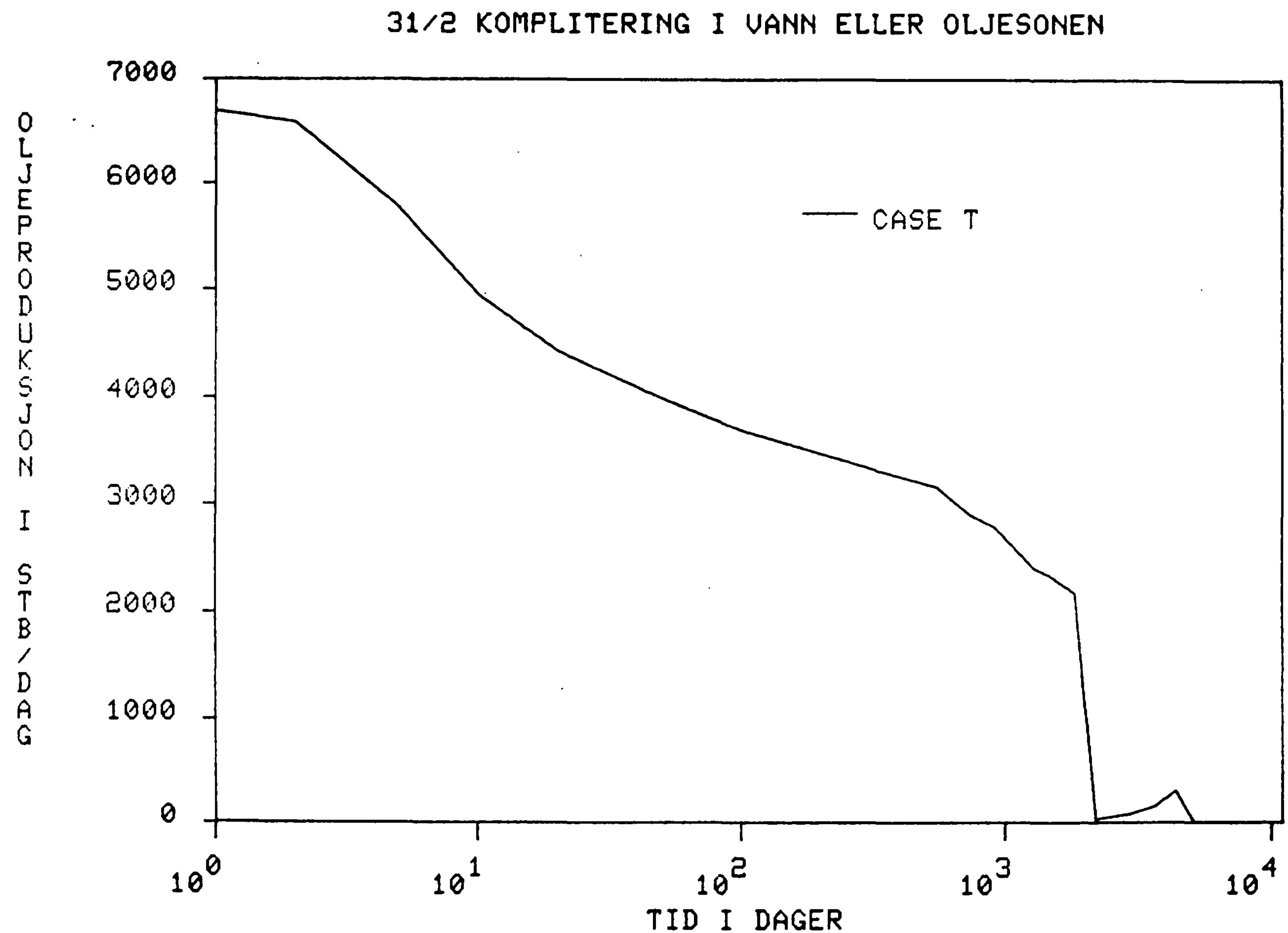


Fig. 34 Oil Production vs Time for Case T, Double Completion.

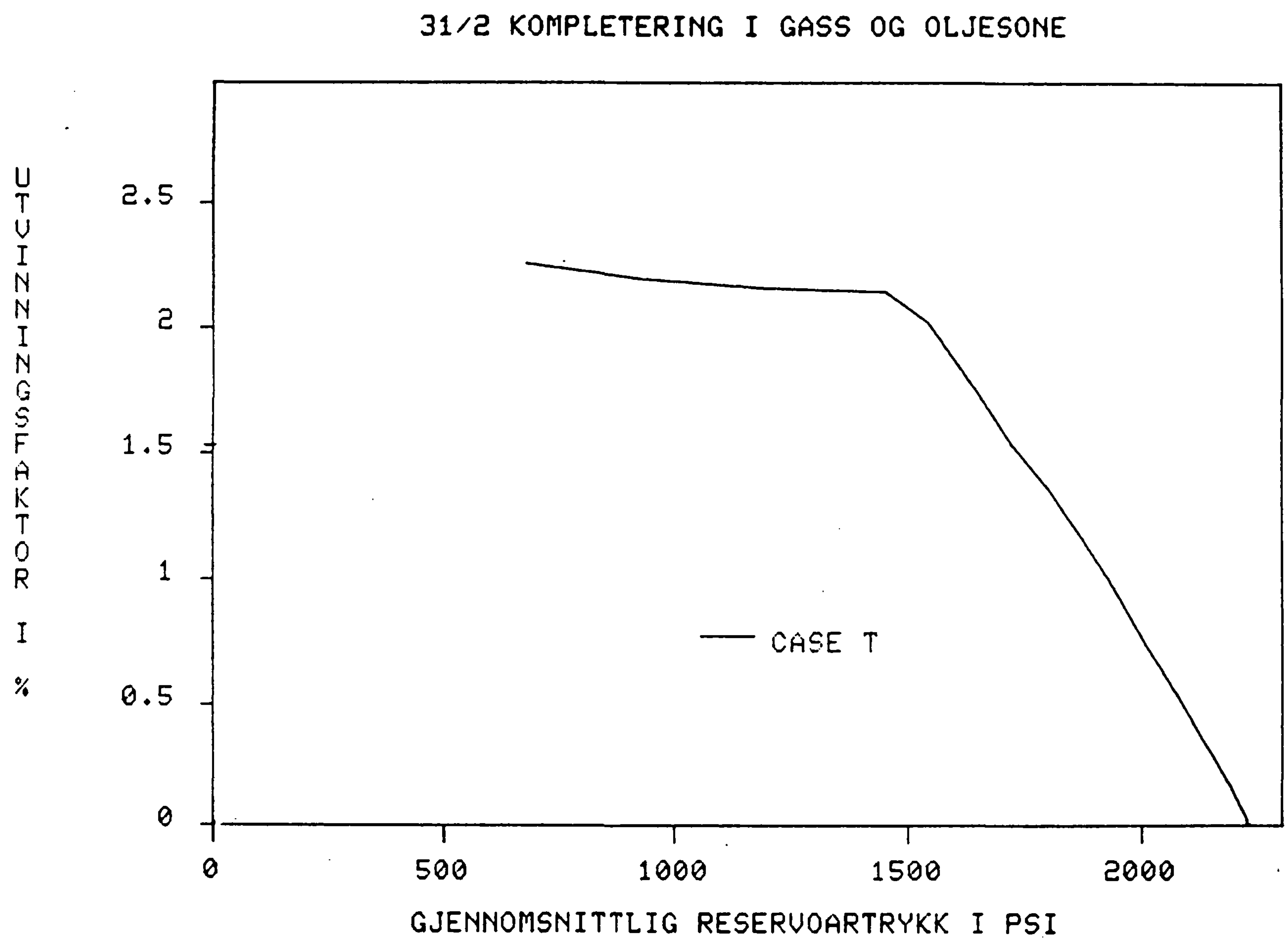


Fig. 35 Recovery vs Average Pressure for Case T, Double Completion.

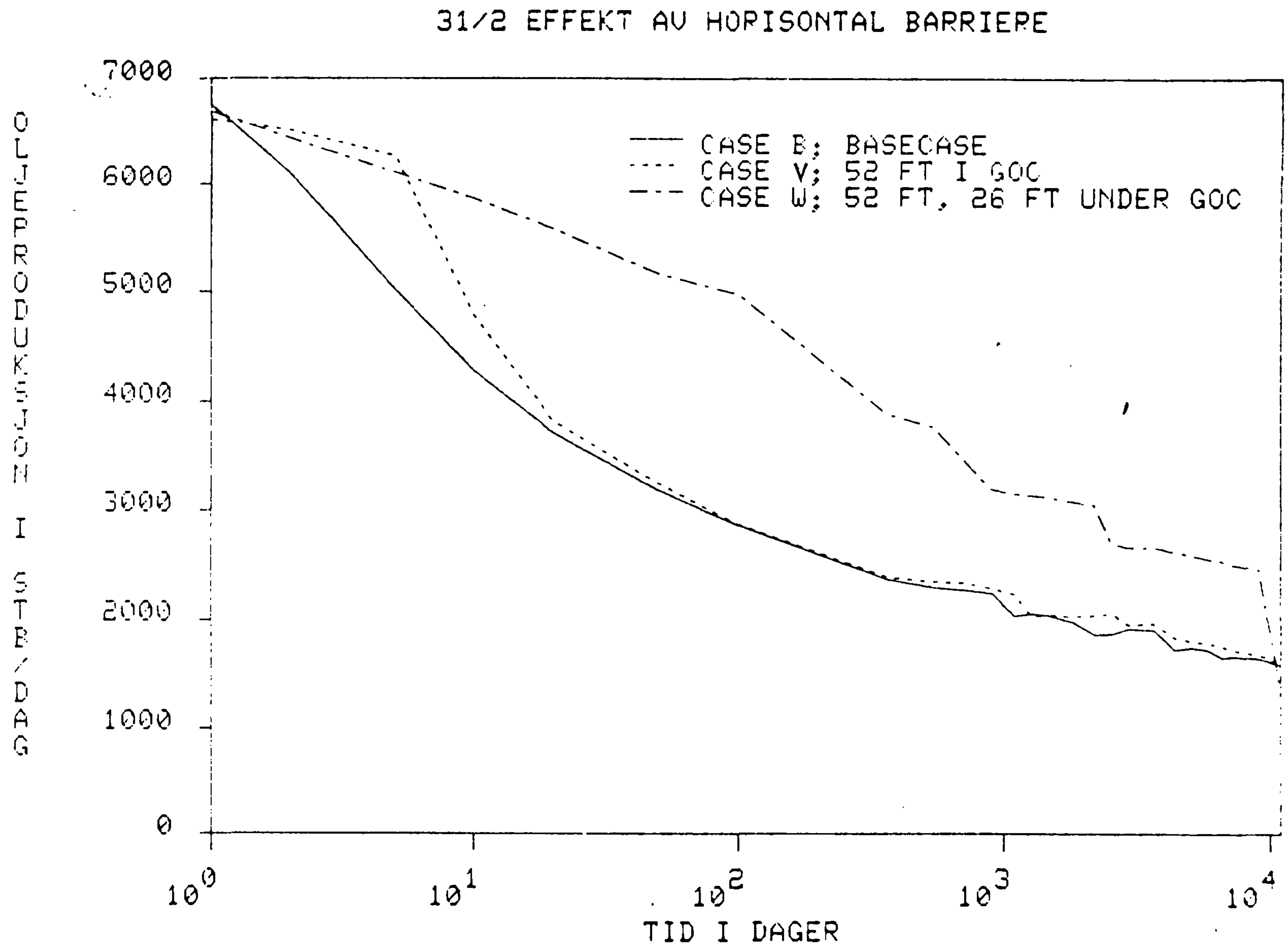


Fig. 36 Oil Production vs Time for Case B, V and W, Effect of Barriers.

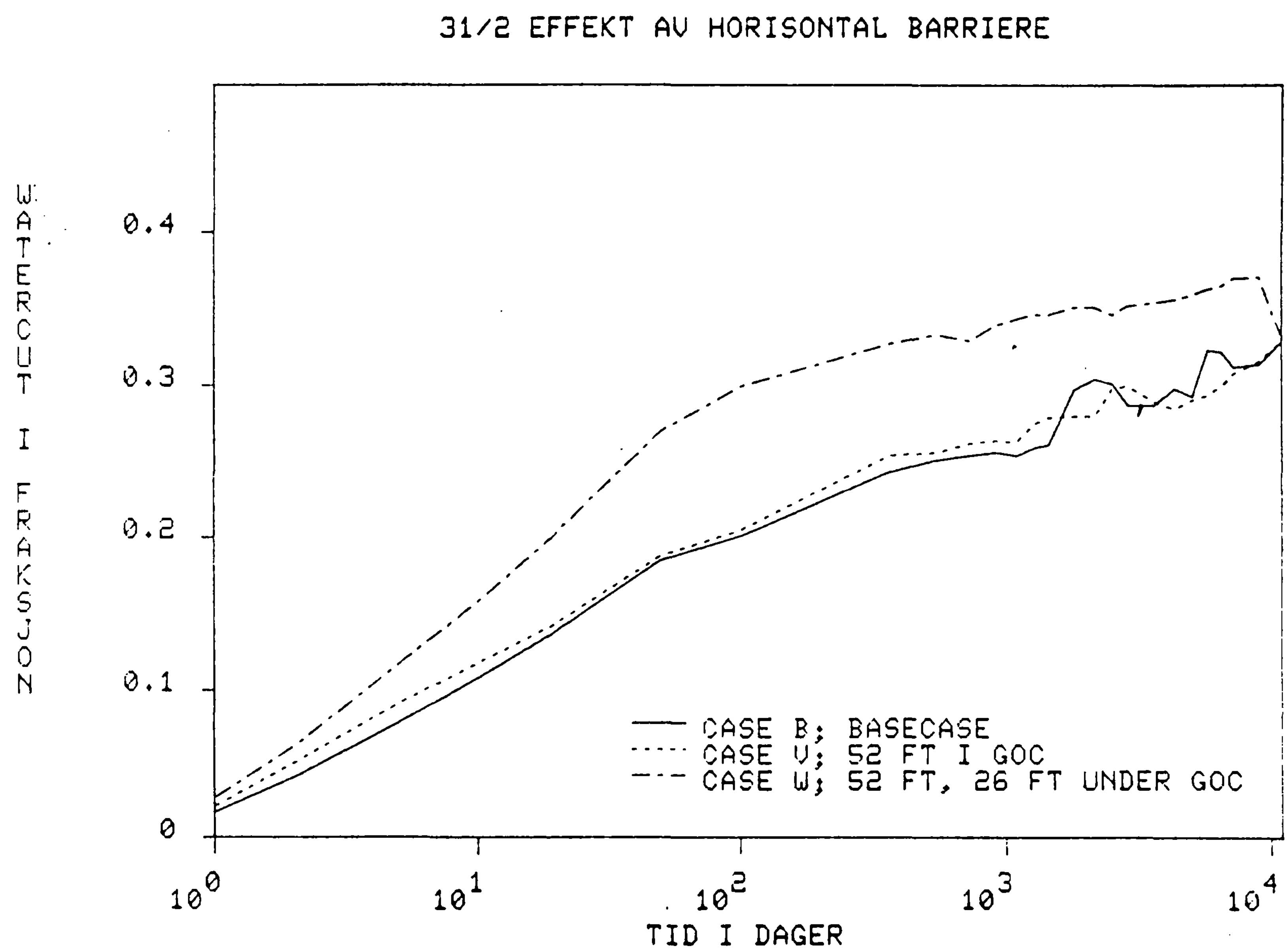


Fig. 37 Watercut vs Time for Case B, V and W, Effect of Barriers.

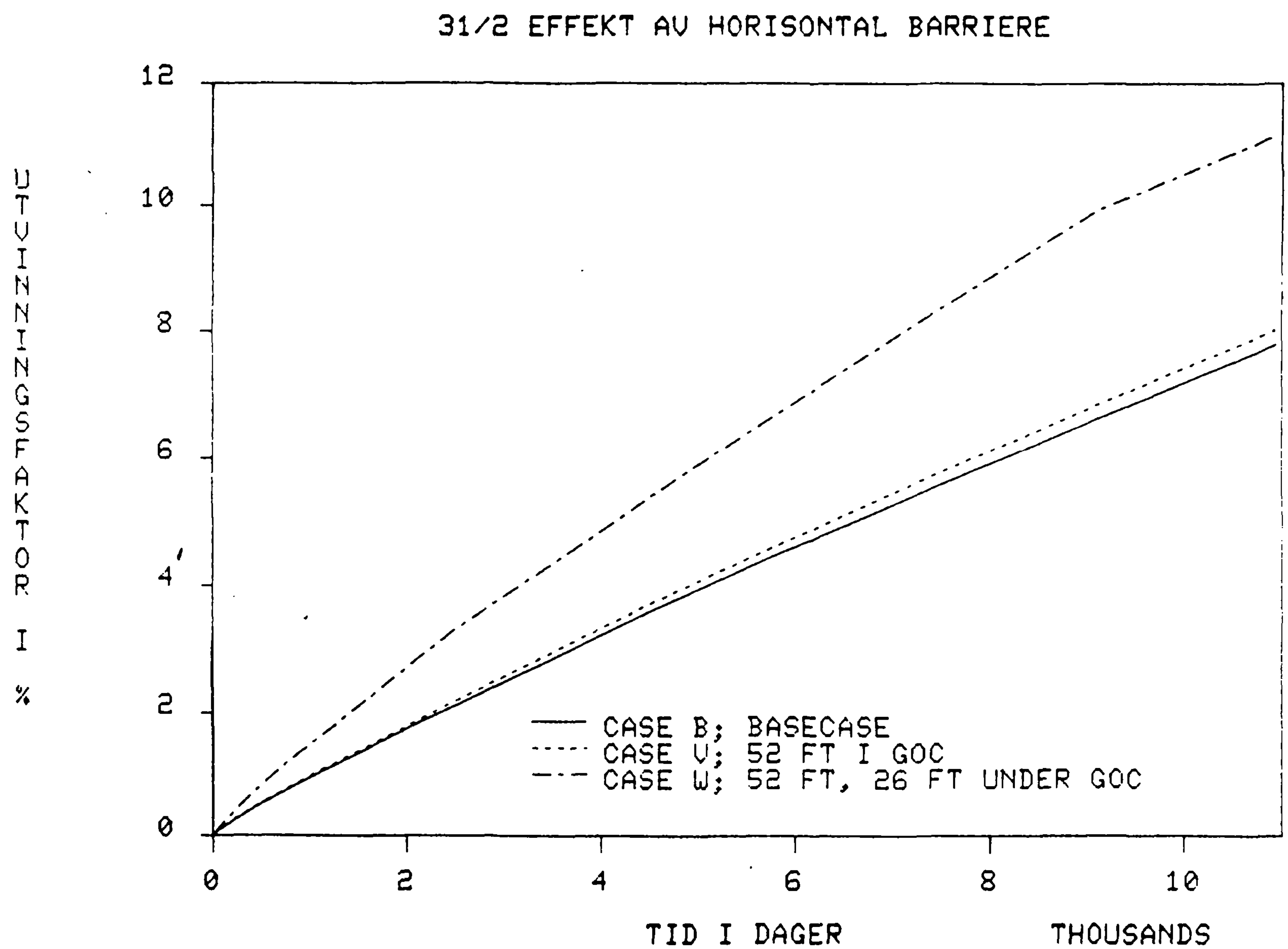


Fig. 38 Recovery vs Time for Case B, V and W, Effect of Barriers