REPORT

INTERPRETATION OF DST 1A AND DST 2,
WELL 34/10-4

NOTE

INTERPRETATION OF PRESSURE TESTS
FROM PARTIALLY PERFORATED WELLS

JANUARY, 1980

TERJE LITLEHAMAR
SVEIN M. SKJÆVELAND

ROGALANDSFORSKNING

REPORT

Interpretation of DST 1A and DST 2, well 34/10-4

Content

1 INTRODUCTION

Pressure test data from DST 1A and DST 2, well 34/10-4 has been interpreted and the results together with sample calculations and plots are presented on the following pages. Special attention has been paid to the effect of partial perforation of the productive height on the pressure response.

2 DST 1A

2.1 DATA

h_t = 90 m, total formation thickness, from CPI-log
h_p = 5 m, perforated interval
ϕ = 32.5%, average formation porosity, from CPI-log
C_w = 3.0×10^{-6} psi^{-1}, compressibility of water
C_f = 3.0×10^{-6} psi^{-1}, compressibility of reservoir rock
C_o = 8.3×10^{-6} psi^{-1}, compressibility of oil, from PVT-report
r_w = 0.106 m, well radius
S_w = 12%, average water saturation, from CPI-log
S_o = 88%, average oil saturation, from CPI-log
B_o = 1.286 RB/STB formation volume factor, from PVT-report
μ_o = 1.32 CP, viscosity of oil, from PVT-report

GAUGE S-N 1054

TEST	P*	m	t*	Δt*	k	S	r_e	S_{ao} -	S_{ae} -	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown 17^{37} - 0^{23}	Not analyzed, the pressure increases.												
Buildup 0^{23} - 9^{50}	4478.7	1.4		8.4+ 34.1	1167.		1269		49				
Drawdown 9^{50} - 12^{05}		25.0			67	8.6	176		49		5.66		
Buildup 12^{05} - BHS	4478.4	1.5		8.4+ 34.1	1121	236	1453		49	187	5.66	308	172

x Difficult to read off the flowing pressure before shutin

\+ Perforated interval located at center of formation

\- In ref. 2, no charts with $h_p < 0.1$

GAUGE S-N 1209

TEST	P*	m	t*	Δt*	k	S	r_e	S_{ao} -	S_{ae}	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown 17^{37} - 0^{23}	Not analyzed, pressure increases												
Buildup 0^{23} - 9^{50}	4487.3	1.5		18.4+ 34.1	1090		1433		49				
Drawdown 9^{50} - 12^{05}		3.0			54.5	8.5	158		49				
Buildup 12^{05} - BHS	4487.8	2.0		8.4+ 34.1	841	152	1261		49	103	5.66	308	172

\+ perforated interval located at center of formation

\- In ref. 2, no charts with $h'_p < 0.1$

GAUGE S-N 1092

TEST	P*	m	t*	Δt*	k	S	r_e	S_{ao}	S_{ae}	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown $17^{37} - 0^{23}$	Not analyzed, the accuracy of the pressure recorder is not sufficient												
Buildup $0^{23} - 9^{50}$	Not analyzed, the accuracy of the pressure recorder is not sufficient												
Drawdown $9^{50} - 12^{05}$		28			60.0	8.6	165		49				
Buildup 12^{05} - BHS	Not analyzed, the accuracy of the pressure recorder is not sufficient												

- In ref. 2, no charts with $h'_p<0.1$

P* : Extrapolated pressure from buildup (psi)

m : Slope of straight line from semilog plot (psi/cycle)

t* : Time when the second straight line is reached, drawdown test, ref. 1 (min)

Δt* : Time when the second straight line is reached, buildup test, ref. 1 (min)

k : Horizontal permeability (md)

S : Total skinfactor from test

r_e : Drainage redius (ft)

S_{ao} : Apparent skinfactor caused by geometrical effects from Odeh, ref. 2

S_{ae} : Apparent skinfactor caused by geometrical effects, ref. 1

S_t : True Skinfactor caused by damage

ΔP_{sk}: Pressure drop caused by total skin (psi)

ΔP_{sk}: Pressure drop caused by total skin (psi)

PI_{acc} Actual productivity index (STB/DAY/psi)

PI_{id}: Ideal productivity index (STB/DAY/psi)

2.3 SAMPLE CALCULATIONS

2.3.1 Introduction

Buildup test starting at 12^{05}, Gauge S-N 1054

Flow period	Flow rate	Volume produced
16^{33} - 16^{35}		4.73 STB
17^{37} - 23^{30}	1750 STB/DAY	428.99 "
23^{30} - 0^{23}	350 "	12.88 "
9^{51} - 12^{05}	1800 "	167.55 "
		614.2 STB

$$t_p = \frac{V_p}{Q} \times 24 \times 60 = \frac{614.2 \text{ STB}}{1800 \text{ STB/DAY}} \times 24 \times 60 = \underline{492 \text{ min}}$$

t_p : time produced (min)
V_p : total volume produced (STB)
Q : last flowrate before shut in (STB/DAY)

2.3.2 Transition to second straight line, ref. 1

The perforated interval is located in the lower half of the pay zone. We therefore estimate the transition to the second straight line for two cases: Perforated interval at center and at bottom of formation.

Perforated interval at bottom of formation

$$F(\Delta t_D) \approx \frac{2}{\pi^2 (h'_p)^2} \cdot R_1^{\,2} \cdot \frac{t_D + \Delta t_D}{t_D} \cdot \exp(-\pi^2 \Delta t_D / h_D^{\,2})$$

$$R_1^{\,2} = (\sin \pi h'_p \cos \tfrac{\pi}{2} h'_p)^2$$

Perforated interval at center of formation:

$$F(\Delta t_D) \approx \frac{2}{\pi^2 (h'_p)^2} \cdot R_2^{\,2} \frac{t_D + \Delta t_D}{t_D} \cdot \exp(-4\pi^2 \Delta t_D / h_D^{\,2})$$

$$R_2^{\,2} = \sin^2 2\pi h'_p$$

Common data

$h'_p = h_p/h_t = 5./90. = \underline{0.055}$

$h'_1 = h_1/h_t = 42.5/90 = \underline{0.472}$

$h_D = h_t/r_w = 90./0.35.0.3048 = \underline{843}$

$C_t = (S_o \cdot C_o + S_w \cdot C_w + C_f) = (0.88 \times 8.3 + 0.12 \times 3.0 + 3.0) \times 10^{-6} =$

$\underline{10.66 \cdot 10^{-6}}$

$k_h = k_v = 1000$ md (assumed)

2.3.2.1 Transition to second straight line, perforated interval at bottom of formation.

$t = 492$ min

$$t_D = \frac{k \cdot t}{\phi \mu C_t \cdot (r_w)^2 x3800}$$

$$R_1^2 = (\sin\pi x\ 0.055 \times \cos\frac{\pi}{2} \times 0.055)^2 = \underline{0.029}$$

$$t_D = \frac{1000 \times 492/60}{0.325 \times 1.32 \times 10.66 \times 10^{-6} \times (0.35)^2 x3800} = \underline{3.85 \times 10^6}$$

$$0.05 = \frac{2}{\pi^2 \cdot (0.055)^2} \times \frac{3.85 \times 10^6 + \Delta t_D}{3.85 \times 10^6} \times 0.029 \exp(-\pi^2 \Delta t_D/843)$$

$$\ln(\frac{3.85 \times 10^6}{3.85 \times 10^6 + \Delta t_D} \times 0.0257) = -\pi^2 \cdot \Delta t_D/(843)^2$$

$$\Delta t_D = -\frac{843^2}{\pi^2} \ln\left(\frac{3.85 \times 10^6}{3.85 \times 10^6 + \Delta t_D} \times 0.0257\right)$$

Starting with $\Delta t_D = 3.0 \times 10^5$

$\Delta t_D = 2.7 \times 10^5$

$$\Delta t^* = 3800 \times \frac{1.32 \times 0.325 \times 10.66 \times 10^{-6} \times (0.35)^2}{1000} \times 2.7 \times 10^5 = \underline{0.56 \text{ hrs}}$$

$\underline{\Delta t^* = 34.1 \text{ min}}$

2.3.2.2 Transition to second straight line, perforation located at center of perforation

$t_D = 3.85 \times 10^6$

$R_2^{\ 2} = \sin^2(2\pi \times 0.472) = \underline{0.030}$

$$0.05 = \frac{2}{\pi^2 (0.055)^2} \times 0.030 \ \frac{3.85 \times 10^6 + \Delta t_D}{3.85 \times 10^6} \times \exp(-4\pi^2/843^2)$$

$$\Delta t_D = -\frac{843^2}{4\pi^2} \ln\left(\frac{3.85 \times 10^6}{3.85 \times 10^6 + \Delta t_D} \times 0.0248\right)$$

Starting with $\Delta t_D = 3.0 \times 10^5$

$\Delta t_D = 1.29 \times 10^5$

$$\Delta t^* = 3800 \times \frac{0.325 \times 1.32 \times 10.66 \times 10^{-6} \times (0.35)^2 \times 1.29 \times 10^5}{1000} = \underline{0.14 \text{ hrs}}$$

$\underline{\Delta t^* = 8.4 \text{ min}}$

2.3.4 Permeability, skinfactor and productivity index

Permeability:

$$m = \frac{162.5 \times B_o \times \mu_o \times Q_o}{k \times h}$$

From fig. 2.1 m = 1.5 psi/cycle

$$k = \frac{162.5 \times 1.286 \times 1.32 \times 1800}{1.5 \times 90 \times 3.28}$$

$$k = \underline{1121 \text{ md}}$$

Skinfactor:

$$S = 1.151 \left(\frac{P_{1HR} - P_{wf}}{m} - \log\frac{k}{\phi \cdot \mu \cdot C_t \,(r_w)^2} + 3.23\right)$$

From fig. 2.1 P_{1HR} = 4477 psi

$$S = 1.151 \left(\frac{4477.0 - 4160.7}{1.5} - \log\frac{1121}{0.325 \times 1.32 \times 10^{-6} \times (0.35)^2} + 3.23\right)$$

$$S = \underline{236}$$

$$S_{ae} = \frac{2}{\pi^2 (h' - h'_1)^2} \sum_{n=1}^{\infty} R_n^2 \; K_o(n\pi r_d), \text{ ref. 1.}$$

$$S_{ac} = 49$$

$$S_t = S - S_{ac} = 236 - 49 = \underline{187}$$

$$r_e = \sqrt{\frac{0.00105 \; k \; t}{\phi \cdot \mu \cdot C_t}} = \sqrt{\frac{0.00105 \times 1121 \times 492/60}{0.325 \times 1.32 \times 10.66 \times 10^{-6}}}$$

$$r_e = \underline{1453 \text{ ft}}$$

Actual productivity index:

$$PI_{acc} = \frac{Q}{P^* - P_{wf}} = \frac{1800}{4478.4 - 4160} = 5.65 \text{ STB/DAY/psi}$$

Ideal productivity index:

$$PI_{id} = \frac{Q}{P^* - P_{wf} - \Delta P_{sk}}$$

$$\Delta P_{sk} = 0.87 \cdot S \cdot m = 0.87 \times 236 \times 1.5 = 307.9$$

$$PI_{id} = \frac{1800}{4478.4 - 4160 - 307.9} = \underline{172.7 \text{ STB/DAY/psi}}$$

P_{ws} (psi)	$\frac{t+\Delta t}{\Delta t}$
4465.88	493.
4471.93	165.
4473.36	99.4
4475.17	55.6
4475.52	45.7
4475.52	38.8
4476.23	29.8
4476.23	26.6
4476.23	24.2
4476.55	20.5
4476.55	19.0
4476.95	17.5
4476.52	15.7
4476.87	14.8
44.76.52	14.1
4476.86	12.8
4476.86	12.3
4476.86	11.8
4476.81	10.9
4477.17	10.5
4477.17	10.1
4477.14	9.5
4476.80	9.2
4477.14	9.1
4477.58	5.0
4477.58	5.0
4477.70	2.5
4477.70	2.5
4478.0	2.1

Table 2.1 Data plotted in Fig. 2.1

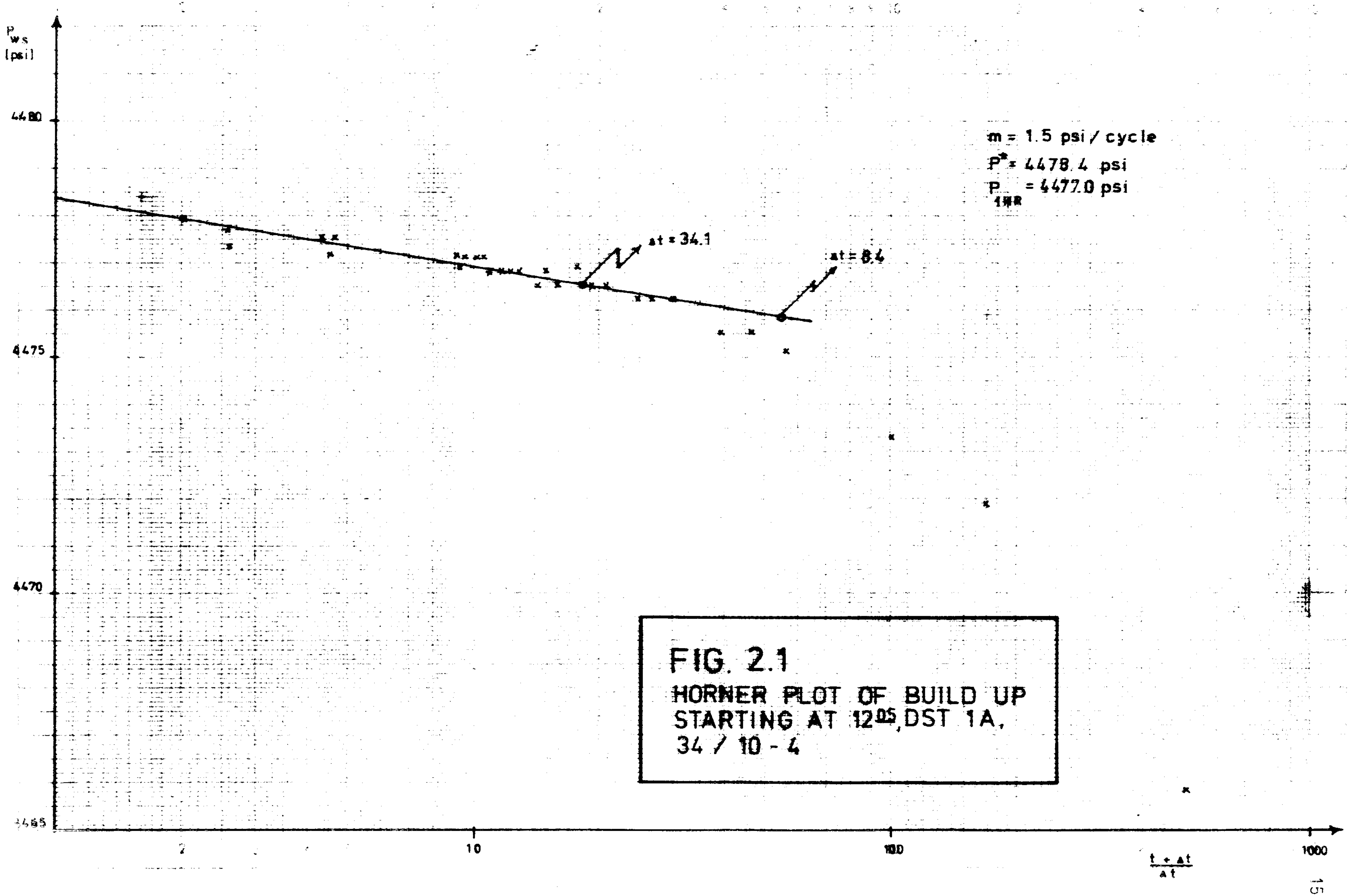


FIG. 2.1
HORNER PLOT OF BUILD UP STARTING AT 12⁰⁵, DST 1A, 34 / 10 - 4

2.4 DISCUSSION

From simulation with a two dimensional radial reservoir simulator and the theory presented in ref. 1, it seems rather clear that in this highly permeable formation that one should use total formation thickness in the kh product.

It is possible from ref. 1 to estimate when the second straight line is reached. Using a total formation thickness of 90 m, gives a Δt^* between 8 min and 34 min, depending on where the perforated interval is located.

These shutin times matches rather well with the beginning of the straight line on Fig. 2.1. However, if a total thickness h_t = 42.5 is used, ref. 1, the transition to the second straight line should have occured within 1 min after shutin.

We are not presently able to explain the 15 - 20 fold difference in permeability from buildup and drawdown test. It may be caused by a time-dependent skin other than the geometrical skin. The permeability values from buildup test are probably more reliable than the ones from drawdown, and corresponds better to the core measured values.

2.5 CONCLUSION

Based on interpretation of data we think that the buildup test starting at $12^{\underline{05}}$, gauge S-N 1054, gives the most reliable results. The test gives a horizontal permeability of 1121 md which corresponds rather well with the measured core permeability. The estimated start of the second straight line matches the beginning of the straight line on the Horner plot, fig. 2.1. The results from DST 1A are then:

Horizontal permeability:

$k = 1121$ md

Extrapolated pressure:

$P^* = 4478.4$ psi

True skinfactor:

$S_t = 187$

Ideal productivity index:

$PI_{id} = 172$ STB/D/psi

3 DST 2

3.1 DATA

h_t = 90 m, total formation thickness, from CPI-log
h_p = 2 m, perforated interval
ϕ = 32.5%, average formation porosity, from CPI-log
C_w = 3.0×10^{-6} psi^{-1}, compressibility of water
C_f = 3.0×10^{-6} psi^{-1}, compressibility of reservoir rock
C_o = 8.3×10^{-6} psi^{-1}, compressibility of oil, from PVT-report
r_w = 0.106 m, well radius
S_w = 12%, average water saturation, from CPI-log
S_o = 88%, average oil saturation, from CPI-log
B_o = 1.286 STB/RB, formation volume factor, from PVT-report
μ_o = 1.32 CP, viscosity of oil, from PVT-report

GAUGE S-N 1054

TEST	P*	m	t*	Δt*	k	s	r_e	$\bar{S}_{ao}$	S_{ae}	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown $10^{\underline{40}}$ - $18^{\underline{10}}$	Great variations in pressure recordings												
Buildup $18^{\underline{10}}$ - $19^{\underline{21}}$	4419.6	0.7		32	1667	85	1686		65.5	20.5	21.9		
Drawdown $19^{\underline{21}}$ - $22^{\underline{21}}$	Pressure is nearly constant												
Buildup $22^{\underline{21}}$ - $23^{\underline{48}}$	Great variations in pressure recordings												
Drawdown $23^{\underline{48}}$ - $3^{\underline{08}}$	Pressure is nearly constant												
Buildup $3^{\underline{08}}$ - $3^{\underline{56}}$	4420.3	0.5		31.2	653	28.5	2220		65.5		21.4		
Multirate drawdown $3^{\underline{56}}$ - $12^{\underline{26}}$	Difficult to analyze												
Buildup $12^{\underline{26}}$ - $17^{\underline{30}}$	4419.2	2.3		32.6	1645.0	99.0	1809		65.5	33.5	18.8	198	246
Multirate builtup $12^{\underline{26}}$ - $17^{\underline{30}}$	4419.3	2.8		32.6	1351	80.1	1639		65.5	14.6	18.9	195	207

- In ref. 2, no charts with $h'_p < 0.01$

GAUGE S-N 1209

TEST	p*	m	t*	Δt*	k	s	r_e	$\bar{S}_{ao}$	S_{ae}	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown $10^{40} - 18^{10}$	Not analyzed the pressure increases												
Buildup $18^{10} - 19^{21}$	4422.5	1.6		32	729	34	1115		65.5		25.2		
Drawdown $19^{21} - 22^{21}$	Nearly constant pressure												
Buildup $22^{21} - 23^{48}$	4422.5	0.9		31.6	378	11			65.5		22.1		
Drawdown $23^{48} - 3^{08}$	Nearly constant pressure												
Buildup $3^{08} - 3^{56}$	4422.6	0.7	-	31.2	466	16	1875		65.5				
Multirate drawdown $3^{56} - 12^{26}$	Difficult to analyze												
Buildup $12^{26} - 17^{30}$	4421.0	2.5		32.6	1513.0	90.8	1734		65.5	25.3	18.8	197	199.1
Multirate builtup $12^{26} - 17^{30}$	4421.0	2.6		32.6	1455	87	1701		65.5	21.5	18.8	196	199.3

- In ref. 2, no charts with $h'_p < 0.01$

GAUGE S-N 1092

TEST	P*	m	t*	Δt*	k	s	r_e	S_{ao}	S_{ae}	S_t	PI_{ac}	ΔP_{sk}	PI_{id}
Drawdown $10^{\underline{40}} - 18^{\underline{10}}$	Not analyzed, pressure increases												
Buildup $18^{\underline{10}} - 19^{\underline{21}}$	The accuracy of the pressure recorder is not sufficient												
Drawdown $19^{\underline{21}} - 22^{\underline{21}}$				"									
Buildup $22^{\underline{21}} - 23^{\underline{48}}$				"									
Drawdown $23^{\underline{48}} - 3^{\underline{08}}$				"									
Buildup $3^{\underline{08}} - 3^{\underline{56}}$				"									
Multirate drawdown $3^{\underline{56}} - 12^{\underline{26}}$	Difficult to analyze												
Buildup $12^{\underline{26}} - 17^{\underline{30}}$	The accuracy of the pressure recorder is not sufficient												
Multirate builtup $12^{\underline{26}} - 17^{\underline{30}}$				"									

P^* : Extrapolated pressure from buildup (psi)

m : Slope of straight line from semilog plot (psi/cycle)

t^* : Time when the second straight line is reached, drawdown test, ref. 1 (min)

Δt^* : Time when the second straight line is reached, buildup test, ref. 1 (min)

k : Horizontal permeability (md)

S : Total skinfactor from test

r_e : Drainage redius (ft)

S_{ao} : Apparent skinfactor caused by geometrical effects from Odeh, ref. 2

S_{ae} : Apparent skinfactor caused by geometrical effects, ref. 1

S_t : True Skinfactor caused by damage

ΔP_{sk}: Pressure drop caused by total skin (psi)

ΔP_{sk}: Pressure drop caused by total skin (psi)

PI_{acc} Actual productivity index (STB/DAY/psi)

PI_{id}: Ideal productivity index (STB/DAY/psi)

3.3 SAMPLE CALCULATIONS

3.3.1 Introduction

Buildup $12^{\underline{26}}$ - $17^{\underline{30}}$, Gauge S-N 1054

Flow period	Flow rate	Volume produced
Initial flow		2.5 STB
$10^{\underline{46}}$ - $18^{\underline{10}}$	1248.5 STB/DAY	304.6 "
$19^{\underline{21}}$ - $22^{\underline{21}}$	365.0 "	45.6 "
$23^{\underline{48}}$ - 3.08	350 "	46.7 "
$3^{\underline{56}}$ - $5^{\underline{21}}$	1082 "	106.3 "
$5^{\underline{21}}$ - $6^{\underline{47}}$	2217 "	132.4 "
$6^{\underline{47}}$ - $8^{\underline{16}}$	2850 "	145.1 "
$8^{\underline{16}}$ - $9^{\underline{42}}$	3280 "	195.8 "
$9^{\underline{42}}$ - $10^{\underline{09}}$	3530 "	47.8 "
$10^{\underline{09}}$ - $10^{\underline{55}}$	3710 "	118.6 "
$10^{\underline{55}}$ - $12^{\underline{26}}$	4050 "	267.2 "
		1462.6 STB

$$t_p = \frac{V_p}{Q} \times 24 \times 60 = \frac{1462.6}{4050} \times 24 \times 60 = \underline{520 \text{ min}}$$

t_p : time produced (min)

V_p : total volume produced (STB)

Q : last flowrate before shutin (STB/DAY)

3.3.2 Transition to second straight line

Perforated interval at top of formation

$$F(\Delta t_D) \approx \frac{2}{\pi^2 (h'_p)^2} R_1^{\,2} \frac{t_D + \Delta t_D}{\Delta t_D} \exp(-\pi^2 \cdot \Delta t_D / h_D^{\,2})$$

$h'_p = h_p/h_t = 2/90 = 0.022$

$h_D = h_t/r_w = 90/(0.35 \times 0.3048) = 843$

$R_1^2 = (\sin\pi h'_p \times \cos\frac{\pi}{2}h'_p)^2 = 0.004$

$t = 520$ min

$$t_D = \frac{k\ t}{\phi \cdot \mu \cdot C_t\ (r_w)^2 \times 3800}$$

$C_t = (0.88 \times 8.3 + 0.12 \times 3.0 + 3.0) \times 10^{-6} psi^{-1} = 10.66 \times 10^{-6} psi^{-1}$

Assumed: $k_h = k_v = 1600$ md

$$t_D = \frac{1000 \times 520/60}{0.325 \times 1.32 \times 10.66 \times 10^{-6} \times (0.35)^2 \times 3800} = \underline{6.51 \times 10^6}$$

$$0.05 = \frac{2}{\pi^2 \times (0.022)^2} \times 0.004 \times \frac{6.51 \times 10^6 + \Delta t_D}{6.51 \times 10^6} \exp(-\pi^2 \Delta t_D/843^2)$$

$$\ln\left(\frac{6.51 \times 10^6}{6.51 \times 10^6 + \Delta t_D} \times 0.02985\right) = -\pi^2 \Delta t_D/843^2$$

$$\Delta t_D = -\frac{843^2}{\pi^2} \times \ln\left(\frac{6.51 \times 10^6}{6.51 \times 10^6 + \Delta t_D} \times 0.02985\right)$$

Starting with $\Delta t_D = 3.0 \times 10^5$

$\Delta t_D = 2.6 \times 10^5$

$$\Delta t^* = \frac{0.325 \times 1.32 \times 10.66 \times 10^{-6} \times (0.35)^2 \times 3800}{1600} \times 2.6 \times 10^5 = \underline{0.34 \text{ hrs}}$$

$\underline{\Delta t^* = 20.5 \text{ min}}$

3.3.3 Permeability, skinfactor and productivity index

Permeability:

$$m = \frac{162.5 \times B_o \mu_o Q_o}{k\ h}$$

From Fig. 3.1 m = 2.3 psi/cycle

$$k = \frac{162.5 \times 1.286 \times 1.32 \times 4050}{2.3 \times 90 \times 3.28} = \underline{1645 \text{ md}}$$

Skinfactor:

$$S = 1.151 \left(\frac{P_{1HR} - P_{wf}}{m} - \log\frac{k}{\phi \cdot \mu \cdot C_t (r_w)^2} + 3.23\right)$$

From Fig. 3.1 P_{1HR} = 4417.3

$$S = 1.151\left(\frac{4417.3 - 4205}{2.3} - \log \left(\frac{1645}{0.325 \times 1.32 \times 10.66 \times 10^{-6} (0.35)^2}\right) + 3.23\right)$$

$$S = \underline{99}$$

$$S_{ae} = \frac{2}{\pi^2 (h' - h'_1)^2} \sum_{n=1}^{\infty} R_n^2 K_o(n\pi r_d), \text{ ref. 1.}$$

$$S_{ae} = 65.5$$

$$S_t = S - S_{ae} = 99 - 65.5 = \underline{33.5}$$

$$r_e = \sqrt{\frac{0.00105\ kt}{\phi \cdot \mu \cdot C_t}} = \sqrt{\frac{0.00105 \times 1645 \times 520/60}{0.325 \times 1.32 \times 10.66 \times 10^{-6}}} = \underline{1809 \text{ ft}}$$

Actual productivity index

$$PI_{ac} = \frac{Q}{P^* - P_{wf}} = \frac{4050}{4419.2 - 4204.66} = \underline{18.8\ \text{STB/DAY/psi}}$$

$$\Delta P_{sk} = 0.87\ m\ S = 0.87 \times 2.3 \times 99 = 198\ \text{psi}$$

Ideal productivity index:

$$PI_{id} = \frac{Q}{P^* - P_{wf} - \Delta P_{sk}} = \frac{4050}{4419.2 - 4204.66 - 198} = 246\ \text{STB/DAY/psi}$$

P_{ws} (psi)	$\frac{t+\Delta t}{\Delta t}$
4408.41	520
4412.69	265
4414.10	104
4414.84	58
4415.19	46.5
4415.56	40.0
4415.89	31.3
4415.56	28.0
4415.89	25.5
4416.24	21.5
4416.24	20
4416.59	18.5
4416.23	16.5
4416.23	15.5
4416.23	14.5
4416.58	13.7
4416.93	12.9
4416.93	12.4
4416.58	11.3
4416.89	10.7
4416.89	9.6
4417.16	7.7
4417.16	7.3
4417.16	7.1
4417.16	6.7
4417.52	6.4
4417.48	6.2

Table 3.1.1 Data plotted on fig. 3.1.1

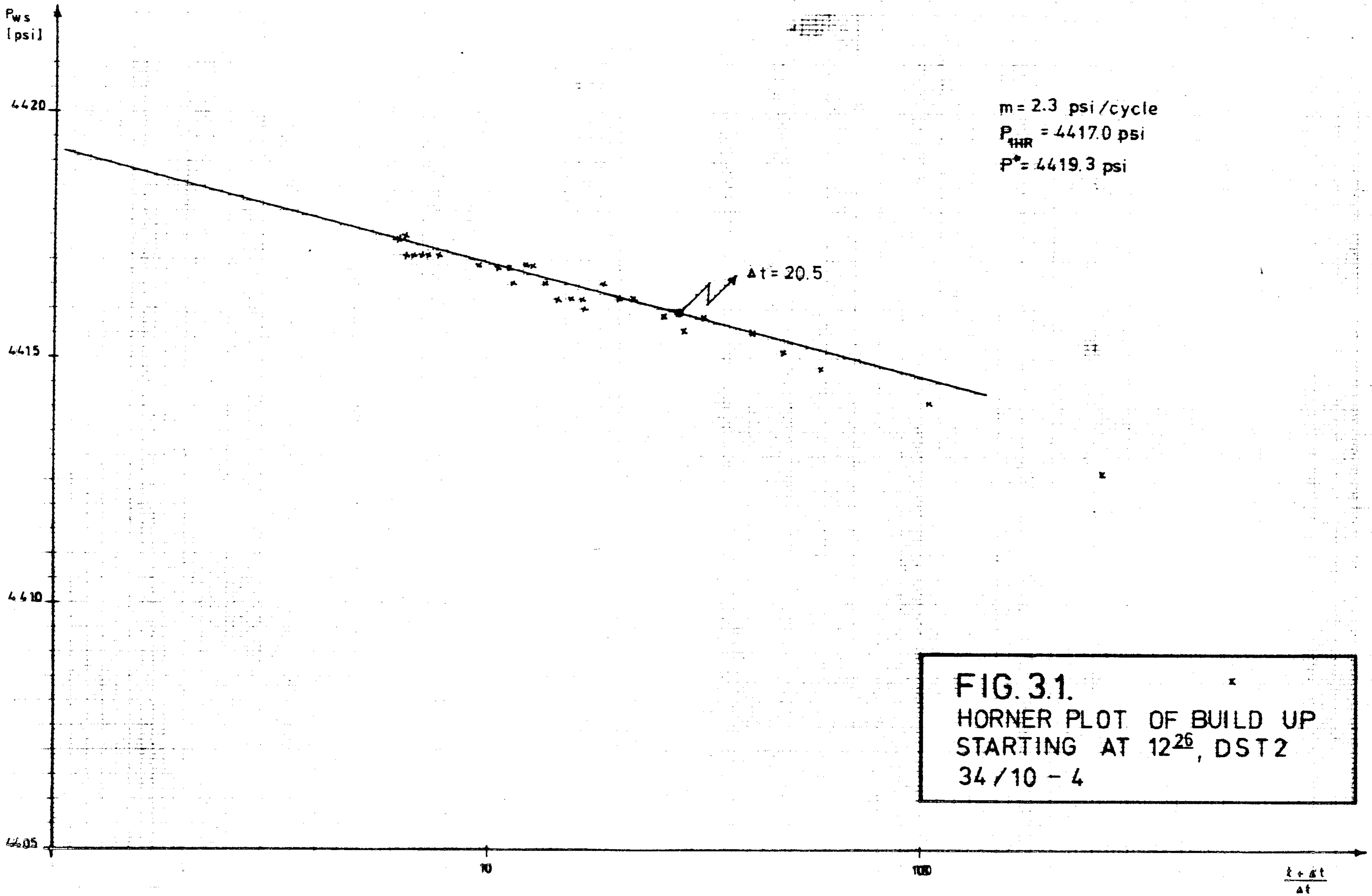


FIG. 3.1.
HORNER PLOT OF BUILD UP STARTING AT 12[26], DST 2 34/10 - 4

3.4 DISCUSSION

Based on the discussion in sec. 2.4 we have assumed a total reservoir thickness of 90 m.

3.5 CONCLUSION

Based on interpretation of data we think the multirate buildup starting at $12^{\underline{26}}$ gives the most reliable results, because of the long production time and the rather large flow-rates.

The results from DST 2 are then:

Horizontal permeability:

$k = \underline{1351\ \text{md}}$

Extrapolated pressure:

$P^* = \underline{4419.3\ \text{psi}}$

True skinfactor:

$S_t = \underline{14.6}$

Ideal productivity index:

$PI_{id} = \underline{207.2\ \text{STB/DAY/psi}}$

4 REFERENCES

1. Note. Interpretation of pressure tests from partially perforated wells, Rogalandsforskning, January 1980.

2. Odeh, A.S.: "Steady-State Flow Capacity of Wells With Limited Entry to Flow", Soc.Pet. Eng. J. (March 1968) 43 - 51; Trans., AIME, 243

ROGALANDSFORSKNING

NOTE

INTERPRETATION OF PRESSURE TESTS FROM PARTIALLY PERFORATED WELLS

January 1980

Content

1 INTRODUCTION

Many pressure tests are performed on North Sea wells where the perforated interval is less than the height of the pay zone. It is therefore sometimes difficult to decide on which h to use in the kh-product. This note clarifies this problem.

2 THEORY

2.1 ANALYTICAL SOLUTION

Fig. 2.1 illustrates a partially perforated well located in a productive zone.

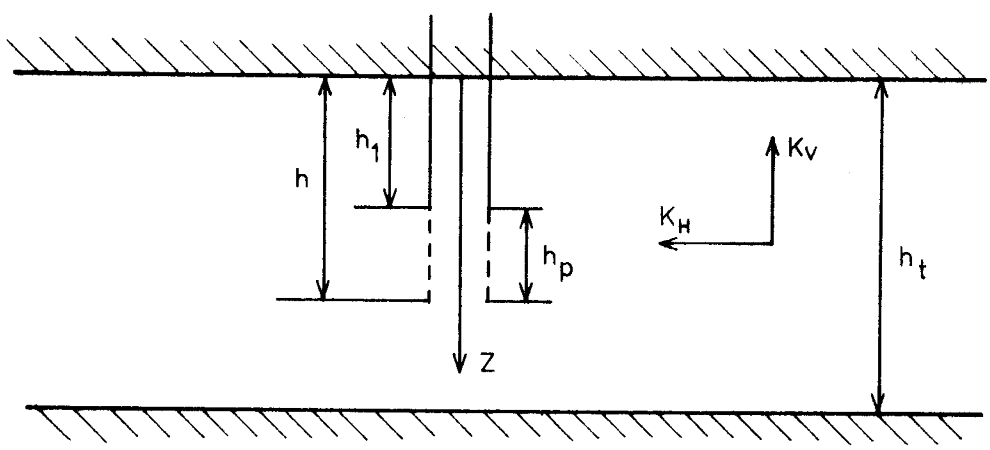


Fig. 2.1 Partially perforated well.

The pressure solution for this problem is given i refs. 1 and 2. The symbols are defined in Section 3. For a drawdown test:

$$\Delta P_D(r,z,t) = \tfrac{1}{2}(-Ei(-\frac{r^2}{4\eta t}) + 2s_a(h', h'_1, r_D, z', t_D)) \qquad (1)$$

$$s_a = \frac{1}{\pi(h'-h'_1)} \sum_{n=1}^{\infty} \frac{1}{n}(\sin(n\pi h')-\sin(n\pi h'_1)) \cdot \cos(n\pi z') W(\frac{1}{4t_D}, n\pi r_D) \quad (2)$$

To get a uniform pressure distribution, eqn. (2) is integrated over the perforated interval to give

$$s_a = \frac{1}{\pi^2 (h'-h'_1)^2} \sum_{n=1}^{\infty} R_n^2 W(\frac{1}{4t_D}, n\pi r_D) \quad (3)$$

$$R_n = \frac{1}{n}(\sin(n\pi h')-\sin(n\pi h'_1)) \quad (4)$$

As $t \rightarrow \infty$, $W(\frac{1}{4t_D}, n\pi r_D)$ is reduced to $2K_o(n\pi r_D)$ and thereby

$$s_a = \frac{2}{\pi^2 (h'-h'_1)^2} \sum_{n=1}^{\infty} R_n^2 K_o(n\pi r_D) \quad (5)$$

2.2 DISCUSSION

- Eqns (1) and (3) express the pressure drop as a function of time and position. The pressure response in the well is obtained with $r = r_w$. For short times, a semilog plot will give a straight line with a slope corresponding to h_p. At longer times there will be a transition to a second straight line with the slope corresponding to h_t.

- In high permeability layers with large h'_p, the transition to the second straight line may occur within one minute of the test. In low permeability layers (K<10md) and low h'_p more than 100 hrs may pass before the transition is reached.

- The interpretation will be difficult if the datapoints fall in the transition interval between the two straight lines. This should be avoided, if possible, in the design of the test.

- DST-tests may give vertical variation in K_H if the data plot on the first straight line which corresponds to the perforated interval only.

- For a pressure buildup test, the solution is given by the superposition principle and eqns (1) and (3). Otherwise, the same remarks are valid as for a drawdown test. At short shutin times the Horner straight line corresponds to h_p with a later transition to h_t.

- Eqn (5) may be used to calculate the apparent skinfactor caused by geometrical effects. This skinfactor is time independent and may be subtracted from the skinfactor from the Hornerplot to give the true skinfactor of the formation.

- In order to use Odeh's method, ref. 3, to calculate s_a one has to estimate the drainage radius, r_d. This is not necessary if the easily programmable eqn (5) is used.

- The transition between the two straight lines may be estimated by calculating and plotting ΔP_D from eqns (1) and (3), or by the following approximations, ref. 2. The transition is completed when s_a becomes time independent, or, in numerical approximation, when

$$F(t_D) = 2 \frac{\partial s_a}{\partial(\ln t_D)} < 0.05$$

Drawdown

i) Flow entry restricted to either of the extremities of the bed:

$$F(t_D) \approx \frac{2}{\pi^2 (h'_p)^2} R_1^2 \exp(-\pi^2 t_D / h_D^2) \tag{6}$$

ii) Flow entry centered in bed

$$F(t_D) \approx \frac{2}{\pi^2 (h'_p)^2} R_2^2 \exp(-4\pi^2 t_D / h^2_D) \tag{7}$$

Buildup

i) Flow entry situated at the lower extremity

$$F(\Delta t_D) \approx \frac{2}{\pi^2 (h'_p)^2} \cdot \frac{t_D + \Delta t_D}{t_D} \cdot R_1^2 \exp(-\pi^2 \Delta t_D / h_D^2) \tag{8}$$

ii) $$F(\Delta t_D) \approx \frac{2}{\pi^2 (h'_p)^2} \frac{t_D + \Delta t_D}{t_D} R_2^2 \exp(-4\pi^2 \Delta t_D / h_D^2) \tag{9}$$

- Eqns (6) - (9) may also be used to estimate h_t. In some cases it is difficult, from logs only, to decide if a slightly tighter zone is sealing or not. The equations will indicate the transition between the two straight line segments as a function of h_t and may make a unique determination of h_t possible.

2.3 EXPRESSIONS FOR NUMERICAL COMPUTATIONS

Cfr. refs. 2 and 4

$$Ei(-u) = \gamma + \ln u + \sum_{n=1}^{\infty} (-1)^n \frac{u_n}{n \cdot n!}$$

$$W(u,v) = \sum_{n=0}^{\infty} E_n$$

$$E_n(u,v) = \frac{v^2}{4n^2} \left(E_{n-1} + \frac{(-1)^n (v^2)^{n-1}}{(n-1)!(4)^{n-1}} \cdot \frac{\exp(-u)}{u^n}\right)$$

$$E_o(u,v) = \int_u^{\infty} \frac{e^{-\lambda}}{\lambda} d\lambda = -Ei(-u)$$

$$E_1(u,v) = \frac{v^2}{4} \left(E_o - \frac{\exp(-u)}{u}\right)$$

$$K_o(z) = - \sum_{m=o}^{\infty} \frac{(\frac{1}{2}z)^{2m}}{(m!)^2} \{\ln(\tfrac{1}{2}z) + \gamma + \frac{1}{m+1} - \sum_{K=1}^{m+1} \frac{1}{K}\} \qquad (8)$$

Eulers constant $\gamma = 0.57721566$

$o! = 1$

3 SYMBOLS

The equations are presented in dimensionless form. If oil field units are to be used:

70.6 q/T substitutes $q/(4\pi T)$

0.00633 T/S substitutes $\eta = T/S$

with the time expressed in days.

Dimensioned variables

h : distance from top of formation to bottom of perforated interval, ft
h_1 : distance from top of formation to top of perforated interval, ft
h_p : $h - h_1$, ft
h_t : formation thickness, ft
K_H : horizontal permeability, md
K_V : vertical permeability, md
ΔP : $P_{wf} - P_i$, psi; P_{wf} flowing bottom hole pressure; P_i initial pressure
r : radius, ft
r_w : wellbore radius, ft
r_d : drainage radius, ft
S : $\phi c h_t$, ft/psi
t : producing time, days
Δt : shutin time, days
T : $K_H h_t/\mu$, md•ft/cp
z : depth from top of formation, ft
η : T/S, ft^2/day
μ : viscosity, cp
ϕ : porosity, fraction
c : total compressibility, psi^{-1}

Dimentionless variables

h' : h/h_t
h'_1 : h_1/h_t
h_D : $h_t/(r_w\sqrt{K_v/K_H})$
h'_p : h_p/h_t
ΔP_D : $2\pi T\Delta P/q$
r_D : $\sqrt{K_v/K_H}\ r_w/h_t = 1/h_D$
t_D : $\eta t/r^2$
Δt_D : $\eta\Delta t/r^2$
z' : z/h_t
s_a : apparent skinfactor caused by geometrical effects
K_o : modified Bessel function of second kind of zero order

4 SAMPLE CALCULATIONS

4.1 DST - TEST 1A, 34/10-4

Measured data

ϕ = 0.33
μ_o = 1.32 cp
S_o = 0.88
C_o = 8.3×10^{-6} psi^{-1}
r_w = 0.35 ft
t = 492 min
h_t = 42.5 m or 90 m
h_1 = 20 m or 85 m
h = 25 m or 90 m
h_p = 5 m

Remark: There are two cases, (h_t, h_1, h) = (42.5 m, 20 m, 25 m) or (90 m, 85m, 90 m) depending on the tightness of layer at 42.5 m from top.

Assumed data (from correlations)

C_f = 3.0×10^{-6} psi^{-1}
C_w = 3.0×10^{-6} psi^{-1}
K_H = K_V = 1000 md

This gives $C_t = 10.66 \times 10^{-6}$ psi^{-1}

4.1.1 Transition to second straight line

Case 1, $(h_t, h_1, h) = (42.5\ m, 20\ m, 25\ m)$

$$h'_p = 5/42.5 = 0.12$$
$$h_D = 42.5 \times 3.28/0.35 = 400$$
$$R_2^2 = \sin^2(2\pi h'_1) = \sin^2(2\pi \frac{20}{42.5}) = 0.0338$$

Using eqn (7) for drawdown

$$0.05 = \frac{2}{\pi^2\ 0.12^2} \cdot 0.0338 \cdot \exp(-4\pi^2 t_D/400^2)$$

$$\ln(0.1051) = -4\pi^2 t_D/400^2$$

$$t_D = 9130$$
$$t = 3800 \cdot \frac{\phi\mu C_t r_w^2}{K} t_D = 0.0197 \text{ hrs}$$

$$t = 1.2 \text{ min}$$

The second straight line occurs after 1.2 min for drawdown, and from eqn (9) we get the same estimate for buildup.

This drawdown test was also simulated with a 20 x 12 radial grid system. The results are plotted i Fig. 4.1. The transition to the second straight line is in good agreement with the estimate.

Case 2, $(h_t, h_1, h) = (90\ m, 85\ m, 90\ m)$

Eqn (6) is now applicable for drawdown

$$h'_p = 5/90 = 0.0556$$
$$h_D = 90 \times 3.28/0.35 = 800^2$$
$$R_1^2 = (\sin\pi - \sin(\pi \cdot \frac{85}{90}))^2 = 0.0302$$

$$0.05 = \frac{2}{\pi^2 \cdot 0.0556^2} \cdot 0.0302 \exp(-\pi^2 t_D/800^2)$$

$$\ln(0.0253) = -\pi^2 t_D/800^2$$

$$t_D = 23843 \cong 2.38 \times 10^5$$

$$t = 3800 \cdot \frac{\phi \mu C_t r_w^2}{K} t_D = 0.5075 \text{ hrs}$$

$$\underline{t = 30.4 \text{ min}}$$

This value corresponds well with Fig. 4.2 generated by the numerical model.

For buildup, using eqn (8):

$$t_D = 3.80 \times 10^6$$

$$0.05 = \frac{2}{\pi^2 \cdot 0.0556^2} \cdot \frac{3.80 \times 10^6 + \Delta t_D}{3.80 \times 10^6} \cdot 0.0302 \exp(-\pi^2 \Delta t_D/800^2)$$

$$\ln\left(\frac{3.80 \times 10^6}{3.80 \times 10^6 + \Delta t_D} \times 0.0253\right) = -\pi^2 \cdot \Delta t_D/800^2$$

$$\Delta t_D = -\frac{800^2}{\pi^2} \ln\left(\frac{3.80 \times 10^6}{3.80 \times 10^6 + \Delta t_D} \times 0.0253\right)$$

Starting with $\Delta t_D = 2.39 \times 10^5$ and iterating we get

$$\Delta t_D = 2.42 \times 10^5$$

$$\underline{\text{and } \Delta t = 30.9 \text{ min}}$$

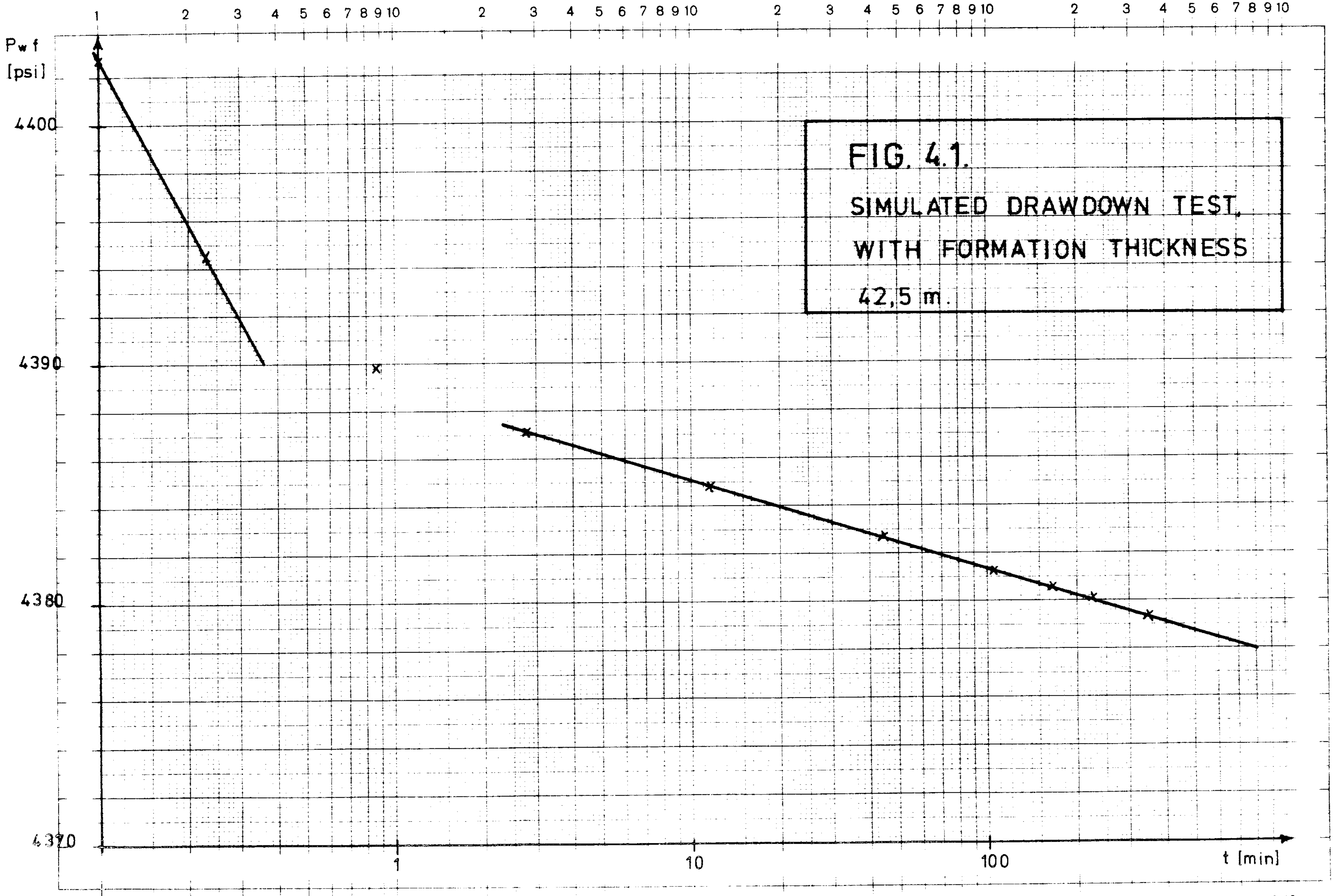
From the Hornerplot of this test it is then quite clear that a total formation thickness of h_t = 90 m has to be used in order to account for the transition to the second straight line.

4.1.2 Geometrical skinfactor s_a

Eqns (4), (5) and (8) are easily programmed and give

$$\underline{s_a = 49}$$

It should be noted that this method is better than the one suggested by Odeh, ref. 3. In the latter case one has to first estimate the radius of investigation and there are no charts for $h'_p < 0.1$.



Pwf [psi]
4400
4390
4380
4370
1
10
100
t [min]
FIG. 4.1.
SIMULATED DRAWDOWN TEST, WITH FORMATION THICKNESS 42,5 m.

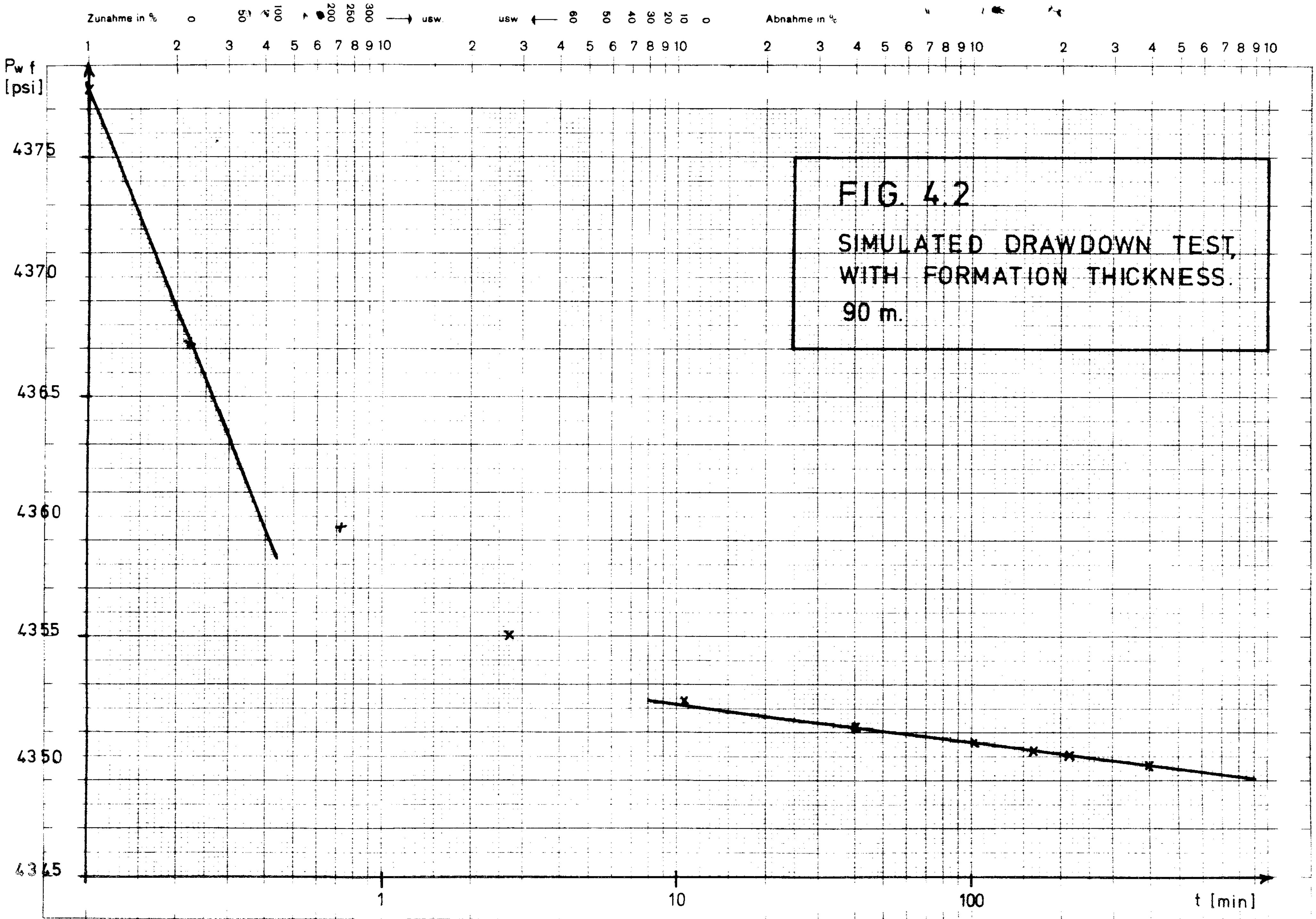


FIG. 4.2
SIMULATED DRAWDOWN TEST, WITH FORMATION THICKNESS. 90 m.
Pwf [psi]
4375
4370
4365
4360
4355
4350
4345
1
10
100
t [min]

5 References

1. Streltsova - Adams, T.D.: "Pressure Drawdown in a Well With Limited Flow Entry", J. Pet. Tech. (Nov. 1979) 1469 - 1476

2. Kazemi, H. and Seth, M.S.: "Effect of Anisotropy and Stratification on Pressure Transient Analysis of Wells With Restricted Flow Entry", J. Pet. Tech. (May 1969) 639 - 647; Trans., AIME, 246.

3. Odeh, A.S.: "Steady - State Flow Capacity of Wells With Limited Entry to Flow", Soc. Pet. Eng. J. (March 1968) 43 - 51; Trans., AIME, 243.

4. Whittaker, E. T. and Watson, G.N., "Modern Analysis", Cambridge University Press, 1946, p. 373.