MMS U.S. Department of the Interior
Minerals Management Service

OMB APPROVAL NO. 1010-0045
EXPIRES OCTOBER 31, 1991
SUBMIT. Original, two copies, and one public information copy.

SUNDRY NOTICES AND REPORTS ON WELLS

1. FIELD NAME Wildcat	2. MMS LEASE, UNIT OR COMM. NO. (6) Y 0866 0	3. MMS OPERATOR NUMBER (5) 0635

4. OPERATOR WELL NUMBER (6) 1	5. API NUMBER (10) or (12) STATE (2) COUNTY (3) WELL CODE (5) SIDE TRACK(2) 55 171 00008	COMPLETION CODE (3) NA	6. TYPE WELL (1) E	7. CORRECTED ELEVATION (5) -169' (ML-RKB)

8. OPERATOR NAME AND ADDRESS (SUBMITTING OFFICE) ARCO Alaska, Inc. PO Box 100360 Anchorage, AK 99510-0360	9. CURRENT WELL DEPTH (5) MD 8500' TVD 8500' LEAVE BLANK	10. CORRECTED WATER DEPTH (5) 103'

11. CORRECTED LOCATION OF WELL (12) Surface: 5884' FWL and 5598' FSL of Block 673 Production zone: NA Total depth: NA	12. OPERATING AREA CODE (2) FI	13. BLOCK NUMBER (6) 0673
	14. MAP OR OFFICIAL PROTRACTION DIAGRAM NUMBER (7) NR 6-4, Flaxman Island	

15. OPERATOR LEASE, UNIT OR COMMUNITIZATION NAME Kuvlum	16. RIG/PLATFORM NAME BeauDril - Kulluk	17. RIG TYPE (2) SS

18. WELL STATUS, e.g., shut-in, drilling, etc. Testing BOP Equipment	19. LAST CASING STRING: size, lb/ft, grade, and setting depth (MD) 9-5/8", 53.5#, L-80, BTC @ 8459' MD	20. APPROXIMATE START DATE (6) YYMMDD 92 09 18

21. PRESENT PRODUCTION ZONE, IF ANY, AND PRODUCTIVE CAPABILITY

NA

22. CHECK APPROPRIATE ACTIVITY:

	Fracture/acidize	☐	Artificial Lift	☐	Other	☒
	Pull or alter casing	☐	Repair well	☐	Perforate	☒
Data correction ☐	Sidetrack	☐	Deepen	☐	Plug back	☐
Change plans ☐	Reenter to complete	☐*	Multiple complete	☐*	Recomplete	☐*
Request approval ☒						
Subsequent report ☐						

Note: Submit a separate Well (Re) Completion Report and a subsequent report of operations on this form for each completion. *Alternatively*, submit a Well (Re) Completion Report for each completion with a narrative as in item 23 of this form.

23. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details in this space and on the reverse, and/or on an attachment, and give pertinent dates, including estimated date for starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.

1. Attached with this Sundry request for approval to complete / test the subject well is a general testing procedure and test string schematic. It should be noted that sand procuction problems are no longer anticipated due to data obtained during logging operations.
2. Pressure data indicates that the reservoir to be tested has a pressure equivalent to an 8.8 ppg EMW. Anticipated brine weight for the test is 9.5 ppg. (+/-240 psi overbalanced.)
3. The perforated interval outlined in Attachment 5 may be compressed upon futher evaluation of the open hole logs.

Attachments:
1 General Procedure
2 Tool Operation Pressures
3 Test String Schematic
4 Test String Description
5 Perforation Interval

Form MMS-331 (November 1991)
(Supersedes Form MMS-331 (July 1988) which will not be used)

CONTINUED ON REVERSE
COMPLETE REVERSE SIDE, SIGN, AND DATE

23. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (continued from page 1)

SUBSURFACE SAFETY VALVE: SUBSURFACE CONTROLLED ☐ SURFACE CONTROLLED ☐ SET AT DEPTH OF ______

MANUFACTURER: ______________________ MODEL NO. __________ SERIAL NO. __________

WARNING: PUBLIC LAW 97-451 provides civil and criminal penalties for false or inaccurate reporting. Failure to report as required under the terms of the lease, permit, or contract may result in suspension of operations or other enforcement actions.

CONTACT NAME (First, MI, Last) Lowell R. Crane	PHONE NUMBER (10) (907) 265-1544	EXTENSION NUMBER (4)
AUTHORIZING NAME (First, MI, Last) Mike B. Wintree	TITLE New Ventures Area Drilling Engineer	
AUTHORIZING SIGNATURE	DATE YYMMDD (6) 92 09 15	

(THIS SPACE IS FOR FEDERAL OFFICE USE)

CONDITIONS OF APPROVAL FOR SPECIAL CIRCUMSTANCES: ARE ATTACHED ☐ NONE ☐

☐ APPROVED BY: DATE (6) YYMMDD

☐ ACCEPTED BY: ______________________ TITLE ______________

PAPERWORK REDUCTION ACT STATEMENT

The Paperwork Reduction Act of 1980 (44 U.S.C. 3501 et seq.) requires us to inform you that: This information is being collected to obtain knowledge of the equipment and procedures to be used during well-completion, workover, and production operations. This information will be used by the District Supervisor to evaluate and approve or disapprove the adequacy of the equipment and procedures to safely perform the proposed operations. Response to this request is mandatory (43 U.S.C. 1334).

Public reporting burden for this form is estimated to average 1/2 hour per response, including the time for reviewing instructions, gathering and maintaining data, and completing and reviewing the form. Direct comments regarding the burden estimate or any other aspect of this form to the Information Collection Clearance Officer, Mail Stop 631, Minerals Management Service, 12203 Sunrise Valley Drive, Reston, VA 22091; and Office of Information and Regulatory Affairs, Office of Management and Budget, Washington, DC 20503.

ATTACHMENT 1

KUVLUM TEST PROCEDURE

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PRIOR TO TEST:

i) Measure initial formation pressure using formation tester.

ii) Obtain rotary sidewall cores for rock strength analysis and brine compatability test.

iii) Develop Sand Strength Analysis Log using data from Sonic Dipole and LDT. Correlate to sidewall core rock strength data.

iv) If 9-5/8" casing has been drilled thru, run corrosion log to ensure casing strength (RD circ valve set at 5000 psi).

SET TEST STRING/PERFORATE:

Tubing Conveyed Perforating

1) Replace mud with clear brine.

2) RIH with test string/TCP guns. Tie in to perf interval, set packer.

3) Open OMNI circ valve and inject diesel down tubing to create an underbalance (volume to be determined by onsite New Ventures Engineer). Shut OMNI circ valve.

4) Fire TCP guns with well shut in at surface.

5) RIH with SRO probe assembly and latch in place to monitor bottomhole pressure.

$\phi = 20\%$ ±
?,
Pi = ?,
OAPI = ?,
ΔP = ?,
T = ?,
BS+W = ?,

BEGIN TEST:

6) Open well to flow. Limit drawdown per sand strength analysis to minimize sand production. Stabilize rate (target = 1000 - 2000 BOPD). Flow at stabilized rate for 24 hours. 12 hrs 9/29/92

7) Shut in for pressure buildup. Shut in time to be determined by onsite New Ventures Engineer (estimated 12 - 96 hours).

8) Open well at low rate to condition for bottomhole sample. Shut in well. RIH with MSST/HUM/~~Gradio~~/Pres/Temp, obtain sample in oil column, POOH.

See notes for revised procedure

9) Gradually open well to high rate for maximum flowrate test. Flow time to be based on rate and available tank capacity. Shut in well. (4000 bbls) TOTAL

10) Reinject all produced liquids into formation using mud pumps.

IF WELL WON'T FLOW/LOADS UP:

11) POOH with SRO probe assembly.

12) Hold open tester valve with annulus pressure. RIH with wireline and remove jet pump isolation dummy (below tester valve).

KUVLUM TEST PROCEDURE (CONT.)

13) RIH with jet pump on wireline (below tester valve) and latch in place. POOH with WL.

14) Increase annulus pressure to open jet pump valve and begin injecting power fluid down annulus.

15) After hydrocarbon appears at surface, drop annulus pressure to shut pump. Monitor flowrate. When rate stabilizes, RIH with WL and pull jet pump. RIH with SRO probe assembly and latch in place.

16) Continue test as in steps 6 through 10.

KUVLUM DOWNHOLE TEST EQUIPMENT
Operating Requirements

Tool	Preparation	To Open	To Close
LPR-N Tester Valve	OMNI ball open	Apply 1500 psi to annulus	Drop annulus pres below 1500 psi
OMNI Circ. Valve	None	Cycle annulus pres @ 1500 psi	Cycle annulus pres @ 1500 psi
Jet Pump Assembly	Set pump w/WL	Pull isolation dummy, apply > 2200 psi to annulus	Drop annulus pres below 2000 psi
RD Safety Circ Valve	None	Apply 5000 psi to annulus	Can't reclose once open

Tool	Preparation	To Set/Fire
Champ III Packer	Reach test depth	Raise to set position, rotate 1/2 turn right, apply tubing weight
Differential Firing Head	Set packer	Apply 2000 psi to tubing

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ATTACHMENT 2

ATTACHMENT 3

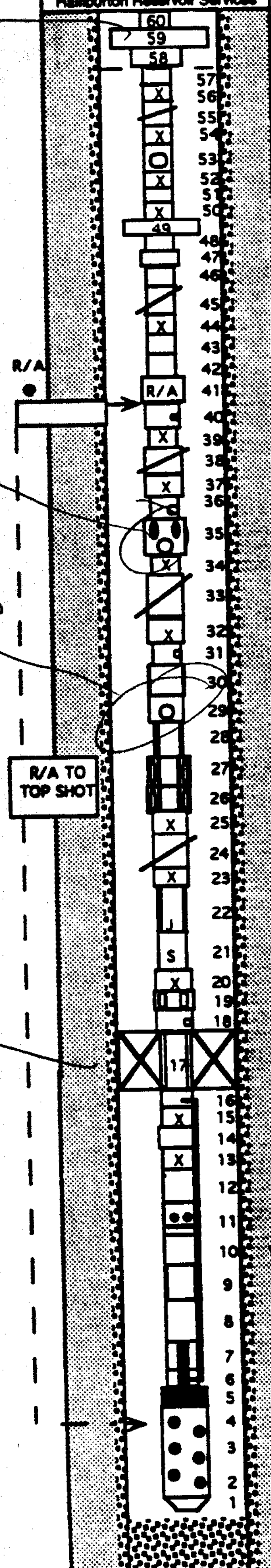
IN BOP

OMNI CIRC. VALVE

LPR-N TESTER VALVE

RTTS PACKER

HRS Halliburton Reservoir Services



PBTD =
TVD - PKR =
TVD - TOP SHOT =

HRS - INSTALLATION

COMPANY: ARCO ALASKA		COMPANY REP: MR. B. BERG		DATE: 8-25-92
WELL NAME KUVLUM #1		FIELD W/C	COUNTY: NORTH SLOPE	STATE: ALASKA
CASING	SIZE 9-5/8"	WEIGHT 53.5#	GRADE L-80	TOP
LINER	SIZE	WEIGHT	GRADE	TOP
TUBING	SIZE 3-1/2"	WEIGHT 12.9#	THREAD PH-6	GRADE
VANN GUN	SIZE 6"	JSPF 12	CHARGE 32 GM DP	EXPLO. RDX
PERFORATION INTERVAL			MAX. DEV. DEG.	BH TEMP DEG. F

ITEM	DESCRIPTION	I.D."	O.D."	LENGTH FT.	DEPTH
60	X-OVER TO LUBRICATOR				
59	HRS TEST TREE	3.06			
58	SWIVEL	2.68			
57	STIFF JOINT	2.50	7.87	9.45	
56	3-1/2" PH-6 P X 5-3/4 4STB ACME B				
55	3-1/2 PH-6 & SPACER SUBS AS NEEDED	2.75	3.50		
54	X-OVER, 4-1/2" 4STB P X 3-1/2 PH-6 B				
53	WIRELINE LUBRICATOR VALVE	3.00	10.75	5.95	
52	X-OVER, 3-1/2" PH-6 X 4-1/2" 4 STB B				
51	1 - JOINT 3-1/2" PH-6	2.75	3.50		
50	X-OVER, 4-1/2" 4 STB X 3-1/2" PH-6				
49	SUB SEA TEST TREE	3.00	13.00	5.62	
48	SLICK JOINT	3.00	5.00	3.00	
47	ADJUSTABLE FLUTED HANGER	3.00			
46	3-1/2" PH-6 P X 4-1/2 4 STB ACME B	2.50	4.50	1.46	
45	3-1/2" PH-6 TUBING	2.75	3.50		
44	XO 3-1/2" IF PIN X 3-1/2" PH-6 BOX	2.75	4.75	0.85	
43	SLIP JOINT	2.25	5.03	13.15	
42	SLIP JOINT	2.25	5.03	13.15	
41	RADIOACTIVE MARKER	2.68	4.75	2.01	
40	RD SAFETY CIRCULATING VALVE	2.25	5.03	7.53	
39	X-OVER 4-1/2" IFPIN X 3-1/2" IF BOX				
38	2 - JOINTS OF 6 1/2" DC'S	2.25	6.50	62.09	
37	X-OVER, 3-1/2" IF PIN X 4-1/2" IF BOX				
36	DRAIN VALVE	2.25	5.03	.97	
35	APR OMNI VALVE	2.25	5.03	21.15	
34	X-OVER, 4-1/2" IF PIN X 3-1/2" IF BOX				
33	2 - JOINTS OF 6 1/2" DC'S	2.25	6.50	61.97	
32	X-OVER, 3-1/2" IF PIN X 4-1/2" IF BOX				
31	DRAIN VALVE	2.25	5.03	.97	
30	MODEL "E" VALVE	1.87	5.00	13.53	
29	LPR-N TESTER VALVE	2.25	5.03	15.61	
28	JET PUMP RECEPTICLE	1.75	5.53	7.00	
27	INSTREAM BUNDLE CARRIER	2.25	5.50	7.77	
26	FUL FLO BUNDLE CARRIER	2.25	5.38	7.77	
25	X-OVER, 4-1/2" IF PIN X 3-1/2" IF BOX				
24	2-STANDS OF 6-1/2" DC'S	2.25	6.50	180.00	
23	X-OVER, 3-1/2" IF PIN X 4-1/2" IF BOX				
22	BIG JOHN JARS	2.37	5.03	5.14	
21	VR SAFETY JOINT	2.25	4.62	4.09	
20	X-OVER, 4 1/2" IF PIN X 3 1/2" IF BOX				
19	RTTS BYPASS	3.00	6.12	4.20	
18	ANNULAR PSI TRANSFER RESERVOIR				
17	9 5/8" RTTS PACKER	4.00	8.25	6.48	
16	ANNULAR PRESSURE TRANSFER SUB	2.37	6.12	1.50	
15	X-OVER, 3 1/2" IF P X 3 1/2" 8RD B				
14	BELOW PACKER SAFETY JOINT				
13	X-OVER, 2 7/8" 8RD P X 3-1/2" IF B	1.87	3.38	1.80	
12	2 7/8" X 10' TUBING SUB	2.44	3.06	10.00	
11	2-7/8" BALANCED ISOLATION TOOL	2.45	3.75	2.24	
10	2 7/8" X 10' TUBING SUB	2.44	3.06	10.00	
9	2 7/8" APF MECH. TUBING RELEASE	1.88	3.38	1.89	
8	2 - 2 7/8" TUBING JOINTS	2.44	3.06	60.00	
7	TIME DELAY FIRING HEAD	N/A	3.38	2.00	
6	ANNULAR PRESSURE FIRING HEAD	N/A	3.38	3.70	
5	BLANK SECTION OF GUN	N/A	6.00	5.00	
4	VANNGUN TOP SHOT	N/A	N/A	0.00	
3	6" X 12 SPF 32GM DP VANNGUN	N/A	6.00	0.00	
2	VANNGUN BOTTOM SHOT	N/A	N/A	0.00	
1	BULL PLUG	N/A	6.00	.75	

BY K. CODER | 3000 "C" ST., SUITE 200 ANCHORAGE, ALASKA 99503 | PHONE: 907-261-7750 | FAX: 907-562-1612

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KUVLUM #. OL STRING

ITEM	TOOL	ID (IN.)	OD (IN.)	LENGTH (FT.)	CONNECTION
1	BULL PLUG	N/A	3.380	0.75	
2	6" 12 SPF TUBING CONVEYED GUNS	N/A	6.000	?	
3	ANNULAR PRESSURE FIRING HEAD	N/A	3.750	3.70	
4	TIME DELAY FIRER	N/A	3.375	2.00	2 7/8" PIN UP
5	2 - 2 7/8" TUBING JOINTS	2.440	2.870	60.00	2 7/8" P X B
6	2 7/8" APF MECHANICAL TUBING RELEASE	1.880	3.375	1.89	2 7/8" P X B
7	2 7/8" X 10' TUBING SUB	2.440	2.870	10.00	2 7/8" P X B
8	2 7/8" BALANCED ISOLATION TOOL	2.440	3.750	2.24	2 7/8" 8RD P X B
9	2 7/8" X 10' TUBING SUB	2.440	2.870	10.00	2 7/8" P X B
10	2 7/8" PIN X 3 1/2" IF BOX CROSSOVER				
11	BELOW PACKER SAFETY JOINT	1.990	6.000	7.50	3 1/2" IF P X B
12	3 1/2" IF PIN X 3 1/2" 8 RD BOX CROSSOVER				
13	ANNULAR PRESSURE TRANSFER SUB	2.370	6.120	1.50	3 1/2" 8RD PIN X 4 1/4" IF BOX
14	9 5/8" RTTS PACKER	4.000	8.250	6.48	4 1/2" IF P X B
15	ANNULAR PRESSURE TRANSFER RESERVOIR	2.370	6.125	4.34	4 1/2" IF P X B
16	RTTS BYPASS	3.000	6.120	4.20	4 1/2" IF P X B
17	4 1/2" IF PIN X 3 1/2" IF BOX CROSSOVER				
18	VR SAFETY JOINT	2.250	4.680	4.68	3 1/2" IF P X B
19	BIG JOHN JARS	2.250	4.625	5.15	3 1/2" IF P X B
20	3 1/2" IF PIN X 4 1/2" IF BOX CROSSOVER				
21	2 - STANDS 6 1/2" DRILL COLLARS	2.250	6.500	180.00	4 1/2" IF P X B
22	4 1/2" IF PIN X 3 1/2" IF BOX CROSSOVER				
23	FUL FLO BUNDLE CARRIER	2.280	5.380	8.00	3 1/2" IF P X B
24	IN STREAM BUNDLE CARRIER	2.250	5.500	8.00	3 1/2" IF P X B
25	JET PUMP RECEPTICLE	1.750	5.532	7.00	3 1/2" IF P X B
26	LPR-N TESTER VALVE	2.280	5.030	15.94	3 1/2" IF P X B
27	MODEL E VALVE	1.875	13.530	13.53	3 1/2" IF P X B
28	DRAIN VALVE	2.280	5.030	2.75	3 1/2" IF P X B
29	3 1/2" IF PIN X 4 1/2" IF BOX CROSSOVER				
30	2 - JOINTS 6 1/2" DRILL COLLARS	2.250	4.750	60.00	4 1/2" IF P X B

ATTACHMENT 4

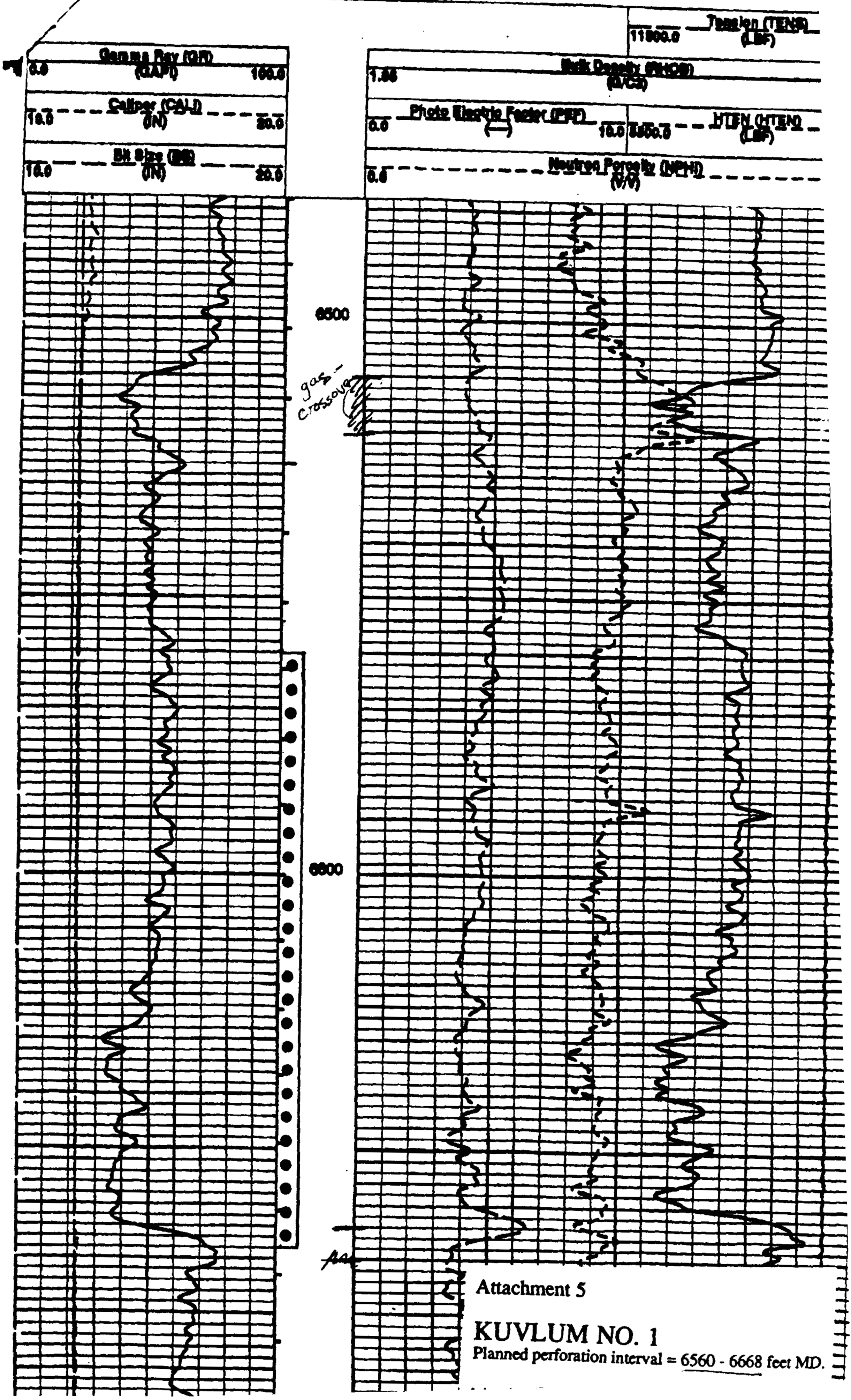
CONFI[illegible]

KUVLUM # . [illegible]OL STRING

31	4 1/2" IF PIN X 3 1/2" IF BOX CROSSOVER				
32	OMNI VALVE	2.280	5.030	21.15	3 1/2" IF P X B
33	DRAIN VALVE	2.280	5.030	2.75	3 1/2" IF P X B
34	3 1/2" IF PIN X 4 1/2" IF BOX CROSSOVER				
35	2 - JOINTS 6 1/2" DRILL COLLARS	2.250	4.750	60.00	4 1/2" IF P X B
36	4 1/2" IF PIN X 3 1/2" IF BOX CROSSOVER				
37	RD SAFETY CIRCULATING VALVE	2.280	5.030	7.52	3 1/2" IF P X B
38	RA SUB	2.680	4.500	2.00	3 1/2" IF P X B
39	SLIP JOINT	2.250	5.030	13.16	3 1/2" IF P X B
40	SLIP JOINT	2.250	5.030	13.16	3 1/2" IF P X B
41	3 1/2" IF PIN X 3 1/2" PH-6 BOX CROSSOVER				
42	3 1/2" PH-6 TUBING	2.750	3.500		3 1/2" PH-6 P X B
43	3 1/2" PH-6 PIN X 4 1/2" 4 STUB BOX XO				
44	ADJUSTABLE FLUTED HANGER	3.000	14.000	3.00	4 1/2" 4 STUB ACME B X P
45	SLICK JOINT	3.000	5.000	6.00	4 1/2" 4 STUB ACME B X P
46	SUB SEA TEST TREE	3.000	13.000	5.62	4 1/2" 4 STUB ACME B X P
47	4 1/2" 4 STUB X 3 1/2" PH-6 CROSSOVER				
48	1 JOINT 3 1/2" PH-6 TUBING	2.750	3.500	30.00	
49	3 1/2" PH-6 PIN X 4 1/2" 4 STUB BOX XO				
50	WIRELINE LUBRICATOR VALVE	3.000	10.750	5.95	4 1/2" 4 STUB ACME B X P
51	4 1/2" 4 STB PIN X 3 1/2" PH-6 BOX XO				
52	3 1/2" PH-6 TUBING AND SUBS AS NEEDED	2.750	3.500		
53	3 1/2" PH-6 PIN X 5 3/4" 4 STUB ACME BOX				
54	STIFF JOINTS	2.500	7.870	9.45	
55	SWIVEL	2.680			
56	TEST HEAD	2.650			3 1/2" IF
57	XO TO LUBRICATOR				

ATTACHMENT 4

Integrated Hole Volume Minor Pip Every 10.0 F3
Integrated Hole Volume Major Pip Every 100.0 F3
Mark Every 60.0 S



Attachment 5

KUVLUM NO. 1

Planned perforation interval = 6560 - 6668 feet MD.

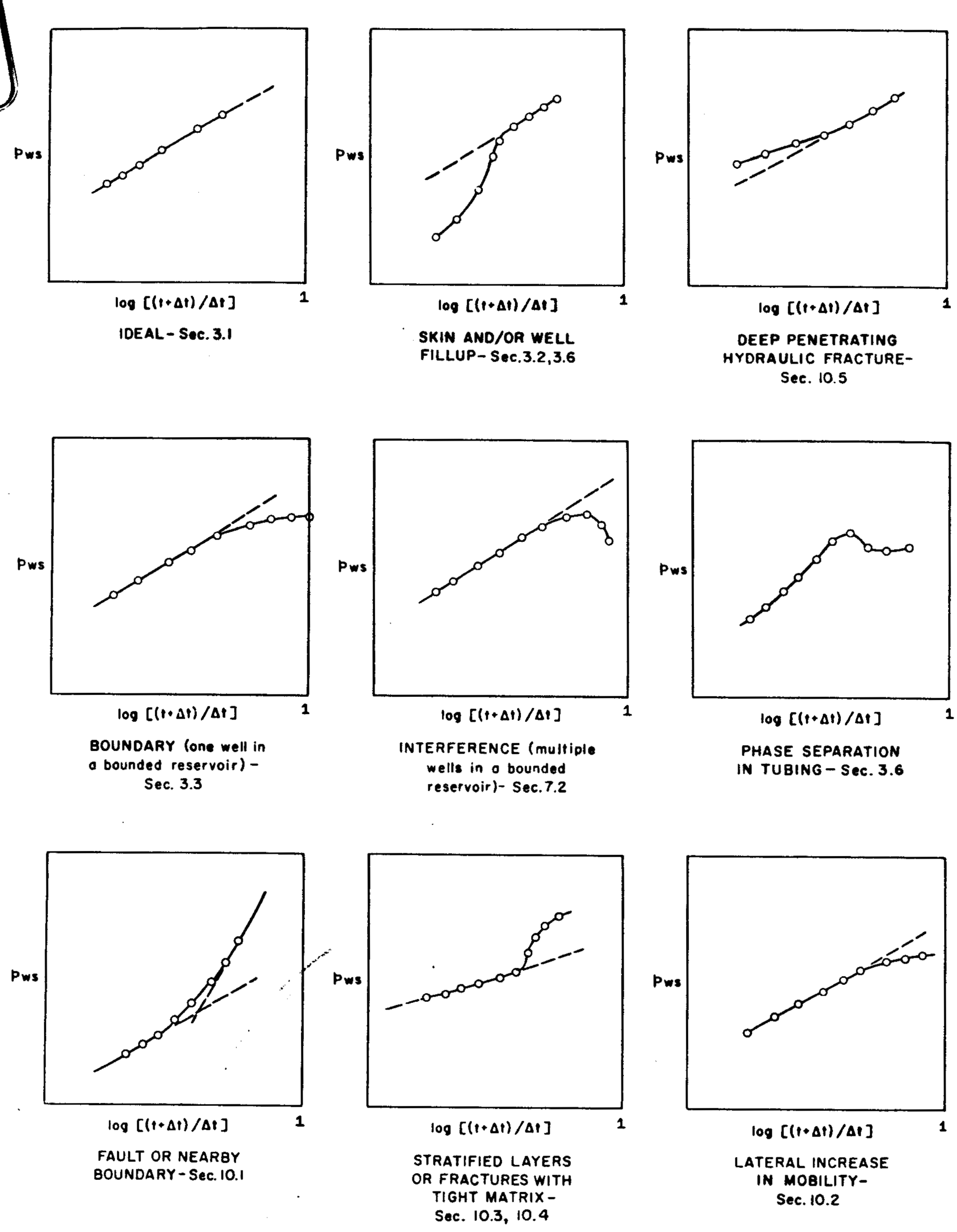


Fig. 11.6 Example buildup curves.

sure from Bottom Hole Pressure Build-up Characteristics", *Trans.*, AIME (1950) **189**, 91-104.

5. Russell, D. G. and Truitt, N. E.: "Transient Pressure Behavior in Vertically Fractured Reservoirs", *J. Pet. Tech.* (Oct., 1964) 1159-1170.
6. Odeh, A. S. and Nabor, G. W.: "The Effect of Production History on Determination of Formation Characteristics From Flow Tests", *J. Pet. Tech.* (Oct., 1966) 1343-1350.
7. Nisle, R. G.: "The Effect of a Short Term Shut-In on a Subsequent Pressure Build-up Test on an Oil Well", *Trans.*, AIME (1956) **207**, 320-321.
8. Lozano, G. and Harthorn, W. A.: "Field Test Confirms Accuracy of New Bottom-Hole Pressure Gauge", *J. Pet. Tech.* (Feb., 1959) 26-29.
9. Jones, L. G.: "Reservoir Reserve Tests", *J. Pet. Tech.* (March, 1963) 333-337.
10. van Poollen, H. K.: "Radius of Drainage and Stabilization Time Equations", *Oil and Gas J.* (Sept. 14, 1964) 133.

NOTES

10/15/82

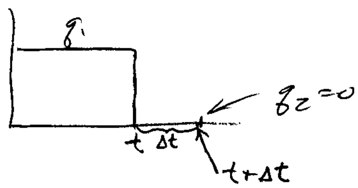
$$t_D = \frac{\lambda K t}{\phi \mu c r_w^2} \rightarrow t_D = \frac{\lambda K (\Delta t)_M}{\phi \mu c r_w^2}$$

- solve for ϕ

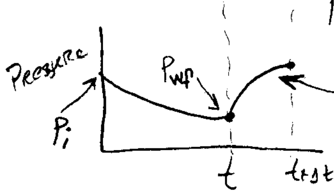
10/18/82

CHAPTER 4 - OIL WELL TESTING TECHNIQUES

Pressure Buildup Testing - most familiar T.T.T. ← TRANSIENT TESTING TECHNIQUE

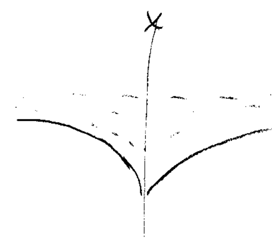


lower a pressure bomb into shut in well



P_{ws} ← shut in pressure, any point on curve

- pressure dist. near wellbore
  - will stabilize due to flow from outside while well is shut in



- Need knowledge of surface & subsurface data

- before starting the test, determine:
  1. Tubing size
  2. Casing size
  3. well depth
  4. Packer locations
  5. Perforation locations

- Typical Plots - all yield straight lines

  * ① Horner Plot (1951) -
  - plot P_{ws} vs $\log\left(\frac{t+\Delta t}{\Delta t}\right)$

  most important

  ② Miller, Dice, & Hutchinson (1950)
  - plot P_{ws} vs. $\log(\Delta t)$

③ Muskat's Plot (1930)

$$\log(\bar{P}_R - \bar{P}_{ws}) \text{ vs. } \Delta t$$

Fundamental Relationships (development for infinite reservoir)

Conceptually, a buildup is treated as the result of 2 superimposed effects.

any value on curve

$$P_i - P_{ws} = P_i q_D P_t((t+\Delta t)_D) + P_i(-q_1)_D P_t(\Delta t)_D$$

P_t evaluated @ $(t+\Delta t)_D$ (a function of)

P_t evaluated @ $(\Delta t)_D$

$$(t+\Delta t)_D = \frac{\lambda k t}{\phi \mu c r_w^2} = \frac{(2.637\times10^{-4})(k)(t+\Delta t)}{\phi \mu c r_w^2}$$

$$\Delta t_D = \frac{(2.637\times10^{-4})(k)(\Delta t)}{\phi \mu c r_w^2}$$

$$q_D = \frac{\gamma B q_{sc} \mu}{kh P_i} = \frac{141.2 B q_{sc} \mu}{kh P_i}$$

$$P_t = -\frac{1}{2} E_i\left(-\frac{1}{4t_D}\right)$$; P_t evaluated @ wellbore

$$P_i - P_{ws} = \frac{141.2 B q_{sc} \mu}{kh}\left[-\frac{1}{2} E_i\left(-\frac{\phi \mu c r_w^2}{(4)(2.637\times10^{-4})(k)(t+\Delta t)}\right)\right]$$

$q_2 - q = 0 - q_1$

$$-\frac{141.2 B q_{sc} \mu}{kh}\left[-\frac{1}{2} E_i\left(-\frac{\phi \mu c r_w^2}{4(2.637\times10^{-4})(k)(\Delta t)}\right)\right]$$

usually (9 times out of 10) → $E_i(-x) < 0.01$,

∴ use logarithmic approximation

– with the logarithmic approximation;

$E_i(-x) \cong \frac{1}{2}\ln\left(\frac{1.781}{4t_D}\right)$

$E_i(-x) = \frac{1}{2}\ln(1.781 x)$ for $x \le 0.01$

$E_i\left(-\frac{1}{4t_D}\right) \cong \frac{1}{2}\ln\left(\frac{4}{1.781} t_D\right)$; $\frac{1}{2}\ln\left(\frac{4}{1.781}\right) = \frac{1}{2}(.809)$

NOTES

10/18/82

$$P_i - P_{ws} = \frac{141.2\, B q_{sc} \mu}{kh} \left\{ \frac{1}{2}\left[\ln\left(\frac{(2.637\times10^{-4})(k)(t+\Delta t)}{\phi \mu c r_w^2}\right) + .809 \right] - \frac{1}{2}\left[\ln\left(\frac{(2.637\times10^{-4})(k)(\Delta t)}{\phi \mu c r_w^2}\right) + .809 \right] \right\}$$

$$P_i - P_{ws} = \frac{141.2\, B q_{sc} \mu}{kh} \left[\frac{1}{2} \ln(t+\Delta t) - \frac{1}{2} \ln(\Delta t) \right]$$

$$P_i - P_{ws} = \frac{141.2\, B q_{sc} \mu}{kh} \left[\frac{1}{2} \ln\left(\frac{t+\Delta t}{\Delta t}\right) \right]$$

$$\boxed{\ln x = 2.3026 (\log x)}$$

$$P_i - P_{ws} = \frac{141.2\, B q_{sc} \mu}{kh} \underbrace{\left(\frac{1}{2}\right)(2.3026)}_{1.1513} \left(\log\left(\frac{t+\Delta t}{\Delta t}\right)\right)$$

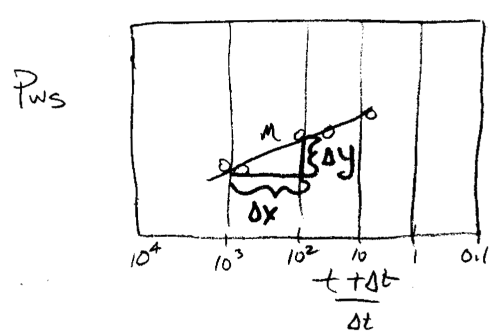
$$P_i - P_{ws} = \frac{162.6\, B q_{sc} \mu}{kh} \left[\log\left(\frac{t+\Delta t}{\Delta t}\right) \right]$$

(Practical field UNITS)

P_{ws}	shut in time
P_{wf}	0
P_{ws_1}	x
P_{ws_2}	x
P_{ws_3}	x
	Δt

$$P_{ws} = P_i - \frac{162.6\, B q_{sc} \mu}{kh} \left[\log\left(\frac{t+\Delta t}{\Delta t}\right) \right]$$

- equation of straight line on semi-log coordinates



← decreasing function

$y = A + B\log x$

$\Delta x = \log 10^3 - \log 10^2$

$\Delta x = 3 - 2 = 1$

Early times, this should be fractions of a minute to account for wellbore storage/unloading

- increase Δt with later times.

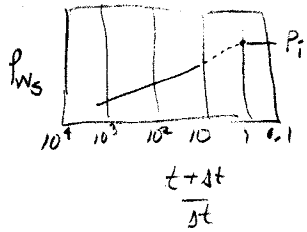
P_{ws}	Δt	$\frac{t+\Delta t}{\Delta t}$
P_{wf}	0	|
P_{ws_1}	Δt_1	|
P_{ws_2}	Δt_2	|

$$\boxed{m = -\frac{162.6\, B q_{sc} \mu}{kh}}$$

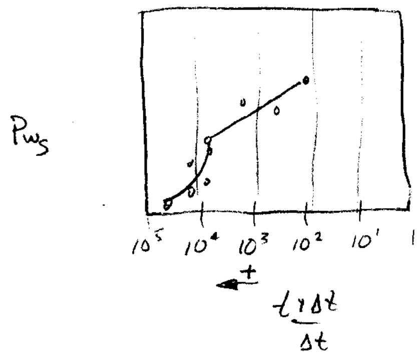
$$kh = -\frac{162.6\, B q_{sc} \mu}{m}$$

when $B \log x$ goes to zero, we obtain an intercept & thus the ultimate shutin pressure ; extrapolate straight line to obtain P_i

when $\frac{t+\Delta t}{\Delta t} \to 1$, extrapolate the straight line & Read P_i



- skin factor will affect this plot



Let P_δ @ $\Delta t = \delta$

P_{wf} @ $\Delta t = 0$

$$P_\delta - P_{wf} = \underbrace{(P_i - P_{wf})}_{\Delta t = 0} - \underbrace{(P_i - P_{\delta F})}_{\Delta t = \delta}$$

No skin ; $P_\delta - P_{wf} = P_t$

skin ; $P_\delta - P_{wf} = P_t + S$

$$\Delta P_D \big|_{well} = P_t + S = \frac{P_i - P_{wf}}{P_i q_D}$$

$$P_\delta - P_{wf} = P_i q_D (P_t + S) - \frac{141.2\, B q_{sc} \mu}{kh}\left[\frac{1}{2}\ln\left(\frac{t+\delta}{\delta}\right)\right]$$

$$P_\delta - P_{wf} = \frac{141.2\, B q_{sc} \mu}{kh}\left[\frac{1}{2}\ln\left(\frac{2.637\times10^{-4}\, k t}{\phi \mu c r_w^2} + .809\right) + S\right] - \frac{141.2\, B q_{sc} \mu}{kh}\left[\frac{1}{2}\ln\left(\frac{t+\delta}{\delta}\right)\right]$$

APPROXIMATION ⇒ Letting $\frac{t+\delta}{\delta} \cong \frac{t}{\delta}$ when $t \gg \delta$

$\frac{.809}{2.3}$

$$P_\delta - P_{wf} = \frac{162.6\, B q_{sc} \mu}{kh}\left[\log 2.637\times10^{-4} + \log\frac{k}{\phi \mu c r_w^2} + \log t + 0.3513 + \frac{2S}{2.3026} - \log t + \log \delta\right]$$

$$P_\delta - P_{wf} = \frac{162.6\, B q_{sc} \mu}{kh}\left[\log\frac{k\delta}{\phi \mu c r_w^2} + 0.8685\, S - 3.2275\right]$$

only unknown is S

- if no deviations from ideal behavior;

$$P_{ws} = P_i - \frac{162.6\, B_g\, q_{sc}\, \mu}{Kh} \log\left(\frac{t+\Delta t}{\Delta t}\right)$$

can determine P_i & K from this relationship

Horner Plot →

define $\boxed{M = -\frac{162.6\, B_g\, q_{sc}\, \mu}{Kh}}$; slope of straight line

$$P_\delta - P_{wf} = -m\left[\log\frac{K\delta}{\phi \mu c r_w^2} + .8685\, S - 3.2275\right]$$

flowing sandface pressure just before shutting well in ($\Delta t = 0$)

S is only unknown

→ solving for S;

$$\boxed{S = 1.1513\left[\frac{(P_\delta - P_{wf})}{-m} - \log\left(\frac{K\delta}{\phi \mu c r_w^2}\right) + 3.2275\right]}$$

- pts located on straight line (smoothed data line) are the points used for P_δ

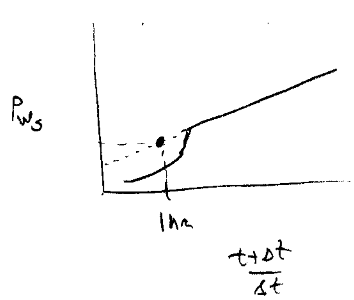
very important →

- note: P_δ should be read from the straight line

set $\delta = 1$ hr

$$\therefore \boxed{S = 1.1513\left[\frac{P_{1hr} - P_{wf}^{(\Delta t=0)}}{-m} - \log\frac{K}{\phi \mu c r_w^2} + 3.2275\right]}$$

if using $\delta = 1$ hr:



- Read value of P_{1hr} from extrapolated straight line

Composite skin factor - includes all effects causing pressure drop
- APPARENT SKIN

From our equation -

$q_{sc} \rightarrow$ may be variable
- well could be shut in for mechanical problems, etc.

$$t = \frac{24(V_p)}{q}$$; $V_p \equiv$ cumulative volume produced (STB)
$q \equiv$ last flow rate before you shut the well in (STB/day)

$t \equiv$ hours — synthetic time, hypothetical time

- gives production time to use in the equation.

Flow efficiency - definitions

Productivity Index $\rightarrow$ $$J_{IDEAL} = \frac{q}{\bar{P} - P_{wf}}$$

$$J_{ACTUAL} = \frac{q}{\bar{P} - P_{wf} - \Delta P_{SKIN}}$$

$\bar{P} \approx P_i$

$\longrightarrow$ Flow efficiency (F.E.) $= \dfrac{J_{actual}}{J_{ideal}}$

$\longrightarrow$ Damage ratio $= \dfrac{1}{F.E.} = \dfrac{J_{ideal}}{J_{actual}}$

$\longrightarrow$ DAMAGE FACTOR $= (1 - F.E)$

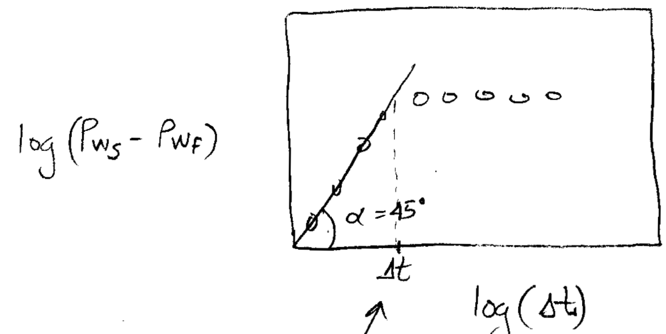
From nomograph #5.

$$F.E = \frac{J_{actual}}{J_{ideal}} = \frac{\bar{P} - P_{wf} - \Delta P_{SKIN}}{\bar{P} - P_{wf}}$$

DAMAGE RATIO $= \dfrac{1}{F.E.}$

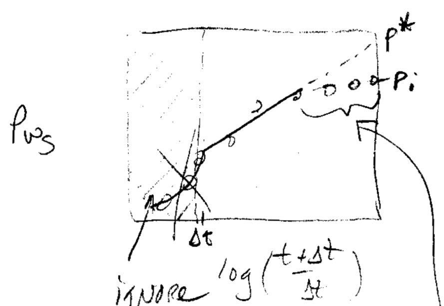
NOTES 10/20/82

Determination of wellbore storage time:



$\alpha = 45$
$m = 1$

No wellbore storage after this time



$\therefore$ data points before Δt on our other graph will be ignored in determining the regression (straight line)

Pressure affects are being felt @ boundaries i.e. - system is finite

p^* - false pressure

PRESSURE BUILD-UP ANALYSIS IN FINITE RESERVOIRS

Relate P_i & P^* as follows:

$$P_{ws} = P^* - m \log\left(\frac{t+\Delta t}{\Delta t}\right)$$

Knowing that (infinite acting system)

$$P_i - P_{ws} = P_i g_D P_t\left((t+\Delta t)_D\right) - P_i g_D P_t\left((\Delta t)_D\right)$$

$$P_{ws} = P_i - P_i g_D \left\{ P_t\left((t+\Delta t)_D\right) - P_t\left((\Delta t)_D\right) \right\}$$

$$P_{ws} = P_i - \frac{141.2\, B q_{sc} \mu}{Kh}\left[P_t\left((t+\Delta t)_D\right) - P_t\left((\Delta t)_D\right)\right]$$

$$(P_i - P_{ws})\frac{Kh}{141.2\, B q_{sc}\mu} = \frac{1}{2}\ln\left[\left((t+\Delta t)_D\right)\right] - \frac{1}{2}\ln\left[\left((t+\Delta t)_D\right)\right] + P_t\left\{\left((t+\Delta t)_D\right)\right\} - P_t\left\{\Delta t_D\right\}$$

$$P_t\{(\Delta t_D)\} \approx \frac{1}{2}\left(\ln(\Delta t_D) + .80907\right)$$

$$\frac{Kh}{141.2\, B_g q_{sc}\, \mu}(P_i - P_{ws}) = P_t\{(t+\Delta t)_D\} - \frac{1}{2}\left(\ln(\Delta t_D) + .80907\right) + \frac{1}{2}\ln\left((t+\Delta t)_D\right)$$

$$\frac{Kh}{141.2\, B_g q_{sc}\, \mu}(P_i - P_{ws}) = \frac{1}{2}\ln\left(\frac{t+\Delta t}{\Delta t}\right) + P_t\left((t+\Delta t)_D\right) - \frac{1}{2}\left[\ln(t+\Delta t)_D + .80907\right]$$

Since $P_{ws} = P^* - m\log\left(\frac{t+\Delta t}{\Delta t}\right)$

OR $P_{ws} = P^* - \frac{141.2\, B_g q_{sc}\, \mu}{Kh}\left(\frac{1}{2}\right)\ln\left(\frac{t+\Delta t}{\Delta t}\right)$

$$\frac{Kh}{141.2\, B_g q_{sc}\, \mu}P_i - \frac{Kh}{141.2\, B_g q_{sc}\, \mu}P^* + \frac{1}{2}\ln\left(\frac{t+\Delta t}{\Delta t}\right) = \frac{1}{2}\ln\left(\frac{t+\Delta t}{\Delta t}\right) + P_t\left((t+\Delta t)_D\right) - \frac{1}{2}\left[\ln(t+\Delta t)_D + .80907\right]$$

$$P^* = P_i - \frac{141.2\, B_g q_{sc}\, \mu}{Kh}\left[P_t\left((t+\Delta t)_D\right) - \frac{1}{2}\left\{\ln(t+\Delta t)_D + .80907\right\}\right]$$

IF $\Delta t \ll t$; $(t+\Delta t)_D \cong t_D$

$$P^* = P_i - \frac{141.2\, B_g q_{sc}\, \mu}{Kh}\left[P_t\{t_D\} - \frac{1}{2}\ln t_D + .80907\right]$$

P_t as a function of t_D

MILLER, DYES & HUTCHINSON ANALYSIS –

– simplified form of Horner Plot.

HORNER Plot –

$$P_{ws} = P_i + m \log\left(\frac{t+\Delta t}{\Delta t}\right)$$

– if m is taken as positive, then:

$$P_{ws} = P_i - m \log\left(\frac{t+\Delta t}{\Delta t}\right)$$

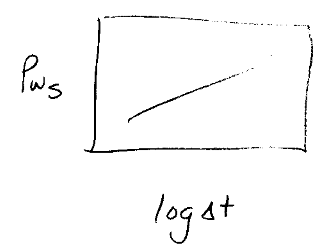
if $t \gg \Delta t$ $\qquad \frac{t+\Delta t}{\Delta t} \approx \frac{t}{\Delta t}$

t: total production time

Δt: shut in time

substituting into our equation:

$$P_{ws} = P_i - m \log\left(\frac{t}{\Delta t}\right) \Rightarrow P_{ws} = P_i - m \log t + m \log \Delta t$$



if $\Delta t = 1\ hr$;

$$P_{ws} = \underbrace{P_i - m \log t}_{P_{1hr}} \quad ; \text{ intercept}$$

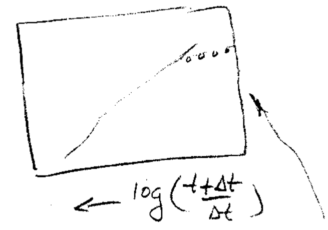
P_{1hr} (from the straight line)

$$\boxed{P_{ws} = P_{1hr} + m \log(\Delta t)}$$

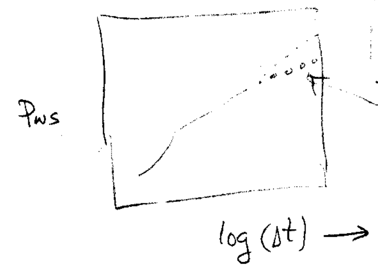
– equation for Miller, Dyes, & Hutchinson Plot

(MDH Plot)

Horner Plot -



MDH Plot -



If these points do not form another straight line, then the system is feeling the pressure drop @ the boundaries.

Monograph Volume 5

$$\Delta t = \frac{\phi \mu C_t A}{0.0002637\, k} \left(\Delta t_{DA}\right)_{esl}$$

Compressibility (total)

end of the semilog straight line

dimensionless shut in time @ the end of the semilog straight line } depends on Reservoir shape & well location

Pg. 50 - Fig. 5.6 - 5.7

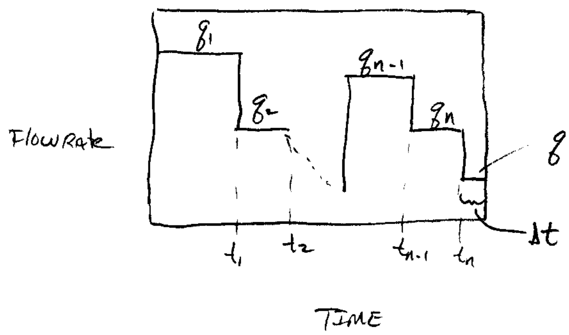
Table 5.2

- useful when know Δt_{DA} & shape of Reservoir

$$t_{DA} = t_D \frac{r_w^2}{A}$$

Build up TEST ANALYSIS when RATE VARIES

Before TESTING

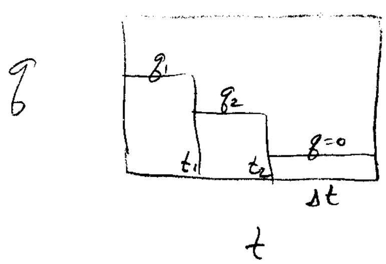


$$P_{ws} = P_i - m \sum_{j=1}^{n} \frac{q_j}{q_n} \log\left(\frac{t_n - t_{j-1} + \Delta t}{t_n - t_j + \Delta t}\right)$$

- Above equation indicates that plot of P_{ws} vs $\Sigma(\ )$ on RHS should yield a straight line with slope m & intercept P_i.

example - 2 different flow rates before shut well in

$n = 2$



$$P_i - P_{ws} = P_i q_{D_1} P_t\{(t_2+\Delta t)_D\} + P_i(q_2-q_1)_D P_t\{((t_2+\Delta t)-t_1)_D\}$$

P_t evaluated @ this

$$+ P_i(0-q_2) P_t\{(\Delta t)_D\}$$

$$P_i - P_{ws} = P_i \frac{\gamma B q_1 \mu}{k h P_i}\left[\frac{1}{2}\{\ln(t_2+\Delta t)_D + .809\}\right]$$

$$+ P_i \frac{\gamma B(q_2-q_1)\mu}{k h P_i}\left[\frac{1}{2}\{\ln((t_2+\Delta t)-t_1)_D + .809\}\right]$$

$$- P_i \frac{\gamma q_2 B \mu}{k h P_i}\left[\frac{1}{2}\{\ln(\Delta t_D) + .809\}\right]$$

$$P_i - P_{ws} = \frac{\gamma B q_1 \mu}{k h}\left[\frac{1}{2}\ln(t_2+\Delta t)_D\right] + \frac{\gamma B q_2 \mu}{k h}\left[\frac{1}{2}\ln(t_2+\Delta t-t_1)_D\right]$$

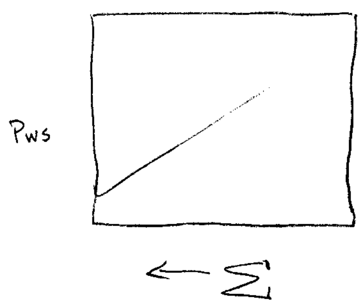
$$- \frac{\gamma B q_1 \mu}{k h}\left[\frac{1}{2}\ln(t_2+\Delta t-t_1)_D\right]$$

$$- \frac{\gamma B q_2 \mu}{k h}\left[\frac{1}{2}\ln(\Delta t)_D\right]$$

$$m = \frac{162.6\, B \mu q_2}{kh}$$

$$P_i - P_{ws} = \underbrace{\frac{162.6\, B \mu q_2}{kh}}_{m} \left[\frac{q_1}{q_2} \log (t_2 + \Delta t)_D + \frac{q_2}{q_2} \log (t_2 - t_1 + \Delta t)_D - \frac{q_1}{q_2} \log (t_2 - t_1 + \Delta t)_D - \frac{q_2}{q_2} \log (\Delta t)_D \right]$$

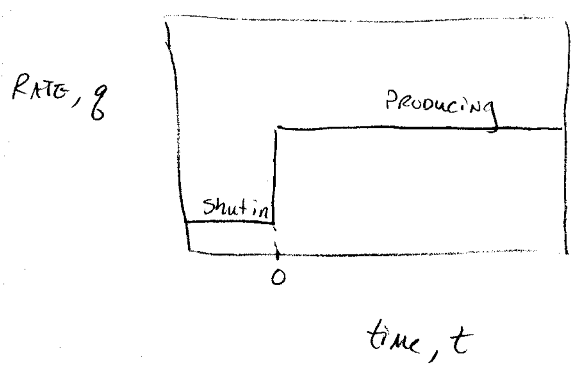
$$P_i - P_{ws} = m \left[\frac{q_1}{q_2} \log \left(\frac{t_2 + \Delta t}{t_2 - t_1 + \Delta t} \right) + \log \left(\frac{t_2 - t_1 + \Delta t}{\Delta t} \right) \right]$$

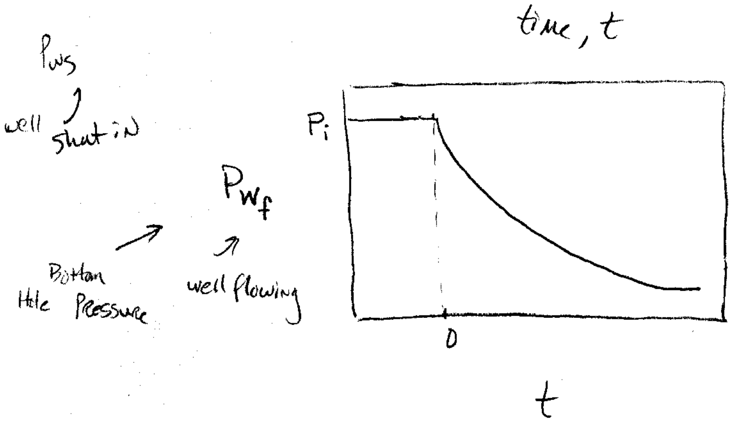


Example 5.5
Monograph V5
Fig. 5.16

PRESSURE DRAWDOWN TESTING -

- Recently discovered well is good candidate for this





- don't have to shut well in before this but constant producing rate is hard to maintain (Trade off)

- test implementation may be hard since constant q is hard to maintain.

- usually a pressure build-up is followed by a drawdown test

Recording P_{wf} as a function of time

P_{wf}	t
P_i	0
⋮	⋮

FUNDAMENTAL RELATIONSHIP

- well acting in an infinite system
- using superposition principle

$$P_i - P_{wf} = P_i q_{D_1} P_t\{(t+\Delta t)_D\} + P_i q_{D_2} P_t(t_D)$$

since $q_{D_1} = 0$ & let $q_{D_2} = q_D$

$$P_i - P_{wf} = P_i q_D P_t\{t_D\}$$

$$t_D = \frac{\lambda K t}{\phi \mu c r_w^2} = \frac{2.637\times10^{-4} K t}{\phi \mu c r_w^2}$$ ← hours

$$q_D = \frac{\gamma B q_{sc} \mu}{K h P_i} = \frac{141.2\, B q_{sc} \mu}{K h P_i}$$

@ the well bore:

$$P_t(t_D) = -\frac{1}{2} E_i\left(-\frac{1}{4t_D}\right)$$

$$P_i - P_{wf} = \frac{141.2\, B q_{sc} \mu}{Kh}\left\{-\frac{1}{2} E_i\left(-\frac{\phi \mu c r_w^2}{(4)(2.637\times10^{-4}) K t}\right)\right\}$$

with Logarithmic Approximation -

$$P_i - P_{wf} = \frac{141.2\, B q_{sc} \mu}{Kh}\left\{\frac{1}{2}\left(\ln \frac{(2.637\times10^{-4}) K t}{\phi \mu c r_w^2} + .809\right)\right\}$$

$$\ln x = 2.3026 \log x$$

$$P_i - P_{wf} = \frac{141.2\, B q_{sc} \mu}{kh}\left[\frac{1}{2}\left(2.3026 \log t + 2.3026 \log 2.637\times10^{-4} + 2.3026 \log\left(\frac{k}{\phi \mu c r_w^2}\right) + .809\right)\right]$$

$$P_i - P_{wf} = \left[\frac{162.6\, B q_{sc} \mu}{kh}\right]\left[\log t + \log \frac{k}{\phi \mu c r_w^2} - 3.2275\right]$$ Practical field units

skin is a dimensionless pressure drop

$S = \frac{(\Delta P)_{skin}}{P_i q_D}$

If consider skin effects:

$q_0 = \frac{\gamma B q_{sc} \mu}{kh}$

$$P_i - P_{wf} = \frac{162.6\, B q_{sc} \mu}{kh}\left[\log t + \log \frac{k}{\phi \mu c r_w^2} - 3.2275\right] + \left[\quad\right]$$

ΔP_{skin}

$$* \quad P_i - P_{wf} = \frac{162.6\, B q_{sc} \mu}{kh}\left[\log t + \log \frac{k}{\phi \mu c r_w^2} - 3.2275\right] + \left(\frac{141.2\, B q_{sc} \mu}{kh}\right) S$$

$$* \quad P_i - P_{wf} = \frac{162.6\, B q_{sc} \mu}{kh}\left[\log t + \log \frac{k}{\phi \mu c r_w^2} - 3.2275 + 0.86859\, S\right]$$

- the above equation describes a straight line relationship between P_{wf} and $\log t$, such that:

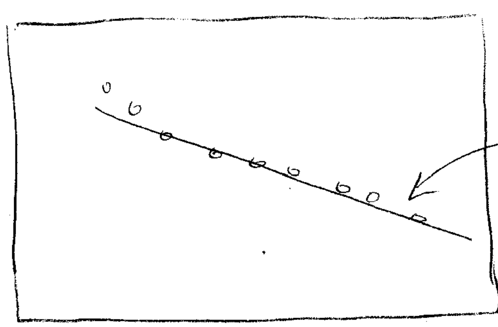
$$P_{wf} = P_{1hr} + m(\log t)$$

where $P_{1hr} = P_i - \frac{162.6\, B q_{sc} \mu}{kh}\left[\log \frac{k}{\phi \mu c r_w^2} - 3.227\right.$
$+ .86859$

$$m = -\frac{162.6\, B q_{sc} \mu}{kh}$$

P_{wf} vs. $\log t$

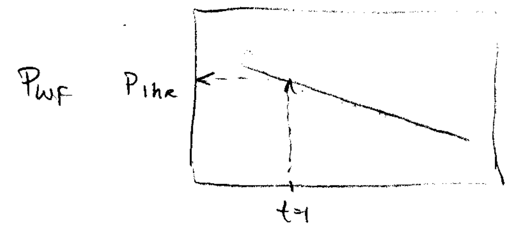
P_{wf}



$m = -\frac{162.6\, B q_{sc} \mu}{kh}$ psia/cycle

$\log t$

when $t = 1$ hour:



Rearranging & solving for S:

$$S = 1.1513\left[\frac{P_{1hr} - P_i}{m} - \log\frac{k}{\phi \mu c r_w^2} + 3.2275\right]$$

use slope with its proper sign

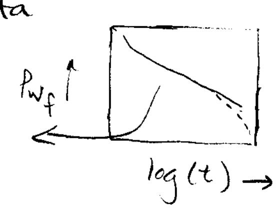
- if drawdown period is fairly long, can determine the volume of the reservoir.
  - called Reservoir Limit testing
  - must record P_{wf} vs t for long time

RESERVOIR LIMIT TESTING -

① plot short time data

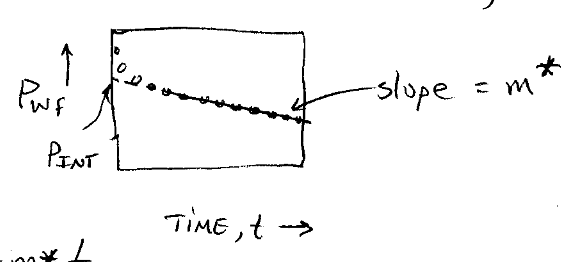
from the standard drawdown analysis →

Read m &
Read P_{1hr}



- extended drawdown analysis

② Plot Long time data (Cartesian Coordinates)



$$P_{wf} = P_{INT} + m^* t$$

intercept

- for Large t_{DA}, when all the boundaries are felt,

@ pseudo-steady state :

$$P_t = \frac{1}{2} \ln\left(\frac{4A}{1.781\, r_w^2 C_A}\right) + 2\pi t_{DA}$$

$$\Delta P_D = 2\pi t_{DA} + \frac{1}{2}\ln\left(\frac{A}{r_w^2}\right) + \frac{1}{2}\ln\left(\frac{2.2458}{C_A}\right) + \overset{\text{composite}}{S}$$

$$P_i - P_{wf} = P_i q_o \left[2\pi \frac{(2.637\times10^{-4}) k t}{\phi \mu c A} + \frac{1}{2}\ln\left(\frac{A}{r_w^2}\right) + \frac{1}{2}\ln\frac{2.2458}{C_A} + S \right]$$

$$P_{wf} = P_i - \frac{141.2\, B q \mu}{kh}\left[2\pi \frac{2.637\times10^{-4} k t}{\phi \mu c A} + \frac{1}{2}\ln\left(\frac{A}{r_w^2}\right) + \frac{1}{2}\ln\left(\frac{2.2458}{C_A}\right) + S \right]$$

$$P_{wf} = P_i - \frac{0.23395\, q B}{\phi c h A} t - \frac{70.60\, q B \mu}{kh}\left[\ln\left(\frac{A}{r_w^2}\right) + \ln\frac{2.2458}{C_A} + 2S \right]$$

$$m^* = -\frac{0.23395\, q B}{\phi c\, hA} \rightarrow \text{res. vol.}$$

- solve for (hA) to get reservoir volume

$P_{INT} \Rightarrow$ @ $t=0$

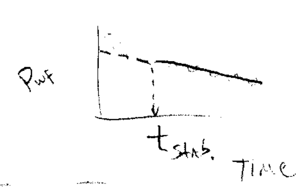
$$P_{INT} = P_i - \frac{70.6\, q \mu B}{kh}\left[\ln\frac{A}{r_w^2} + \ln\frac{2.2458}{C_A} + 2S \right]$$

Solve for C_A & find an approximate configuration

- solve for A in m^*

- need t_{DA} value to accompany C_A

- find time that stabilized conditions take over (when straight line starts) (on the Long time Plot)



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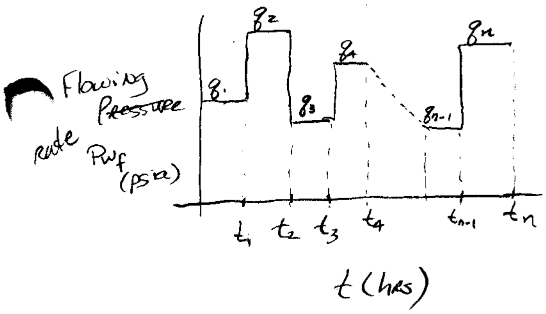
MULTIPLE RATE TESTING



- For a constant flow rate, we have obtained the following expression

$$P_i - P_{wf} = \frac{162.6\, B q_{sc}\, \mu}{kh}\left[\log t + \left\{\log\frac{k}{\phi\mu c r_w^2} - 3.2275 + .86859\, S\right\}\right]$$

Now;

$$\bar{S} = \left[\log\frac{k}{\phi\mu c r_w^2} - 3.2275 + .86859\, S\right]$$

The rate-Time schedule

① $q = q_1$ $\quad 0 \le t < t_1$

② $q = q_2$ $\quad t_1 \le t < t_2$

③ $q = q_3$ $\quad t_2 \le t < t_3$

⋮

④ $q = q_n$ $\quad t_{n-1} \le t < t$

- After applying superposition, we find the pressure drop during the second period to be as follows:

$$P_i - P_{wf} = \frac{162.6\, B q_1 \mu}{kh}\left[\log t + \bar{S}\right] + \frac{162.6\, B(q_2 - q_1)\mu}{kh}\left[\log(t - t_1) + \bar{S}\right]$$

- For the third period;

$$P_i - P_{wf} = \left\{\frac{162.6\, q_1 \mu}{kh}\left[\log t + \bar{S}\right]\right\} + \left\{\frac{162.6\, B(q_2 - q_1)\mu}{kh}\left[\log(t - t_1) + \bar{S}\right]\right\}$$
$$+ \left\{\frac{162.6\,(q_3 - q_2) B\mu}{kh}\left[\log(t - t_2) + \bar{S}\right]\right\}$$

- thus during the $\underline{n^{th}}$ $\underline{\text{time}}$ $\underline{\text{period}}$, the pressure drop is given by:

$$P_i - P_{wf} = \frac{162.6\, B\mu\, q_1}{kh}\left[\log t + \bar{S}\right] + \frac{162.6\, B\mu (q_2 - q_1)}{kh}\left[\log(t - t_1) + \bar{S}\right] + \frac{162.6\, B\mu (q_3 - q_2)}{kh}\left[\log(t - t_2) + \bar{S}\right] + \ldots + \frac{162.6\, B\mu (q_n - q_{n-1})}{kh}\left[\log(t - t_{n-1}) + \bar{S}\right]$$

The above equation can also be written as follows:

$$P_i - P_{wf} = \frac{162.6\,\mu B}{kh}\left[q_1 \log t + (q_2 - q_1)\log(t - t_1) + (q_3 - q_2)\log(t - t_2) + \ldots + (q_n - q_{n-1})\log(t - t_{n-1})\right] + \frac{162.6\,\mu B}{kh} q_n \bar{S}$$

$\underline{\underline{\text{OR}}}$

$$\frac{P_i - P_{wf}}{q_n} = \frac{162.6\,\mu B}{kh}\sum_{j=1}^{N}\left[\left(\frac{q_j - q_{j-1}}{q_N}\right)\log(t - t_{j-1})\right] + \frac{162.6\,\mu B}{kh}\bar{S}$$

$$t_0 = 0 \;;\; q_0 = 0$$

Letting the following:

$$m' = \frac{162.6\,\mu B}{kh} \;;\; b' = \frac{162.6\,\mu B}{kh}\bar{S}$$

$$\therefore\; \frac{P_i - P_{wf}}{q_n} = m' \sum_{j=1}^{N}\left[\left(\frac{q_j - q_{j-1}}{q_N}\right)\log(t - t_{j-1})\right] + b'$$

Multiple rate transient data should appear as a straight line when plotted as

$$\frac{P_i - P_{wf}}{q_N} \quad \text{vs.} \quad \sum_{j=1}^{N}\left[\left(\frac{q_j - q_{j-1}}{q_N}\right)\log(t - t_{j-1})\right]$$

once this data is plotted, the straight line slope & intercept data measured, permeability & skin factor are estimated from the slope & intercept data

$$K = \frac{162.6\,B\mu}{m'h} \quad \& \quad S = 1.1513\left[\frac{b'}{m'} - \log\left(\frac{k}{\phi\mu c r_w^2}\right) + 3.2275\right]$$

Disadvantages of this method -

① initial reservoir pressure, P_i, must be known

if P_i is not known → ② An exceedingly long shut in period is necessary to obtain a reasonable estimate of P_i

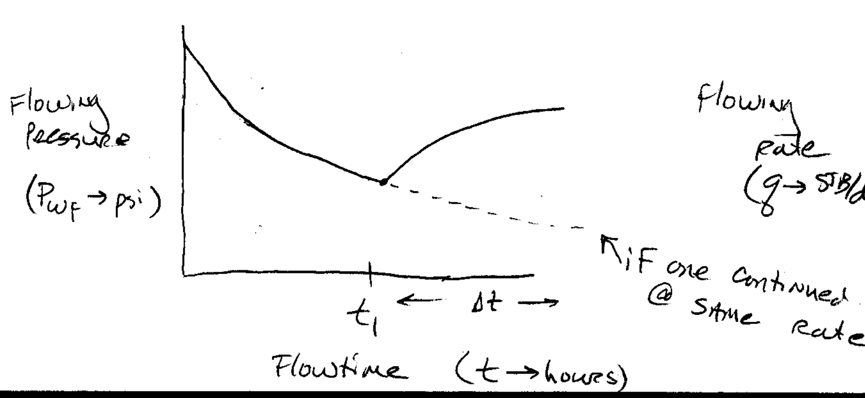
∴ would be good for brand new reservoir

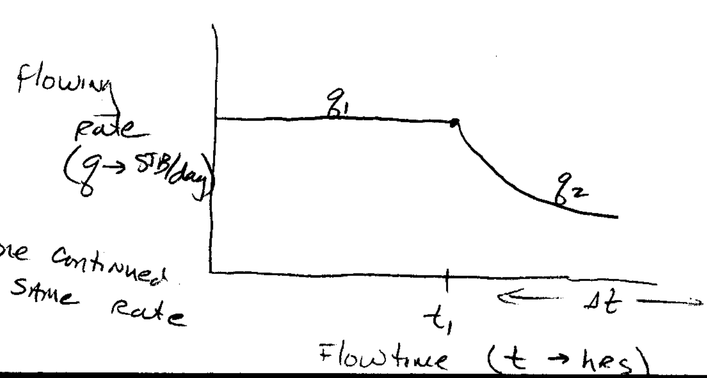
example in text

Two Rate Testing -

- when a multiple rate test consists of only two flow rates both testing & analysis are simplified

- a Two Rate Test provides information about k & S while production continues. Furthermore, wellbore storage effects are often "thought" to be minimized or eliminated by the Two Rate Test.





$$P_{wf} = P_i - \frac{162.6\, B\mu q_1}{Kh}\left[\log(t_1+\Delta t) + \log\frac{K}{\phi\mu c r_w^2} - 3.2275 + .86859\, S\right]$$

$$- \frac{162.6\, B\mu(q_2-q_1)}{kh}\left[\log\Delta t + \log\frac{K}{\phi\mu c r_w^2} - 3.2275 + .86859\, S\right]$$

$$P_{wf} = P_i - \frac{162.6\, q_2 B\mu}{kh}\left[\log\frac{K}{\phi\mu c r_w^2} - 3.2275 + .86859\, S\right] - \frac{162.6\, q_1 B\mu}{kh}\left[\log\left(\frac{t+\Delta t}{\Delta t}\right) + \frac{q_2}{q_1}\log\Delta t\right]$$

- this may be modified into the following form:

$$P_{wf} = M_1' \log\left(\frac{t_1+\Delta t}{\Delta t}\right) + \frac{q_2}{q_1}\log(\Delta t) + P_{INTERCEPT}$$

- this assumes a constant q_1

(if not a constant q_1, a stabilized q_1)

- if have to use a stabilized q_1, we must estimate t_1 as follows:

$$t_1 = \frac{24\, V_p}{q_1}$$; V_p = cumulative volume produced since the last rate stabilization

- if you plot P_{wf} vs. $\left[\log\left(\frac{t+\Delta t}{\Delta t}\right) + \frac{q_2}{q_1}\log\Delta t\right]$ you obtain a straight line, where

$$M_1' = -162.6\,\frac{q_1 \mu B}{kh}$$

$$P_{intercept} = P_i + M_1'\frac{q_2}{q_1}\left[\log\left(\frac{K}{\phi\mu c r_w^2}\right) - 3.2275 + .86859\, S\right]$$

- once the plot of P_{wf} vs $\left[\log\left(\frac{t+\Delta t}{\Delta t}\right) + \frac{q_2}{q_1}\log\Delta t\right]$ is obtained, the reservoir permeability may be obtained from:

$$K = \frac{-162.6\, q_1 B\mu}{M_1' h}$$

- the skin factor S may be estimated from

$$S = 1.153\left[\frac{q_1}{q_2-q_1}\left(\frac{P_{wf}^{\Delta t\to 0} - P_{1hr}}{M_1'}\right) - \log\frac{K}{\phi\mu c r_w^2} + 3.2275\right]$$

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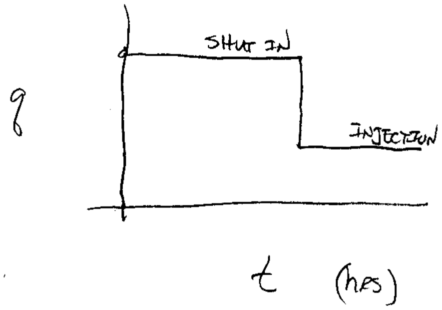
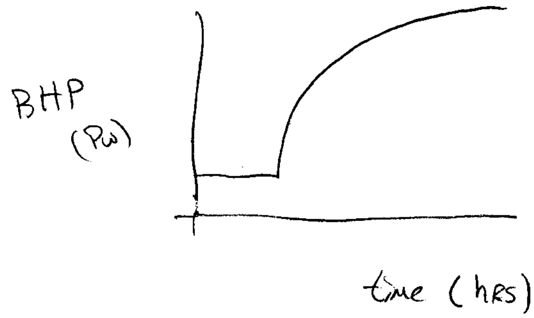
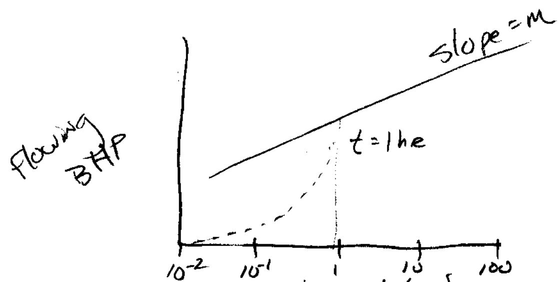
Injection Well Testing

Plot Rate q vs t







semilog plot of typical injectivity data

For the constant rate injection test, the BHP is given by:

$$P_{wf} = P_i - \frac{162.6\,\mu B q}{kh}\left[\log t + \log\left(\frac{k}{\phi\mu c r_w^2}\right) - 3.2275 + .86859\,S\right]$$

OR $$P_{wf} = P_{1hr} + m \log t$$

- The intercept, $$P_{1hr} = P_i + m\left[\log\left(\frac{k}{\phi\mu c r_w^2}\right) - 3.2275 + .86859\,S\right]$$

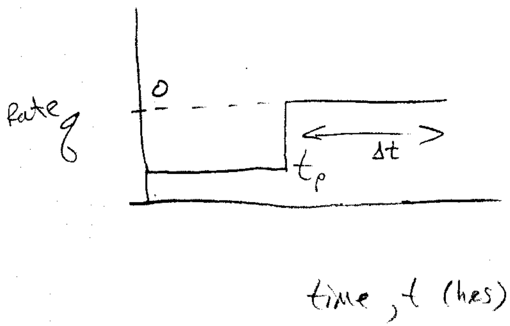
slope;

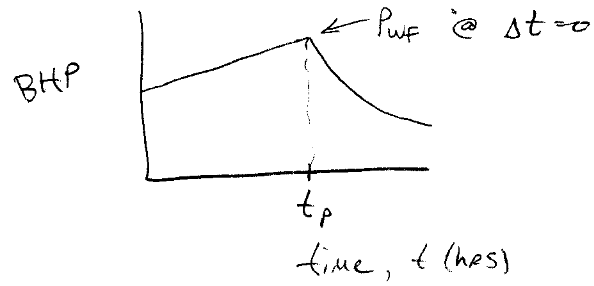
$$m = -\,162.6\,\frac{qB\mu}{kh}$$

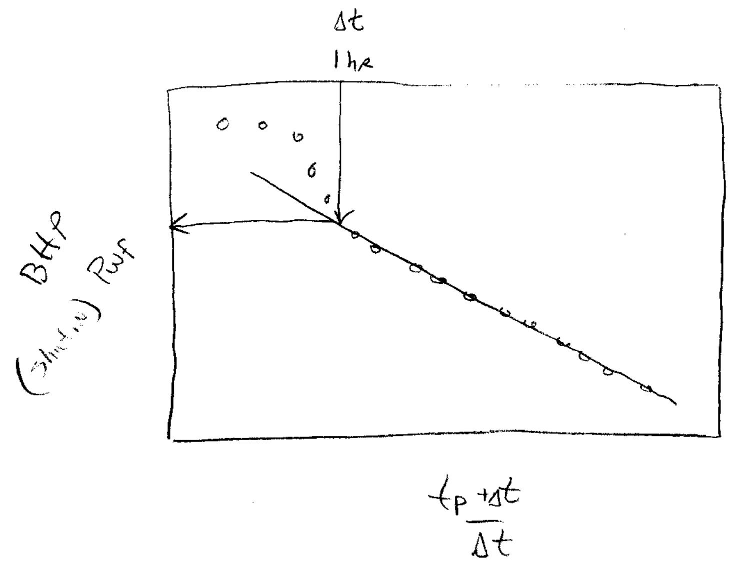
& then skin factor

$$S = 1.1513\left[\frac{P_{1hr} - P_i}{m} - \log\left(\frac{k}{\phi\mu c r_w^2}\right) + 3.2275\right]$$

Fall off Test Analysis for Liquid filled Unit-Mobility-Ratio Reservoirs







Pressure data taken immediately before & during shut-in period are analyzed as pressure build up data are analyzed

$$P_{ws} = P^* - m \log\left(\frac{t_p + \Delta t}{\Delta t}\right) \qquad P^* = P_i$$

$$m = \frac{162.6\, q B \mu}{kh}$$

$$S = 1.1513 \left[\left(\frac{P_{1hr} - P_{wf\,(\Delta t = 0)}}{m}\right) - \log\left(\frac{k}{\phi \mu c r_w^2}\right) + 3.2275\right]$$

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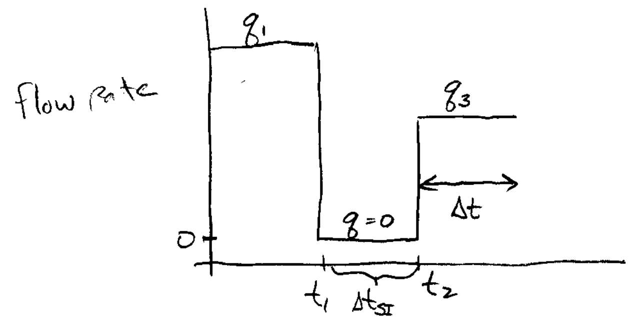
DRAWDOWN TESTING AFTER A SHORT SHUTIN -

It is a common practice to run a drawdown test after a short shutin period (pressure buildup test)



$\Delta t \equiv$ time of test

$$\frac{p_i - p_{wf}}{q_N} = \frac{162.6\,\mu B}{kh} \sum_{j=1}^{N} \left[\left(\frac{q_j - q_{j-1}}{q_N} \right) \log(t - t_j) \right] + \frac{162.6\,\mu B}{kh}\,\bar{s}$$

$$\frac{p_i - p_{wf}}{q_3} = \frac{162.6\,\mu B}{kh} \left[\frac{q_1 - \cancel{q_0}^{=0}}{q_3} \log(t - \cancel{t_0}^{=0}) + \frac{\cancel{q_2}^{=0} - q_1}{q_3} \log(t - t_1) + \frac{q_3 - \cancel{q_2}^{=0}}{q_3} \log(t - t_2) \right]$$
$$+ \frac{162.6\,\mu B}{kh} \left[\log\left(\frac{k}{\phi \mu c r_w^2} \right) - 3.2275 + .86859\, S \right]$$

$$\frac{p_i - p_{wf}}{q_3} = \frac{162.6\,\mu B}{kh} \left[\frac{q_1}{q_3} \log(t) - \frac{q_1}{q_3} \log(t - t_1) + \log(t - t_2) \right]$$
$$+ \frac{162.6\,\mu B}{kh} \left[\log\left(\frac{k}{\phi \mu c r_w^2} \right) - 3.2275 + .86859\, S \right]$$

if we let $t = t_1 + \Delta t_{SI} + \Delta t$

& if we let $t_2 = t_1 + \Delta t_{SI}$

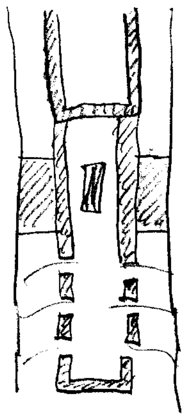
$$\therefore \quad p_{wf} = p_i - \frac{162.6\,\mu B}{kh} q_3 \left[\frac{q_1}{q_3} \log(t_1 + \Delta t_{SI} + \Delta t) - \frac{q_1}{q_3} \log(\Delta t_{SI} + \Delta t) + \log \Delta t \right]$$
$$+ \frac{162.6\,\mu B}{kh} q_3 \left[\log\left(\frac{k}{\phi \mu c r_w^2} \right) - 3.2275 + .86859\, S \right]$$

Let $m_3' = -\frac{162.6\,\mu B}{kh} q_3$

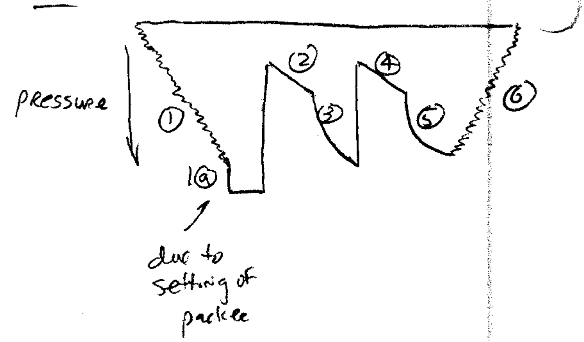
$$P_{int} = P_i + m_3' \left[\log\left(\frac{k}{\phi \mu c r_w^2} \right) - 3.2275 + .86859\, S \right]$$

then finally:

Formation closed in



Classical DST Chart:



① increase in hydrostatic mud pressure

①(a) setting of packer causes compression in the annulus. (mud)

② Inflow from the formation

③ Pressure build up

④ same as ②

⑤ same as ③

⑥ decrease in hydrostatic mud pressure

Data obtained from a DST includes

① physical description of fluids

② volume of recovery

③ Flow times

④ Shut in times and a bottom hole pressure time chart

Reservoir characteristics may be calculated from formation test data are

① permeability

② wellbore damage

③ reservoir pressure

④ Depletion

⑤ Radius of investigation

⑥ Barrier indications

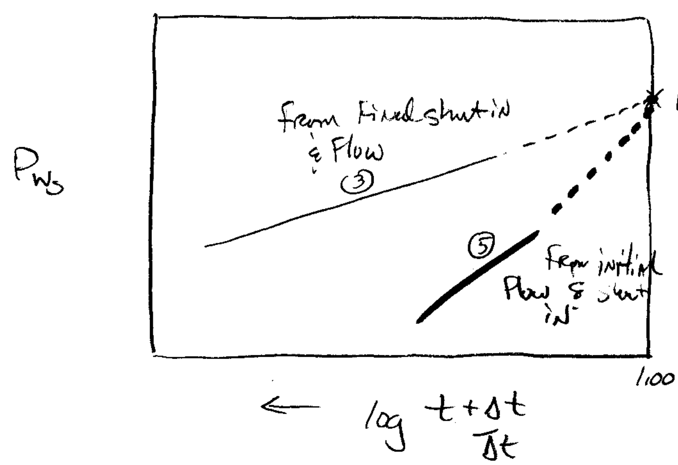
TES

11/1/82

Analyzing DST Pressure Data

- Pressure Buildup data must be analyzed with the Horner Plot (Because Δt & t_p are comparable)

- we need to plot P_{ws} vs $\log\left(\frac{t_p + \Delta t}{\Delta t}\right)$
- The value of t_p is usually the Length of the preceeding Flow period. However, if the initial flow period is very long, it is more accurate to use the sum of the flow period Lengths for t_p for the final buildup



← ideally, the straight lines should approach the value of P_i

if P_i's do not agree, use the final data

$$m = -\frac{162.6 q \mu B}{kh} \quad \text{psia/cycle}$$

In conventional build up analysis in skin factor calculation we assumed that $\frac{t_p + \Delta t}{\Delta t} \approx \frac{t_p}{\Delta t}$

- Not valid for DST since t_p & Δt are fairly close.

Skin factor Analysis for DST Pressure Data -

$$P_\delta - P_{wf} = 141.2 \frac{B q_{sc} \mu}{kh}\left[\frac{1}{2}\left(\ln \frac{2.637\times10^{-4}\, kt}{\phi \mu c r_w^2} + .80907\right) + S\right]$$

$$- \frac{141.2}{kh}\left[\frac{1}{2}\ln\left(\frac{t+\delta}{\delta}\right)\right]$$

since $\frac{t+\delta}{\delta} \not\approx \frac{t}{\delta}$, we have:

$$P_\delta - P_{wf} = 141.2 \frac{B q \mu}{kh}\left[\frac{1}{2}(2.3026)\left(\log \frac{2.637\times10^{-4}\, kt}{\phi \mu c r_w^2} + \frac{0.809}{2.3026}\right) + S\right]$$

$$+\left[-\frac{1}{2}(2.3026)\left(\log(t+\delta) - \log \delta\right)\right]$$

$$P_\delta - P_{wf} = \underbrace{\frac{162.6\, B q \mu}{kh}}_{-m}\left[\log 2.637\times10^{-4} + \log \frac{k}{\phi \mu c r_w^2} + \log t + .3513 + \frac{2S}{2.3026} - \log(t+\delta) + \log \delta\right]$$

Let $\delta = 1$ $\longrightarrow$ P_{1hr} is need (from straight line on Horner plot)

$$P_{1hr} - P_{wf} = -m\left[\log\left(\frac{k}{\phi \mu c r_w^2}\right) + \log\left(\frac{t}{t+1}\right) + \frac{2S}{2.3026} + \log 2.637\times10^{-4} + 0.3513\right]$$

$$\ast \quad \Rightarrow \quad S = 1.1513\left[\frac{P_{1hr} - P_{wf}}{-m}{}^{(\Delta t=0)} + \log\left(\frac{t+1}{t}\right) - \log\left(\frac{k}{\phi \mu c r_w^2}\right) + 3.22\right.$$

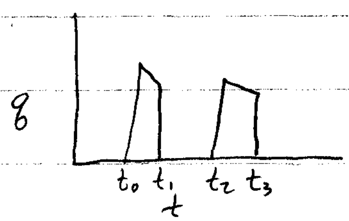
Drillstem Test - DST

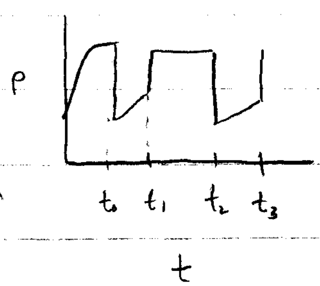
- normally run in a zone of unknown potential in a well being drilled
- provides a temporary completion with the drillstring serving as flowstring.

* - a good DST yields
  1. a sample of reservoir fluid
  2. an indication of flow rates
  3. BHP, both static & flowing
  4. short term pressure transient test

- a DST helps determine
  1. possibility of commercial production
  2. estimate of formation properties & wellbore damage.

- Most DST's include:
  1. short production period (initial flow)
  2. short shutin (initial buildup)
  3. longer production period (final flow)
  4. longer shut in (final build up)





In a standard DST, (1) the initial flow period is usually short (5-10 MIN); the idea is simply to release the high hydrostatic mud pressure
(2) initial shut-in should be long enough to approach stabilized flow.
(experience shows ≈ 1 hour)

DST pressure build up data must be analyzed with the Horner plot (since $t_p \cong \Delta t$)

→ p_{ws} vs. $\log\left(\frac{t_p+\Delta t}{\Delta t}\right)$

→ the value used for t_p is usually the length of the preceding flow period.

- if the initial flow period is very long, it is more accurate to use the sum of the flow-period lengths for t_p for the final buildup

for liquid-producing wells, the flow rate during a drillstem test decreases with time since the backpressure exerted on the formation face increases as the produced fluid moves up the drillstring

* Normally, the decreasing flow rate over the flow period is neglected in analyzing DST pressure buildup data and the average flow rate over the flow period is used.

The controlling factor for flow rate from a porous medium to a wellbore is critical flow thru the perfs in the anchor pipe.

- in this instance, P_{wf} from the flowstring recorder are useless, although shut-in data are analyzable
- all data from the blanked-off recorder can be analyzed in a normal fashion.

wellbore storage is not often significant in the buildup portion of a DST since the well is closed in near the formation face.

- if analysis results are suspicious, the log-log plot ($\log(P_{ws}-P_{wf})$ vs $\log \Delta t$) should be made to determine what part of the data should be analyzed.

(wellbore storage can be significant if thick sections in low permeability reservoirs are being tested)

If the shut-in period is long enough, and if wellbore storage is not dominant, a Horner plot of the buildup data should have a straight line section & slope $= -m$

$$K = \frac{162.6\, q\mu B}{|m| h}$$

$$S' = 1.1513 \left[\frac{P_{1hr} - P_{wf\,(\Delta t=0)}}{m} + \log\left\{ \frac{t_p+1}{t_p} \right\} - \log\left(\frac{k}{\phi \mu c_t r_w^2} \right) + 3.2275 \right]$$

TOTAL SKIN

Damage Ratio : $\dfrac{J_{IDEAL}}{J_{ACTUAL}} = \dfrac{\bar{P} - P_{wf}}{\bar{P} - P_{wf} - \Delta P_s}$; $\Delta P_s = \dfrac{141.2\, q\mu B}{kh} S'$

Initially, the drillpipe will be empty for the DST

- before opening, the pressure existing for the first flow is atmospheric