G. Luethkehans
RB-29

PROJECTED RESERVOIR PERFORMANCE

RIO BLANCO PROJECT

Report Prepared for

ATOMIC ENERGY COMMISSION

by

H. K. van Poollen

Assisted by: J. R. Bergeson
E. H. Timmerman
G. R. Pickett

March 1972

H. K. VAN POOLLEN AND ASSOCIATES

TABLE OF CONTENTS

	Page
SUMMARY AND CONCLUSIONS	1
INTRODUCTION	2
SOURCE OF DATA	3
GENERAL METHOD EMPLOYED	7
1. Buildup and drawdown analysis	7
2. Well log analysis	7
3. Forecast of performance of well after blast	8
BUILDUP AND DRAWDOWN ANALYSIS	9
LOG ANALYSIS	18
FORECAST OF FUTURE PERFORMANCE	22
APPENDIX A	33
APPENDIX B	44
APPENDIX C	87

ILLUSTRATIONS

Figure No.		Page
1	k_r vs. Confining Pressure	5
2	Pressure vs. m	12
3	Pressure vs. m´	13
4	Pressure Values Extrapolated from Buildup Data vs. Depth	15
5	Case 1 (Results of Computer Run I)	24
6	Case 2 (Results of Computer Run II)	25
7	Case 3 (Results of Computer Run III)	26
8	Case 4 (Results of Computer Run IV)	27
9	Case 5 (Results of Computer Run V)	28
10	Case 6 (Results of Computer Run VI)	29
11	Case 7 (Results of Computer Run VII)	30
12	Case 8 (results of Computer Run VIII)	31
13 - 52	Appendix B	47

TABLES

Table No.		Page
I	Analysis of Pressure Related Properties	6
II	Fawn Creek Government No. 1 - Survey of Well Test Data	10
III	Scandard Draw No. 1 - Summary of Well Test Data	11
IV	Formulation-Evaluation Analysis	20
V	Normalized Permeabilities and Viscosities	32

PROJECTED RESERVOIR PERFORMANCE
RIO BLANCO PROJECT

SUMMARY AND CONCLUSIONS

Data from three wells were analyzed to determine basic reservoir parameters and to predict a future reservoir performance assuming nuclear stimulation is carried out. Permeability, as calculated by pressure transient analysis, ranged from 0.0064 to 0.087 md in offset well Fawn Creek Government No. 1.

Log analyses of RB-E-01 indicate an average porosity of 9.4%, average gas saturation of 57% and a net pay of 421 feet.

The permeability from pressure transient analysis averages 0.025 md for the Fort Union and 0.011 md for the Mesaverde. This gives 7.75 md-ft for the Fort Union and 1.23 md-ft for the Mesaverde or a total of 8.98 md-ft.

Reservoir performance was predicted using a single-layer model with an average permeability of 0.0212 md. Cumulative production after 25 years was 19.9 BCF for 640-acre spacing. A two-layer model using the calculated values for the Fort Union and the Mesaverde gave a 25 year cumulative production of 17.9 BCF. Additional predictions made using a range of permeabilities are also included.

One value of pressure dependent permeability was run using 640- and 320-acre spacings. However, it is felt that the information used to determine the pressure dependent permeability was not necessarily valid and should not be given much consideration.

INTRODUCTION

The objective of this report is to evaluate important reservoir parameters and predict reservoir performance after nuclear stimulation of the Fort Union-Mesaverde formation. This stimulation is projected for a presently completed well RB-E-01 located 1080.5' FNL and 1188.49' FWL, Section 14, Township 3S, Range 98W, Rio Blanco County, Colorado.

Initial instructions were given to Mr. J. R. Bergeson during a meeting held at Las Vegas on March 1, 1972, in the office of the Atomic Energy Commission, with Mr. Dick Pastore and Mr. Wayne Johnston of the AEC and Mr. Bob Littlejohn of Fenix and Scisson in attendance. At that time, the data, in the form of several reports (see section entitled "Source of Data"), were transmitted to the evaluating firm. Analysis of raw data obtained from RB-E-01, the emplacement well, Fawn Creek Government No. 1 and to a lesser extent Scandard Draw No. 1, form the basis for the predictions.

Mr. Wayne Johnston was designated as coordinator for this evaluation. Deadline for the completed report was set for March 24, 1972.

SOURCE OF DATA

Mr. Johnston provided original data and supplementary references for this study. A list of these data is as follows:

RB-E-01

BHC Sonic	7859	to 6984	feet
CNP & FDC	7858	to 6984	feet
FDC	7858	to 6984	feet
DIL-LL8	7864	to 6986	feet
CNL	7255	to 110	feet
DIL-LL8	7255	to 839	feet
FDC	7255	to 839	feet
BHC-Sonic	7254	to 839	feet
VDL	7255	to 839	feet

Core Analysis
Mud Log
Schlumberger "Saraband" Analysis
Conoco Analysis
Analysis of Pay - CER
Predicted Recoveries from RB-E-01 - CER
Permeability of Rio Blanco Phase I Experiment Sands - CER

Fawn Creek

NLL Log
IES
GR-N
Fawn Creek Analysis - Conoco

Rio Blanco Project

Feasibility Study - CER
Reservoir Report - CER
Geology of Piceance Basin - CER
Definition Plan - Project Description - CER
Structure Map - RB Unit

Rulison

Mobil's Analysis
Montan's Analysis
CER Letter to Joint Committee
Feasibility Study
Definition Plan
Site Evaluation - Reservoir Report - CER
Site Evaluation - Austral Oil Company, CER

Boies No. 1

Summary of Cores and Tests

Additional visits to various offices could possibly have uncovered more information relative to this project. However, it was thought that the extra time involved would not be warranted in this study. It was also concluded that the information listed above would be sufficient for the calculations that follow.

For the analysis of permeability reduction with confining overburden pressure, use was made of the data presented in the February 1, 1972, letter from Mr. Tom H. Timmins of Mobil Research and Development Corporation to the Subgroup 3 of Gas Technology Task Group. The actual data used is shown in Fig. 1.

Mr. E. Moffat of Conoco, Grand Junction, supplied information on mechanical condition of wells that was used for the afterflow calculations.

Table I shows the relationship between gas deviation factor (z), viscosity, $m(p)$, $m'(p)$ and k_r, and changes in pressure.

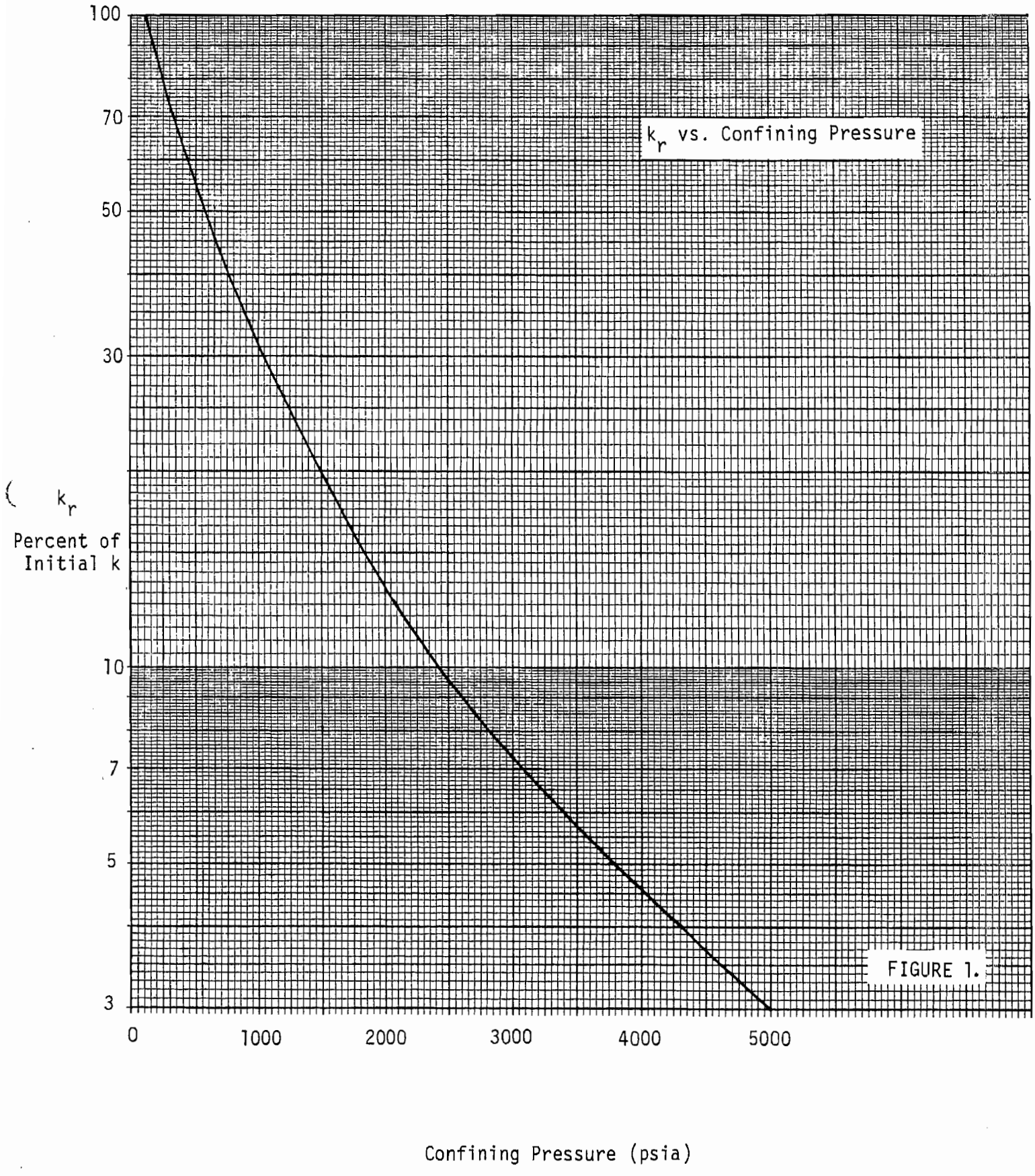

k_r vs. Confining Pressure
100
70
50
30
10
7
5
3
0
1000
2000
3000
4000
5000
(k_r
Percent of Initial k
Confining Pressure (psia)

FIGURE 1.

TABLE I

ANALYSIS OF PRESSURE RELATED PROPERTIES

Pressure psia	z	Viscosity cp	Compressibility psi^{-1}	B Bbls/MCF	m(p) psi^2/cp	Confining Pressure psia	k_r	m'(p) psi^2/cp
100	.996	.0139	1.01×10^{-2}	33.89	0.72×10^6	4900	0.032	0.023×10^6
200	.987	.0140	5.09×10^{-3}	16.79	2.89 "	4800	0.033	0.093 "
300	.978	.0140	3.42 "	11.09	6.52 "	4700	0.034	0.216 "
400	.970	.0141	2.58 "	8.25	1.16×10^7	4600	0.036	0.396 "
500	.962	.0142	2.08 "	6.55	1.82 "	4500	0.037	0.636 "
600	.955	.0144	1.74 "	5.42	2.62 "	4400	0.039	0.942 "
700	.948	.0145	1.50 "	4.61	3.57 "	4300	0.0405	1.318 "
800	.942	.0146	1.32 "	4.01	4.66 "	4200	0.0420	1.769 "
900	.936	.0148	1.17 "	3.54	5.89 "	4100	0.044	2.229 "
1000	.931	.0149	1.06 "	3.17	7.27 "	4000	0.046	2.916 "
1100	.926	.0151	9.61×10^{-4}	2.86	8.78 "	3900	0.048	3.626 "
1200	.921	.0152	8.80 "	2.61	10.42 "	3800	0.050	4.432 "
1300	.917	.0154	8.12 "	2.40	12.20 "	3700	0.053	5.348 "
1400	.913	.0156	7.52 "	2.22	14.10 "	3600	0.055	6.377 "
1500	.910	.0158	7.00 "	2.06	16.13 "	3500	0.0575	7.517 "
1600	.907	.0160	6.54 "	1.93	18.27 "	3400	0.060	8.779 "
1700	.905	.0162	6.13 "	1.81	20.54 "	3300	0.0635	10.177 "
1800	.903	.0164	5.76 "	1.71	22.91 "	3200	0.066	11.715 "
1900	.901	.0166	5.42 "	1.61	25.39 "	3100	0.070	13.407 "
2000	.900	.0169	5.12 "	1.53	27.98 "	3000	0.075	15.282 "
2100	.899	.0171	4.83 "	1.46	30.67 "	2900	0.077	17.320 "
2200	.898	.0173	4.58 "	1.39	33.44 "	2800	0.081	19.520 "
2300	.898	.0176	4.36 "	1.33	36.31 "	2700	0.085	21.914 "
2400	.899	.0178	4.12 "	1.27	39.27 "	2600	0.090	24.512 "
2500	.899	.0181	3.91 "	1.22	42.30 "	2500	0.095	27.334 "
2600	.900	.0183	3.72 "	1.18	45.41 "	2400	0.102	30.416 "
2700	.901	.0186	3.54 "	1.14	48.60 "	2300	0.109	33.795 "
2800	.903	.0189	3.37 "	1.10	51.85 "	2200	0.117	37.482 "
2900	.905	.0192	3.21 "	1.06	55.16 "	2100	0.130	41.571 "
3000	.908	.0194	3.06 "	1.03	58.54 "	2000	0.135	46.040 "
3100	.910	.0197	2.92 "	1.00	61.97 "	1900	0.145	50.847 "

Gas Gravity = .65
Crit. Temp. = 371.9 R
Bottom Hole Temp. = 216°F
Crit. Pres. = 669.3 psia
Barometric Pres. = 11 psia

Molecular Weight = 18.75
Reduced Temp. = 1.82
Base Temp. = 520 R
Initial Pres. = 3000 psig
Base Pres. = 14.7 psia

$$m = 2 \int \left(\frac{p}{\mu z}\right) dp$$

$$m' = 2 \int \left(\frac{pk_r}{\mu z}\right) dp$$

GENERAL METHOD EMPLOYED

The study was divided into three major tasks:

1. Buildup and drawdown analysis

The following field tests were analyzed:

Well	Interval	Type of Test
Fawn Creek Government #1	5747-5792	Buildup #1
		Buildup #2
		Drawdown #2
		Buildup #3
	5600-5630	Buildup #1
		Drawdown #1
		Buildup #2
Scandard Draw	7181-7212	Buildup #1
		Drawdown #1
		Buildup #2
	6810-6833	Buildup #1
	7454-7476	Buildup #1

The conventional real gas potential technique and a technique which includes changes in permeability with confining pressure were both used. The standard plots of the above m(p) functions versus log $\frac{t + \Delta t}{\Delta t}$ and log Δt were used, supplemented by other curves and equations useful in selection of proper data including time intervals.

2. Well log analysis

Information was available for three wells:

RB-E-01

Fawn Creek Government No. 1

Scandard Draw No. 1

Data for RB-E-01 were sufficient for rather complete analysis, but information for the remaining wells limited the analysis of their logs.

3. Forecast of performance of well after blast

A one-dimensional computer model, which included shape factors to account for radial coordinates, was employed. Use of a more elaborate model was considered, but the added expense was not believed worthwhile after review of the basic available data.

Six forecasts were made for 640-acre drainage; with three showing the effect of variation of permeability from 0.01 to 0.10 md and one comparing the use of $m'(p)$ with $m(p)$. One run was made using average values for a single-layer model. Another run was made using a two-layer model and average values for the Fort Union and the Mesaverde. Two forecasts were made for 320-acre drainage to show the effect of two permeability values.

All evaluation efforts are discussed in separate sections in a later portion of this report.

BUILDUP AND DRAWDOWN ANALYSIS

A summary of all analysis is presented in Tables II and III. Pertinent equations used in the analysis are included as Appendix A. The analysis suggests that the drawdown in-situ rock permeability varies from 0 to 0.09 md and the average value may be in the range of 0.01 to 0.04 md.

The pressure drawdown and pressure buildup curves were evaluated using plots of m(p) and m´(p) versus log Δt and log $\frac{t + \Delta t}{\Delta t}$, respectively. Values of real gas potential were calculated as a function of pressure, viscosity and deviation factor, with the use of the equation

$$m(p) = 2 \int \frac{p}{\mu z} dp$$

Values of the modified real gas potential were calculated as a function of pressure, viscosity, deviation factor and permeability with the use of the equation

$$m'(p) = 2 \int \frac{pk_r}{\mu z} dp \ .$$

k_r was used to adjust for the change in true formation permeability with change in confining pressure; i.e., the net pressure effective at the grain contacts. In this study, the change was assumed to occur immediately although some time delay may actually occur in the reservoir. Figures 2 and 3 show the variation of m(p) and m´(p) with respect to pressure. The effect of the pressure sensitive permeability included in m´(p) as compared to m(p) at corresponding pressures is seen to be significant.

TABLE II

FAWN CREEK GOVERNMENT NO. 1

SUMMARY OF WELL TEST DATA

Fig. No.	Date of Test (1970)	Zone	Interval feet	Type Test	Duration of Test hours	Analysis Technique	kh md ft	h	k md	Radius of Investigation feet	Max. Pres Measured psig	Final Pres psia	Remarks
13	06/12-06/16	1	5747 5792	Buildup #1	89.75	m(p)	0.980	35	0.028	80	1308	1590	
14						m´(p)	1.120	35	0.032			1580	
16	07/08-08/01	1	5747 5792	Buildup #2	579.5	m(p)	0.503	35	0.014	140	1653	1800	Mechanical trouble
17						m´(p)	0.525	35	0.015			1800	
19	08/01-08/16	1	5747 5792	Drawdown #2	353.5	m(p)	0.225	35	0.0064	60	1653	-	Permeability apparently decreased during this flow
20						m´(p)	0.296	35	0.0085				
23	08/16-10/13	1	5747 5792	Buildup #3	1341	m(p)	0.225	35	0.0064	140	1732	1920	
25						m´(p)	0.279		0.008			1870	
27	10/30-11/09	2	5600 5630	Buildup #1	241	m(p)	1.740	20	0.087	225	2074	2145	
28						m´(p)	1.790		0.090			2130	
30	11/09-11/19	2	5600 5630	Drawdown #1	229	m(p)	0.677	20	0.034	140	2060	-	
33					155 229	Two Rate Flow	0.566	20	0.028				
31						m´(p)	0.745	20	0.037				
34	11/19-01/17	2	5600 5630	Buildup #2	1429 (2056)	m(p)	0.654	20	0.032	325+	1953 (1998)	2060	
36						m´(p)	0.626	20	0.031			2060	

TABLE III

SCANDARD DRAW NO. 1

SUMMARY OF WELL TEST DATA

Fig. No.	Date of Test (1970)	Zone	Interval feet	Type Test	Duration of Test hours	Analysis Technique	kh md ft	h	k md	Radius of Investigation feet	Max. Pres Measured psig	Final Pres psia	Remarks
38	06/06-06/13	1	7181 7212	Buildup #1	121.25	m(p)	0.210	15	0.014	75	2851	2990	
39						m´(p)	0.222		0.015			2980	
41	06/13-06/20	1	7181 7212	Drawdown #1	167	m(p)	No distinct shape in curves - not analyzed						
42						m´(p)							
44	06/20-06/27	1	7181 7212	Buildup #2	69 (172)	m(p)	0.228	15	0.015	100	2636	2975	Leak after 69 hours
45						m´(p)	0.246		0.016			2910	
47	07/22-08/03	2	6810 6833	Buildup #1	292	m(p)	0.049	16	0.003	50	2203	2370	
48						m´(p)	0.044		0.003			2390	
50	09/06-10/13	3	7454 7476	Buildup #1	874	m(p)	0.0051	-	-	-	1824	2350	
51						m´(p)	0.0050	-	-			2300+	

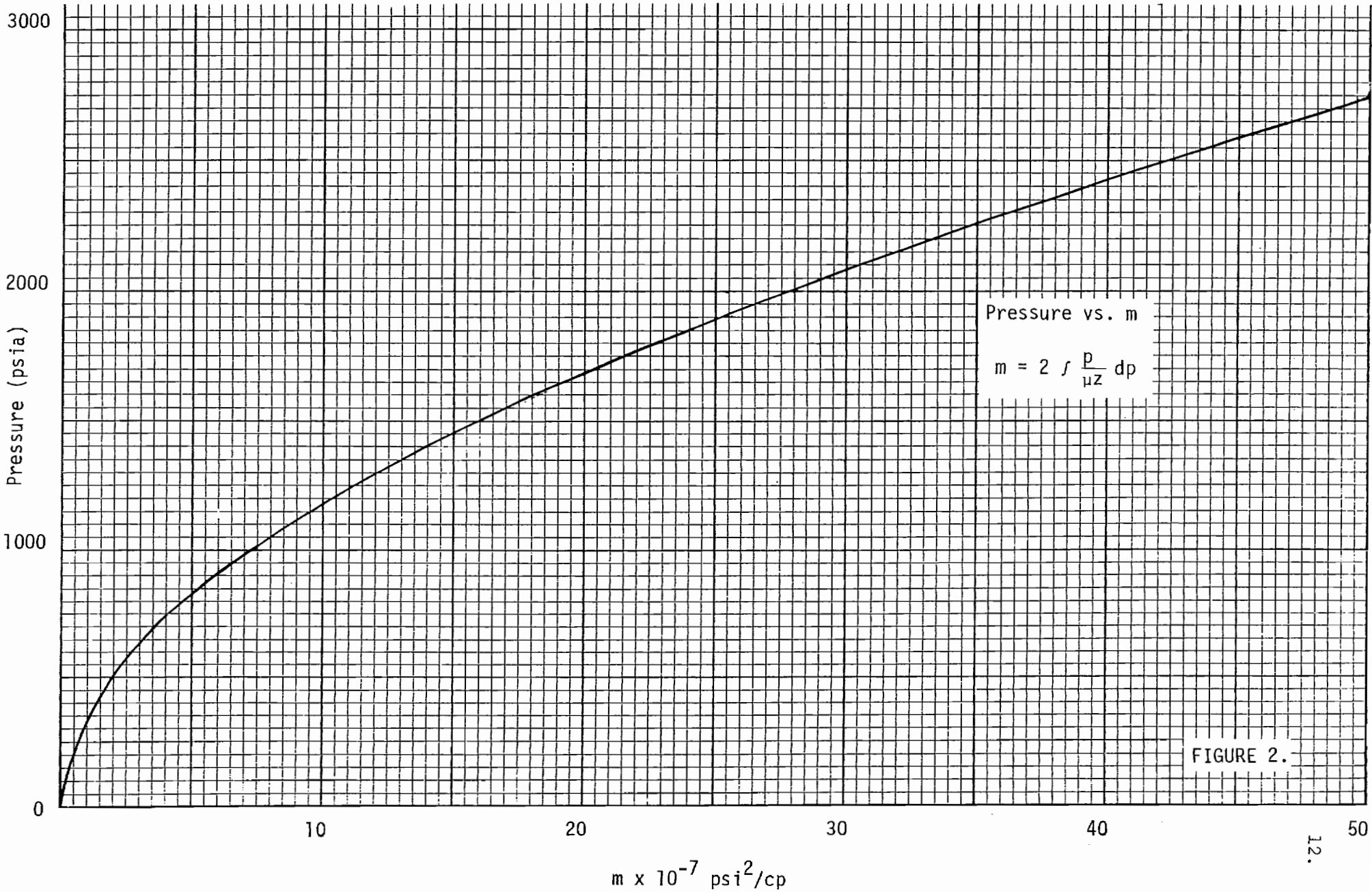

3000
2000
1000
0
Pressure (psia)
10
20
30
40
50
m x 10^-7 psi^2/cp
Pressure vs. m
m = 2 ∫ p/μz dp

FIGURE 2.

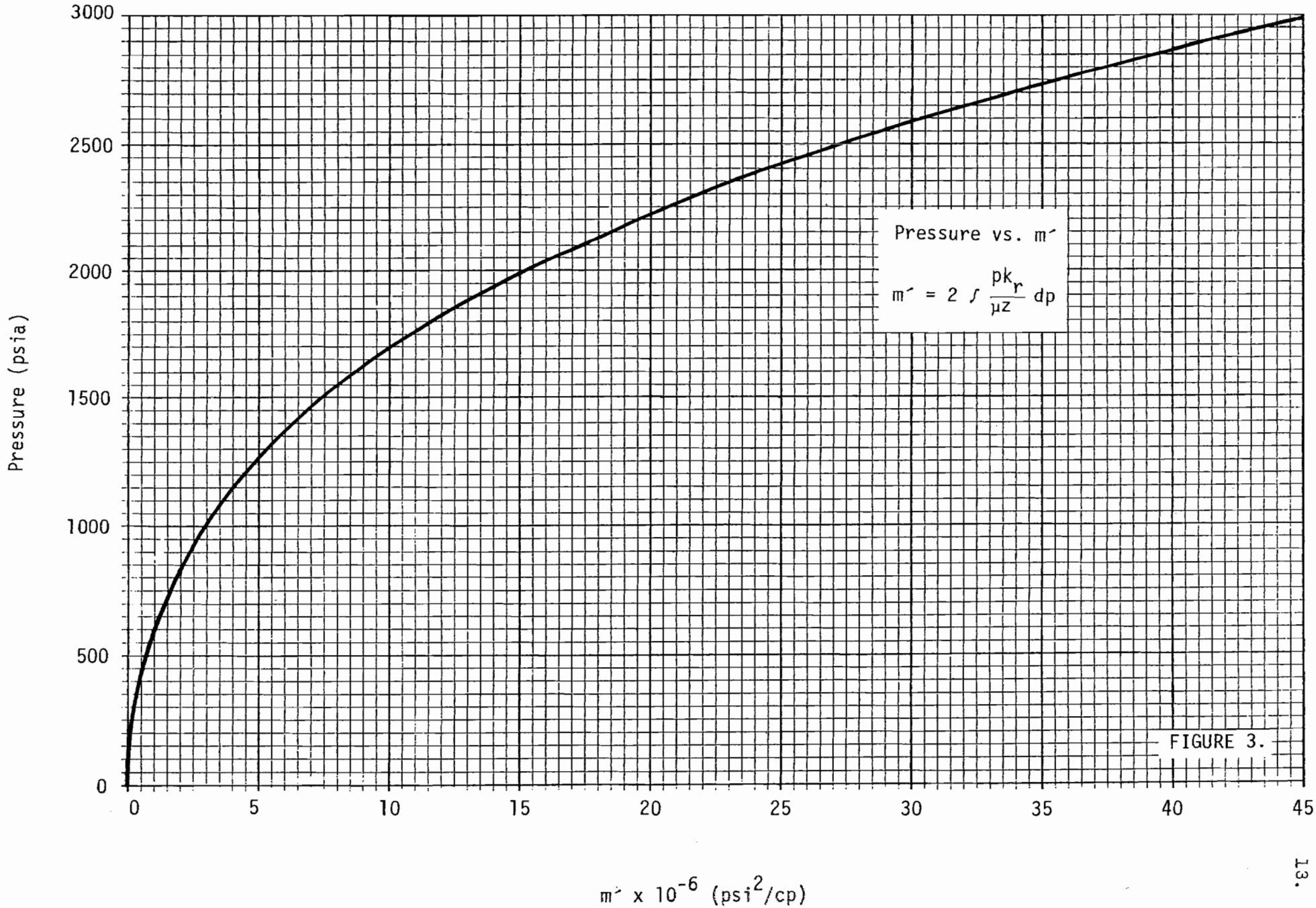

Pressure vs. m´
$m' = 2 \int \frac{pk_r}{\mu z} dp$
Pressure (psia)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
m´ x 10^{-6} (psi^2/cp)

FIGURE 3.

The flowing time, t, used in the buildup equations possibly should be determined using methods of superposition. However, the method is lengthy and depends upon data of superior quality. The usual method of dividing the cumulative production from the interval by the stabilized production rate near end of the flow period may not be completely reliable when short flow tests are interspersed with rather lengthy shut-in periods. Use of the cumulative production during a single test by the average production rate often results in rather small values for t, and the buildup curves frequently do not contain straight line sections. The two later techniques have been plotted and included in Appendix A for comparison purposes for Fawn Creek Government No. 1 for Buildup #3, 5747-5792 foot interval and Buildup #2, 5600-5630 foot interval. Based on experience, the plot using large values of t; i.e., cumulative production from interval divided by production rate, possibly is more useful for determination of permeability although the extrapolation to determine average reservoir pressure may be on low side when flow is entirely transient.

The final buildup pressures do not fit a pressure gradient versus depth relationship, as shown in Fig. 4. It is possible that some zones may be partially depleted; but other explanations such as a very slow recovery of the pressure during buildup, which is not properly reflected by the plots, offers an alternate explanation. An accurate curve showing bottom hole pressure versus depth for the general area might be useful for determination of hydrostatic or initial reservoir pressure before depletion of the zone.

The permeability indicated for both intervals in Fawn Creek Government No. 1 tends to decline with successive tests in the interval. A changing permeability near the well bore resulting from accumulation of condensate

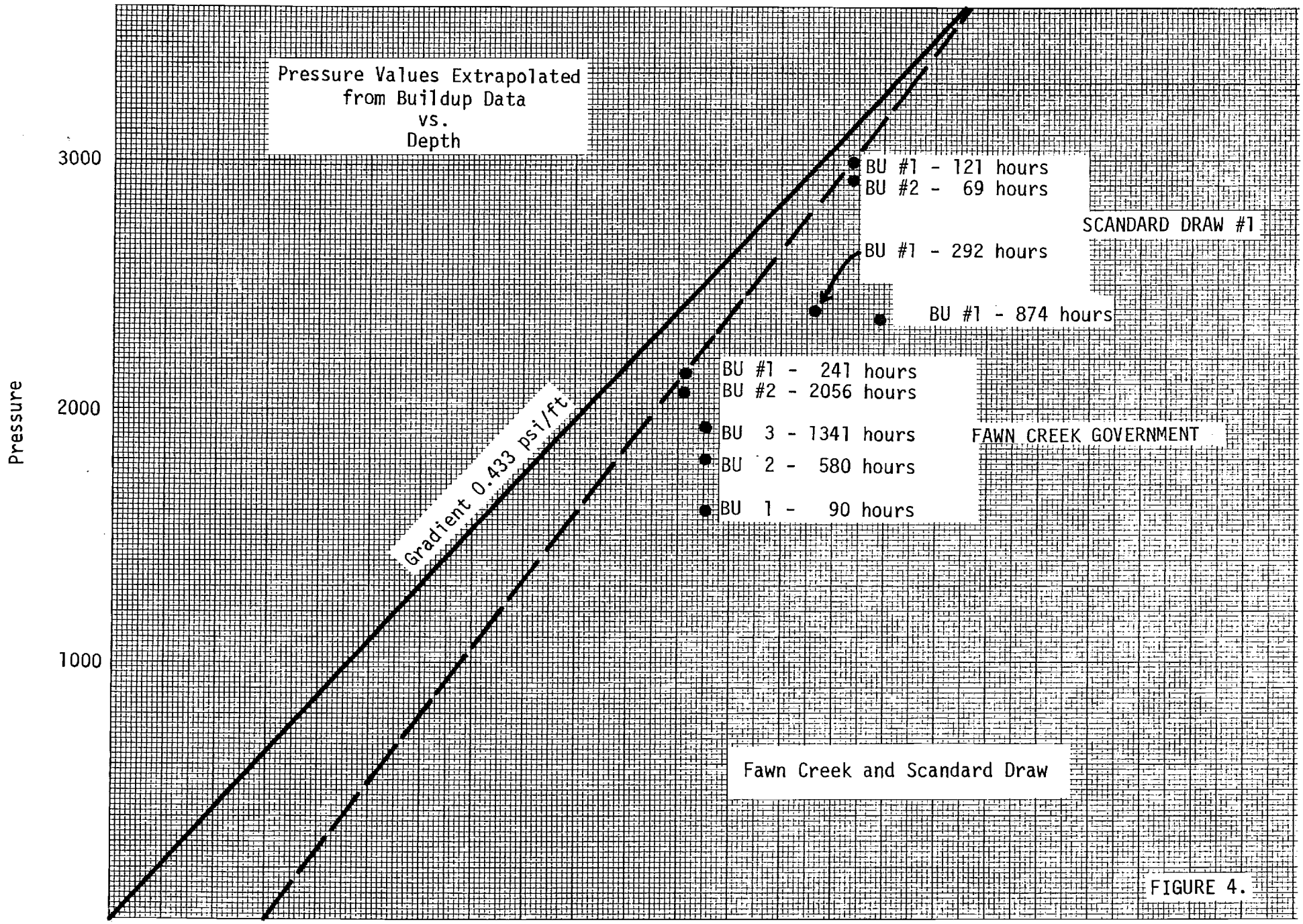

Pressure Values Extrapolated
from Buildup Data
vs.
Depth
BU #1 - 121 hours
BU #2 - 69 hours
SCANDARD DRAW #1
BU #1 - 292 hours
BU #1 - 874 hours
BU #1 - 241 hours
BU #2 - 2056 hours
BU 3 - 1341 hours
FAWN CREEK GOVERNMENT
BU 2 - 580 hours
BU 1 - 90 hours
Gradient 0.433 psi/ft.
Fawn Creek and Scandard Draw
Pressure
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
h (feet) x 10⁻³

FIGURE 4.

or water, solid movement, etc., unmeasured liquid production, the selection of data, and analysis technique and other explanations all may be involved in an understanding of these trends.

The basic equations and data used in analyzing a plot of m(p) versus $\log \frac{t + \Delta t}{\Delta t}$ must be selected with care. The data when first shut in is severely influenced by afterflow or fill-up of the well bore or tubing when packers are used. Also, the wells were fractured so that the flow configuration first is linear or linear-radial and then elliptical before becoming radial, whereas the plot assumes radial flow. At later times the fracture might be considered as an enlarged effective well radius, r_w', so that the p_D rather than log functions may be involved during early life.

Based on a plot of p_D versus logarithm functions, t_{D_w} might have a value of about 10 before the log plot should be used with confidence. Thus, if the reservoir pressure is 2000 psia, μ = 0.0167 cp, c = 0.00025 psi^{-1}, ϕ = 0.11 and k = 0.04 md, the relation between dimensionless time, t_D, and time in hours, t, becomes

$$t_D = 0.000264\ kt/\phi\mu cr^2$$

$$= 0.000264 \times 0.04\ t/0.11 \times 0.0167 \times 0.00025$$

$$t_D = 22.99t/r^2$$

or

$$t = 0.043\ t_D\ r_w'^2$$

With an effective well radius of a normal fractured well assumed at 20 feet

$$t = 0.043 \times 10 \times 20 \times 20$$

$$= 172 \text{ hours}$$

When the well diameter after blast is 250 feet, the value might approach

$$t = 0.043 \times 10 \times 250 \times 250$$

$$= 26{,}875 \text{ hours} = 1120 \text{ days} = 3.1 \text{ years}$$

Well bore effects may be expected to become negligible when

$$t = 114{,}800\ \mu V_w c/kh$$

where

V_w is well bore volume or 0.0086 ft^2 x 5600 ft well depth = 48 cu ft

$$t = 114{,}800 \times 0.0167 \times 48 \times 0.00051/0.04 \times 30 \text{ ft pay thickness}$$

$$= 39 \text{ hours}$$

The change in slope of the curves of m(p) versus $\sqrt{\Delta t}$ for drawdown and $\sqrt{t + \Delta t} - \sqrt{\Delta t}$ for buildup suggest similar time periods.

The effective formation thickness, h, was obtained from logs. However, since complete logs for Fawn Creek Government No. 1 and Scandard Draw No. 1 were unavailable, values used in prior studies were accepted to convert kh to k.

The well radius was computed using the equation

$$r_{inv} = \sqrt{0.00105\ kt/\phi\mu c}$$

The buildup and drawdown tests apparently analyzed a radius of 50 to 325 feet around the well.

Summarizing, the buildup and drawdown tests of the two wells suggest permeabilities varying from zero to 0.09 md. The available data do not permit statistical application to the enlarged gross interval subject to atomic blast, but values of 0.01 to 0.04 md may be used in forecast computations to define the probable limits when an effective net overall section of 370 feet is assumed.

LOG ANALYSIS

A statement on the log analysis of RB-E-01 by Dr. G. R. Pickett and Mr. John L. Bedwell is included on the following page. Table IV gives the results of this analysis. Setting a 30% cut-off for S_g and a 5% cut-off for porosity, the average porosity for the Fort Union and the Mesaverde are 9.58% and 8.82%, respectively. The gas saturations are calculated to be 58% for the Fort Union and 56% for the Mesaverde, using the high limits in Table IV. However, Dr. Pickett recommends that a combination of high values for the Fort Union and low values for the Mesaverde be used, due to variation in water resistivity. This would result in an average gas saturation of 57%.

The net pay for the Fort Union and the Mesaverde are 310 feet and 111 feet, respectively, or 421 feet total. This is arrived at using the same criteria as were used for gas saturation.

Well # RB E 01

Rio Blanco Co., Colorado

The object of this study was to derive estimates of porosity, hydrocarbon saturation, and "net pay" thicknesses between 5260 feet and 7200 feet in the # RB E 01 well, Rio Blanco County, Colorado.

Available core analysis porosities were used to calibrate the sonic log and the latter was then used to estimate porosities. Combined consideration of the induction resistivity, SP, gamma-ray, and sonic logs in the RB E 01 well and of the lifetime log and productivity test recoveries in the Fawn Creek Govt. #1 well leads to the conclusion that the water resistivity (R_w) is approximately 0.05 ohm-m from 5260 feet to 6160 feet and is between 0.08 ohm-m and 0.12 ohm-m from 6160 feet to 7200 feet.

Using estimates of porosities derived as explained above, m=2, n=2, induction log resistivities and limits for R_w of 0.05 ohm-m and 0.12 ohm-m, a range in gas saturation (S_g) was calculated for all potential "net pay" thicknesses. "Net pay" thickness here is taken to mean intervals exhibiting gas saturation greater than zero and exhibiting log deflections from "shale base" on the SP and gamma-ray logs. The results are summarized in the attached table which shows depth interval, h ("net pay" thickness), porosity (ϕ), gas saturation (S_g in %) ---lower limit and upper limit, and $S_g\phi h$ (ft) --- lower limit and upper limit. In addition, the $S_g\phi h$ (ft) "best estimate" is tabulated. The latter corresponds to our opinion that R_w is 0.05 ohm-m from 5260 feet to 6160 feet and is in the range 0.08 ohm-m to 0.12 ohm-m between 6160 feet and 7200 feet.

J.L. Bedwell John L. Bedwell

G.R. Pickett G R Pickett

March 11, 1972

TABLE IV

FORMULATION-EVALUATION ANALYSIS

WELL: No. RB-E-01 COUNTY: Rio Blanco, Colorado

Fort Union

Depth Interval	h	ϕ	High Limit S_g	Low Limit S_g	High Limit $S_g\phi h$	Low Limit $S_g\phi h$	Best Estimate $S_g\phi h$
5260-66	6	8.5	46	19	0.235	0.100	0.235
5266-68	22	13.0	71	56	2.030	1.602	2.030
5606-14	8	2.1	41	09	0.068	0.015	0.068
5614-30	16	10.5	66	48	1.109	0.806	1.109
5630-38	8	3.2	58	37	0.148	0.095	0.148
5684-5710	26	11.0	60	55	1.716	1.573	1.716
5710-16	6	7.5	56	34	0.252	0.153	0.252
5716-28	12	10.0	62	42	0.744	0.504	0.744
5728-50	24	11.0	56	33	1.478	0.871	1.478
5750-60	10	8.5	55	33	0.468	0.281	0.468
5760-80	20	10.5	59	38	1.239	0.798	1.239
5780-92	12	8.0	53	29	0.509	0.278	0.509
5810-15	5	9.0	43	16	0.194	0.072	0.194
5815-42	27	9.5	67	50	1.719	1.283	1.719
5842-50	8	2.9	59	38	0.137	0.088	0.137
5850-62	12	10.5	67	50	0.844	0.630	0.844
5862-74	12	9.0	65	45	0.702	0.486	0.702
5874-84	10	3.2	54	31	0.173	0.099	0.173
5910-18	8	8.5	34	-	0.231	-	0.231
5918-30	12	1.8	20	-	0.043	-	0.043
5948-54	6	2.5	34	-	0.051	-	0.051
5954-60	6	8.0	43	14	0.206	0.067	0.206
5960-66	6	1.1	11	-	0.007	-	0.007
5966-72	6	8.0	49	24	0.235	0.115	0.235
5972-78	6	1.8	29	-	0.031	-	0.031
5998-6012	14	3.2	51	27	0.228	0.121	0.228
6014-24	10	1.4	34	-	0.047	-	0.047
6024-44	20	7.5	54	32	0.810	0.480	0.810
6044-54	10	1.0	41	41	0.041	0.041	0.041
6054-68	14	8.0	53	30	0.594	0.336	0.594
6098-6104	6	1.1	10	-	0.007	-	0.007
6104-24	20	8.0	47	20	0.752	0.320	0.752
6124-34	10	2.9	56	34	0.162	0.099	0.162
6134-46	12	8.0	50	25	0.480	0.240	0.480
6146-52	6	11.5	65	48	0.449	0.331	0.449
6152-60	8	9.0	56	33	0.403	0.238	0.403

TABLE IV

FORMULATION-EVALUATION ANALYSIS (Cont'd)

Mesaverde

Depth Interval	h	ϕ	High Limit S_g	Low Limit S_g	High Limit $S_g\phi h$	Low Limit $S_g\phi h$	Best Estimate $S_g\phi h$	
							Low	High
6180-6220	40	10.5	38	18	1.600	0.756	0.756	1.362
6226-36	10	11.0	49	23	0.539	0.253	0.253	0.401
6252-58	6	2.1	34	-	0.043	-	-	0.023
6272-88	14	11.5	48	22	0.773	0.354	0.354	0.577
6312-16	4	3.2	35	-	0.045	-	-	0.024
6322-30	8	1.4	31	-	0.035	-	-	0.021
6330-34	4	7.5	46	20	0.138	0.060	0.060	0.103
6334-40	6	2.9	39	07	0.068	0.012	0.012	0.041
6340-46	6	2.1	51	26	0.064	0.033	0.033	0.050
6352-56	4	2.9	48	21	0.052	0.024	0.024	0.040
6356-80	24	8.5	53	30	1.081	0.612	0.612	0.862
6380-86	6	7.5	52	28	0.234	0.126	0.126	0.185
6424-32	8	12.5	62	43	0.620	0.430	0.430	0.535
6432-42	10	10.0	54	36	0.540	0.360	0.360	0.473
6450-55	5	1.4	36	-	0.025	-	-	0.014
6455-60	5	8.5	56	33	0.238	0.140	0.140	0.194
6578-6604	26	8.5	65	47	1.436	1.039	1.039	1.245
6686-96	10	2.1	37	-	0.078	-	-	0.039
6696-6710	14	8.5	59	40	0.702	0.476	0.476	0.604
6710-24	14	1.8	40	09	0.101	0.023	0.023	0.064
6758-76	18	8.0	55	32	0.792	0.461	0.461	0.642
6776-82	6	3.2	53	30	0.102	0.058	0.058	0.081
6834-48	14	7.5	50	25	0.525	0.263	0.263	0.398
6848-56	6	8.0	57	36	0.274	0.173	0.173	0.226
6872-82	10	9.5	51	27	0.485	0.257	0.257	0.378
6882-90	8	13.0	31	-	0.322	-	-	0.191
6900-08	8	2.1	28	-	0.047	-	-	0.031
6908-20	12	8.5	46	19	0.469	0.194	0.194	0.340
6920-24	4	2.1	32	-	0.027	-	-	0.015
7012-28	16	7.5	47	20	0.564	0.240	0.240	0.408
7100-06	6	2.5	37	06	0.056	0.009	0.009	0.034
7106-14	8	8.5	50	25	0.340	0.250	0.250	0.260
7184-92	8	8.5	46	19	0.313	0.129	0.129	0.227
7192-96	4	1.4	17	-	0.010	-	-	0.010
7196-7208	12	8.5	46	19	0.460	0.194	0.194	0.340

FORECAST OF FUTURE PERFORMANCE

The results of the first six computer runs shown on Figs. 5 - 10 are based on:

		Permeability	Pressure Function	Drainage Area
Fig. 5	Run I	0.0100	m(p)	640 acres
Fig. 6	Run II	0.0400	m(p)	640 acres
Fig. 7	Run III	0.1000	m(p)	640 acres
Fig. 8	Run IV	0.0400	m´(p)	640 acres
Fig. 9	Run V	0.0400	m(p)	320 acres
Fig. 10	Run VI	0.0400	m´(p)	320 acres
Fig. 11	Run VII	0.0212	m(p)	640 acres
Fig. 12	Run VIII	(0.0250 (0.0110	m(p)	640 acres

The following additional assumptions are common to runs I - VI:

Thickness of gross stimulated interval	1350 ft
Depth to top of stimulated interval	5550 ft
Depth to base of stimulated interval	6900 ft
Net effective pay in gross stimulated interval	370 ft
Porosity-average	11%
Water saturation-average	55%
Mean pressure	2600 psia
Mean temperature	205°F
Initial gas deviation factor	0.92
Gas originally in place in stimulated section	76 BSCF/section of 640 acres
Base pressure	14.7 psia
Base temperature	60°F
Limiting sand face pressure	500 psia
Limiting production rate	8000 MCF
Chimney radius	80 ft

Radius of fractured interval	250 ft
Porosity of fractured interval	20%
Chimney void volume	5×10^6 cu ft

Volume of dry gas filling the void at 370°F and 2700 psia would be 5.4×10^8 SCF.

Permeability in fractured zone

r = 80 ft-chimney face	1000+ md
r = 124 ft	120 md
r = 165 ft	30 md
r = 205 ft	2.0 md
r = 250 ft	0.3 md
r > 250 ft	as specified above, 0.01 or 0.04 md or 0.1

Run VII was made using the above data with the exceptions of thickness = 421 ft, porosity = 9.4%, water saturation = 43% and permeability of unfractured reservoir = 0.0212 md. These represent the average values calculated in this report. Run VIII separated the Fort Union and the Mesaverde into two layers using average values for each zone. These are thickness = 310 ft, porosity = 9.6%, water saturation = 42% and permeability = 0.025 md for the Fort Union and thickness = 111 ft, porosity = 8.8%, water saturation = 44% and permeability = 0.011 md for the Mesaverde. The results are shown on Figs. 11 - 12.

Table V shows the values of normalized permeabilities and viscosities used in the runs which included pressure dependent permeabilities.

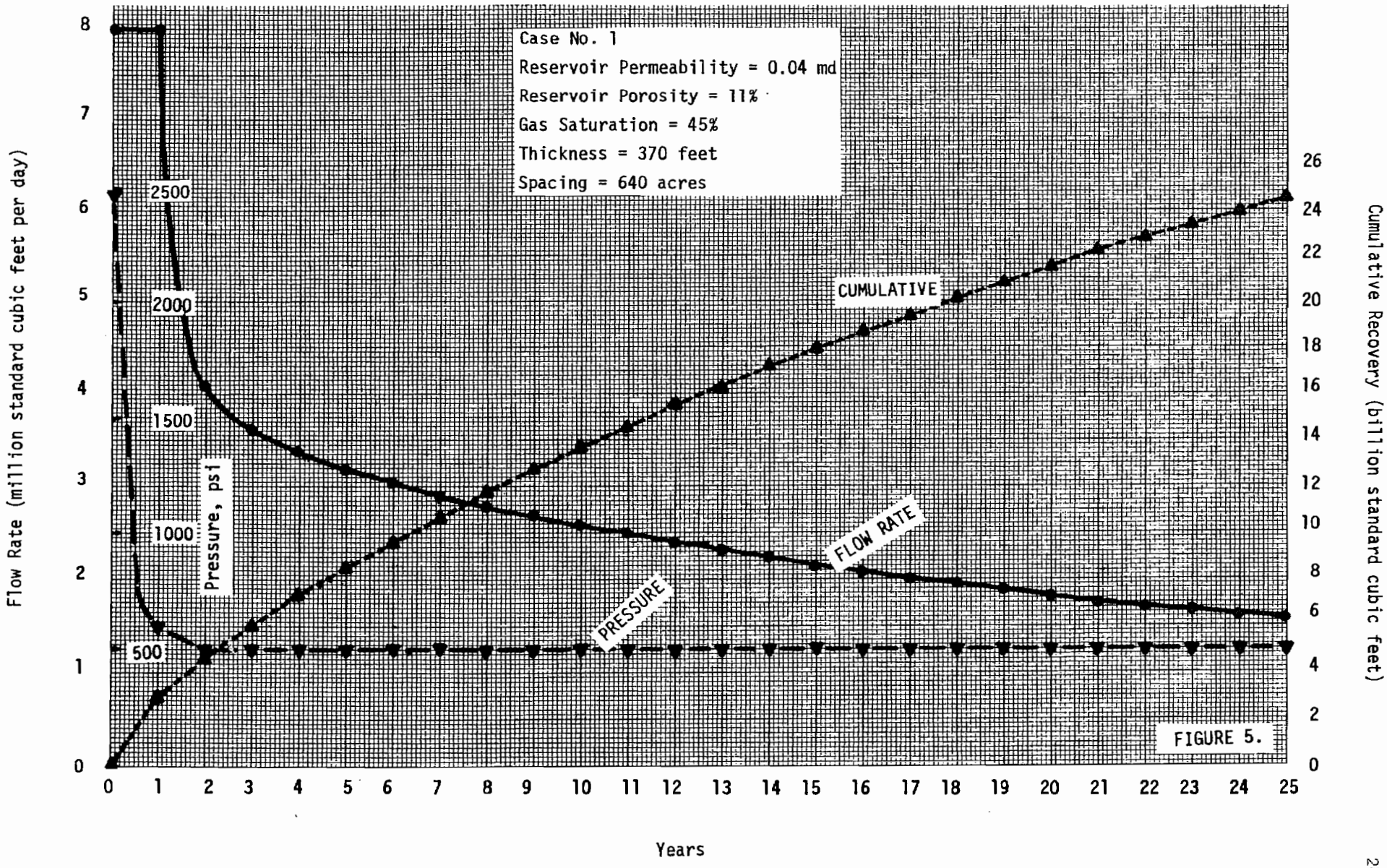

Case No. 1
Reservoir Permeability = 0.04 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 640 acres
2500
2000
1500
1000
500
Pressure, psi
CUMULATIVE
FLOW RATE
PRESSURE
Flow Rate (million standard cubic feet per day)
Cumulative Recovery (billion standard cubic feet)
Years
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14 16 18 20 22 24 26
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

FIGURE 5.

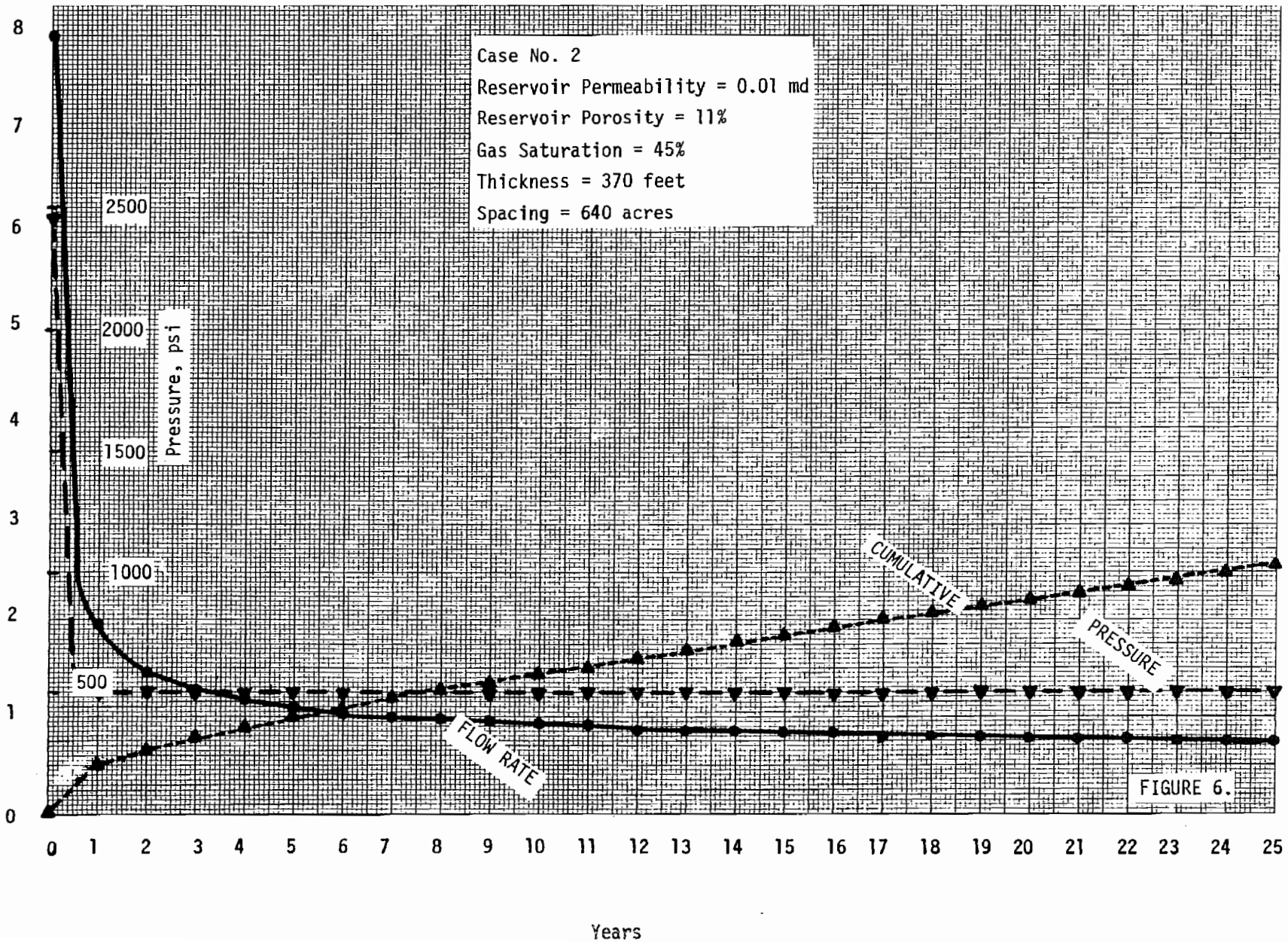

Case No. 2
Reservoir Permeability = 0.01 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 640 acres
2500
2000
1500
1000
500
Pressure, psi
CUMULATIVE
PRESSURE
FLOW RATE
Flow Rate (million standard cubic feet per day)
Cumulative Recovery (billion standard cubic feet)
Years
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14 16 18 20 22 24 26
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

FIGURE 6.

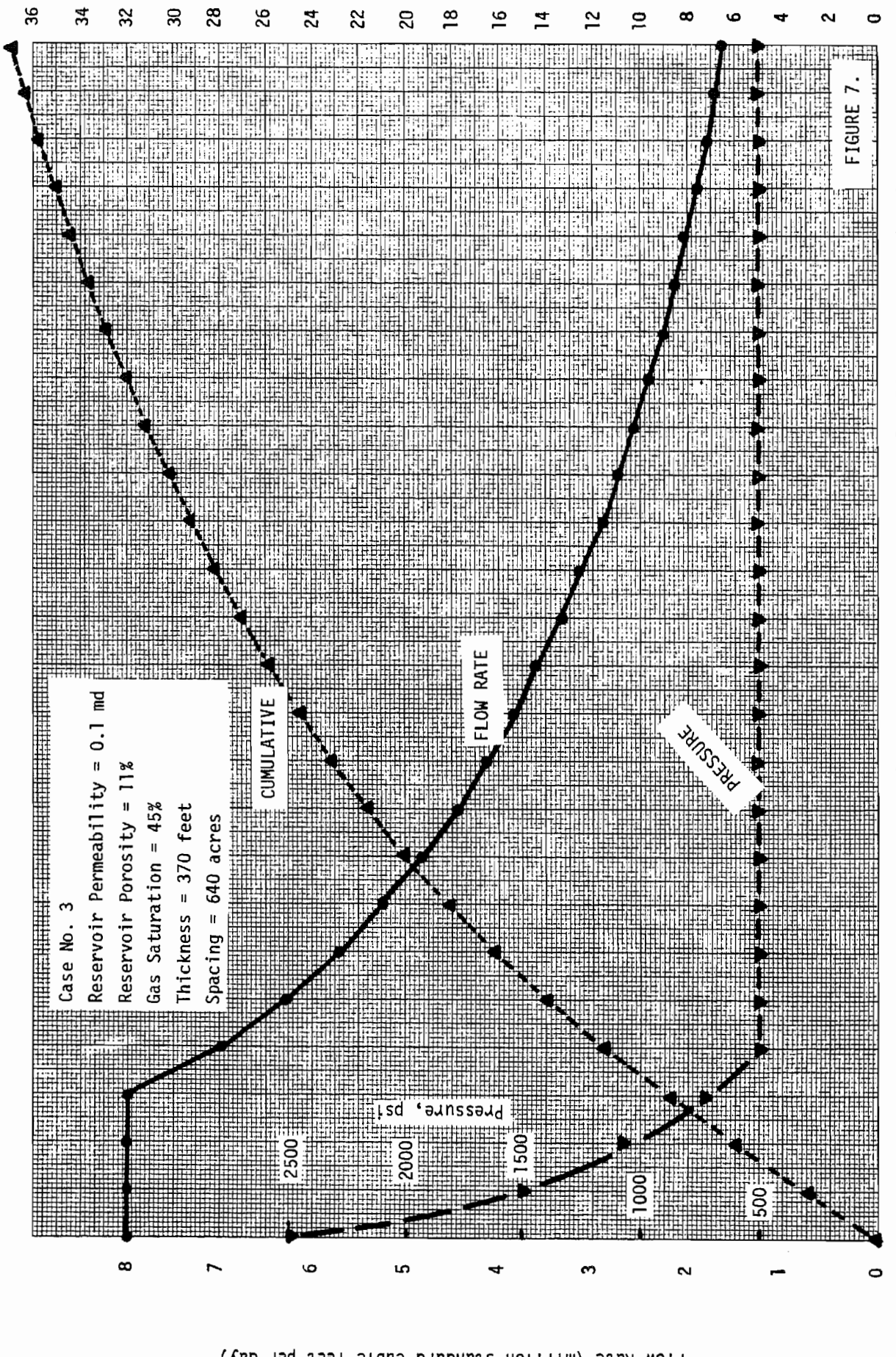

Case No. 3
Reservoir Permeability = 0.1 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 640 acres
CUMULATIVE
FLOW RATE
PRESSURE
Pressure, psi
2500
2000
1500
1000
500
Cumulative Recovery (billion standard cubic feet)
Flow Rate (million standard cubic feet per day)
Years

FIGURE 7.

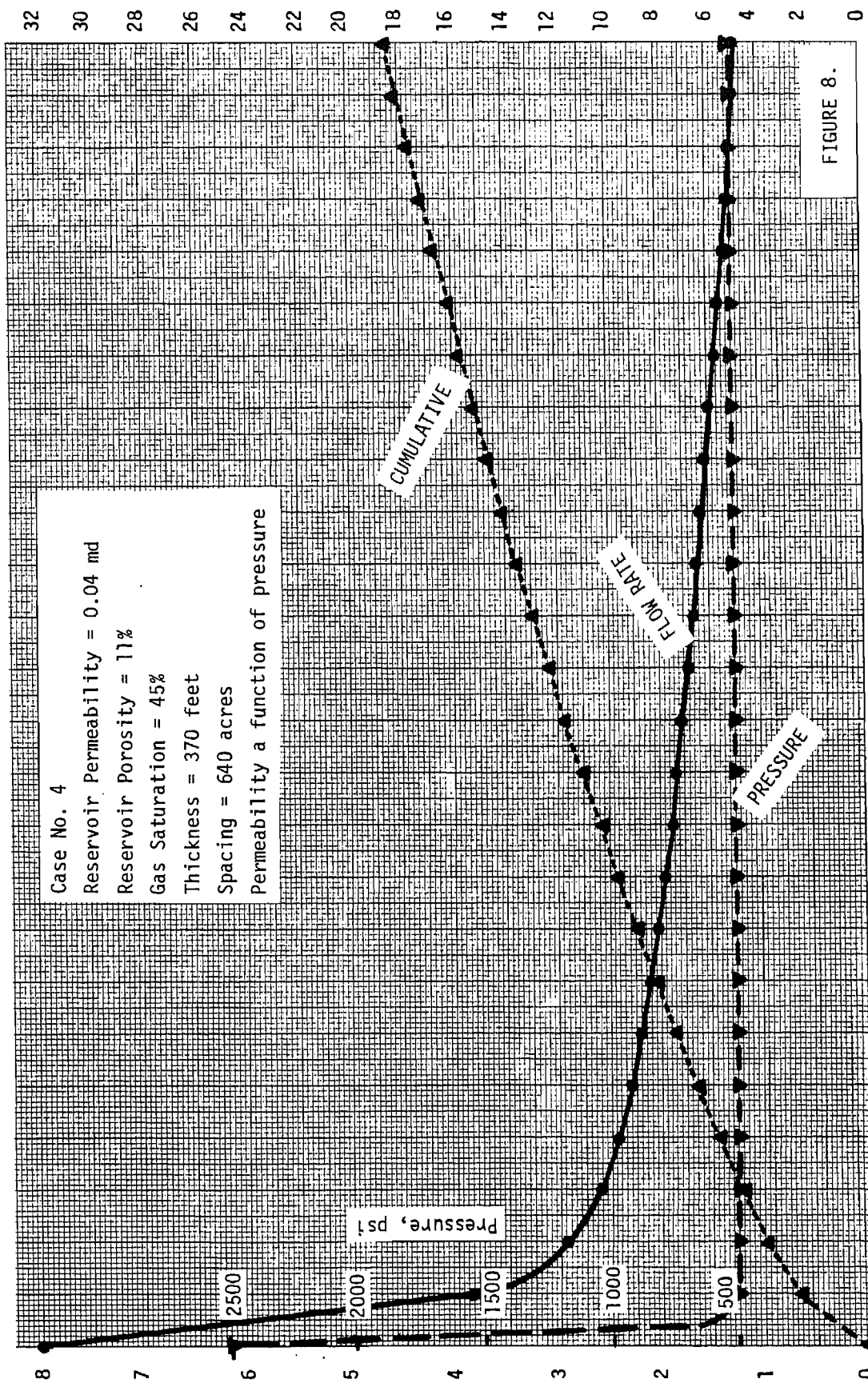

Case No. 4
Reservoir Permeability = 0.04 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 640 acres
Permeability a function of pressure
CUMULATIVE
FLOW RATE
PRESSURE
Pressure, psi
2500
2000
1500
1000
500
Flow Rate (million standard cubic feet per day)
Cumulative Recovery (billion standard cubic feet)
Years

FIGURE 8.

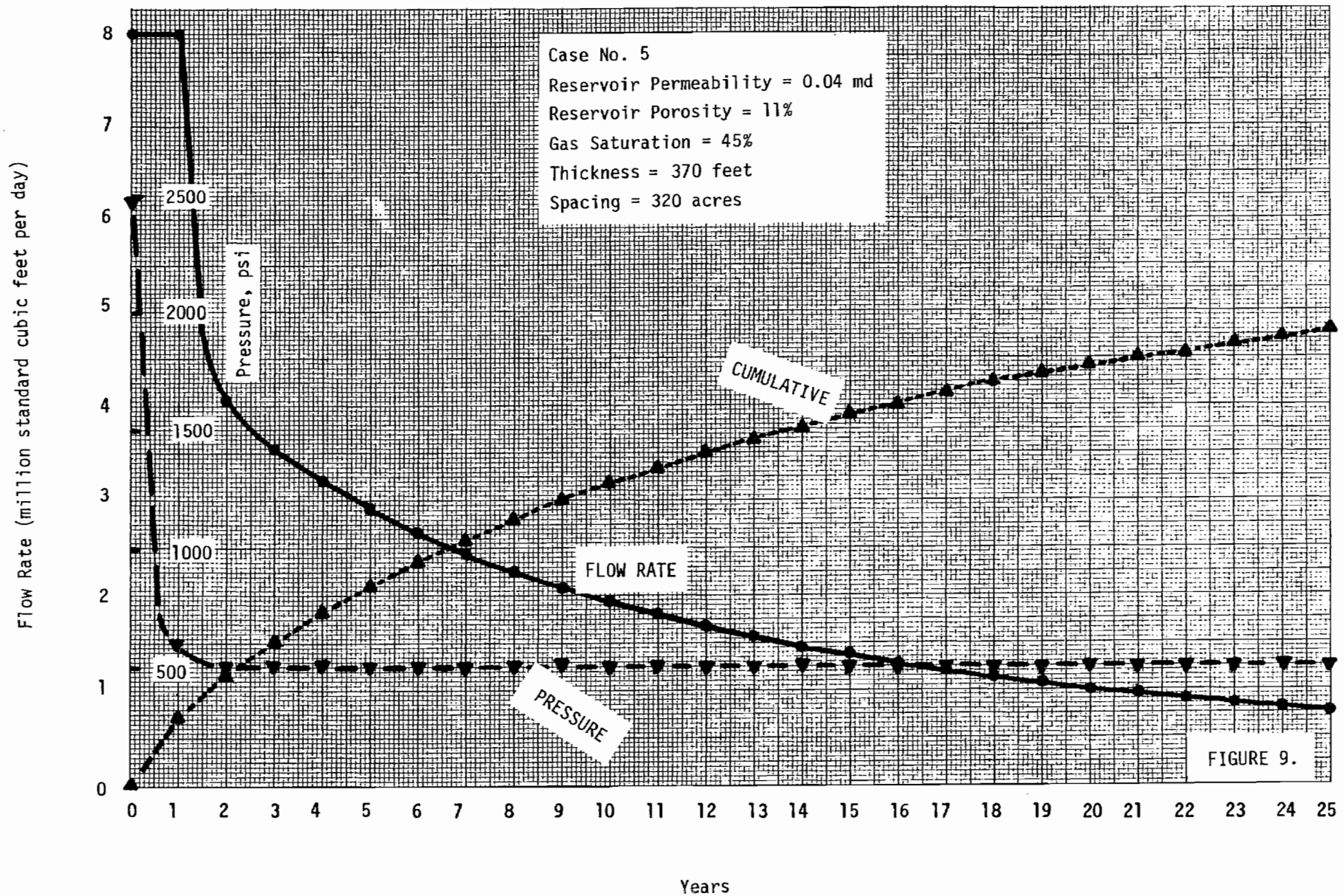

Case No. 5
Reservoir Permeability = 0.04 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 320 acres
2500
2000
1500
1000
500
Pressure, psi
CUMULATIVE
FLOW RATE
PRESSURE
Flow Rate (million standard cubic feet per day)
Cumulative Recovery (billion standard cubic feet)
Years
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

FIGURE 9.

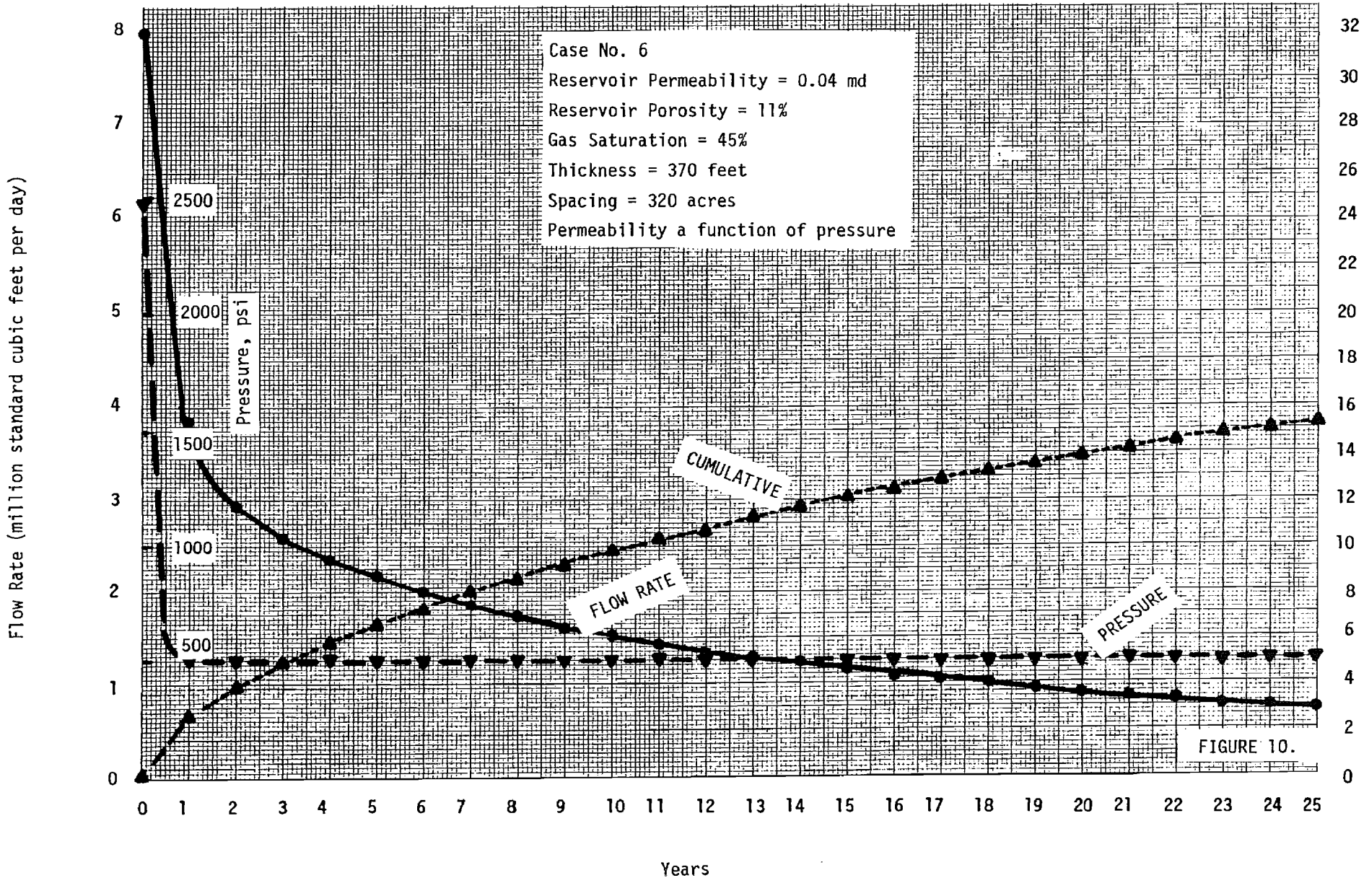

Case No. 6
Reservoir Permeability = 0.04 md
Reservoir Porosity = 11%
Gas Saturation = 45%
Thickness = 370 feet
Spacing = 320 acres
Permeability a function of pressure
Pressure, psi
2500
2000
1500
1000
500
CUMULATIVE
FLOW RATE
PRESSURE
Flow Rate (million standard cubic feet per day)
Cumulative Recovery 9billion standard cubic feet)
Years
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

FIGURE 10.

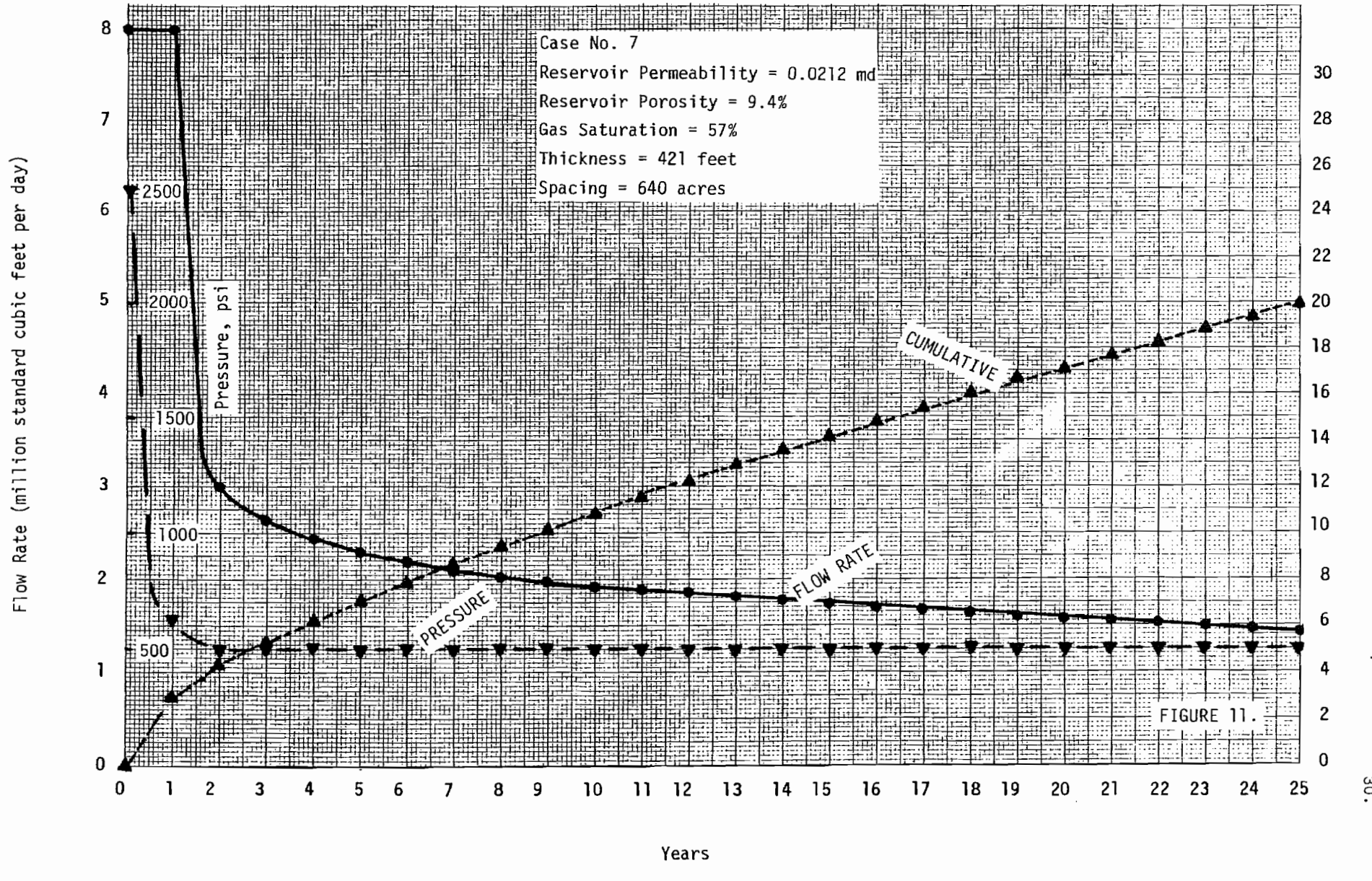

Case No. 7
Reservoir Permeability = 0.0212 md
Reservoir Porosity = 9.4%
Gas Saturation = 57%
Thickness = 421 feet
Spacing = 640 acres
Pressure, psi
2500
2000
1500
1000
500
CUMULATIVE
FLOW RATE
PRESSURE
Flow Rate (million standard cubic feet per day)
Cumulative Recovery (billion standard cubic feet)
Years
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30

FIGURE 11.

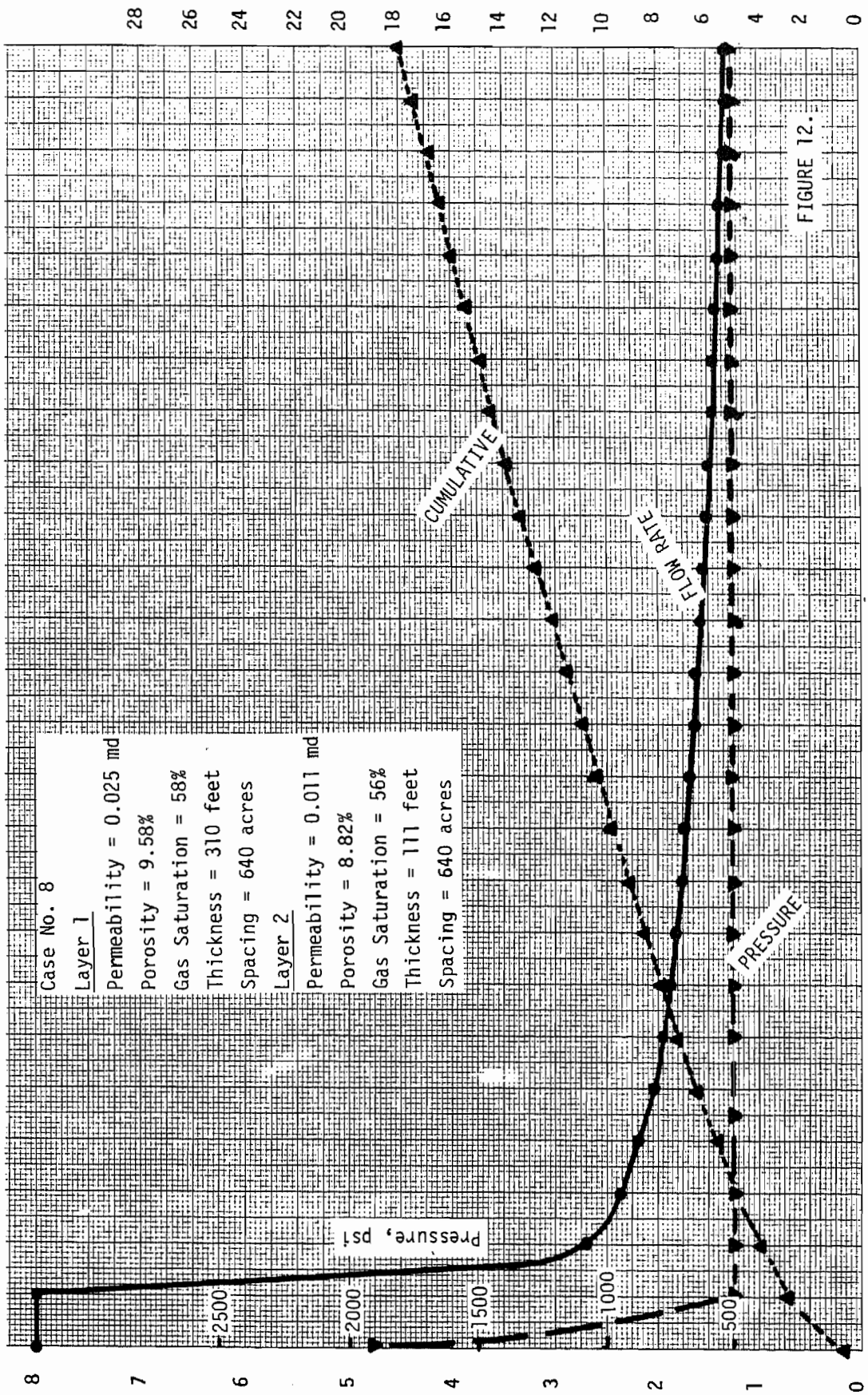

Cumulative Recovery (billion standard cubic feet)
Flow Rate (million standard cubic feet per day)
Years
Pressure, psi
CUMULATIVE
FLOW RATE
PRESSURE
Case No. 8
Layer 1
Permeability = 0.025 md
Porosity = 9.58%
Gas Saturation = 58%
Thickness = 310 feet
Spacing = 640 acres
Layer 2
Permeability = 0.011 md
Porosity = 8.82%
Gas Saturation = 56%
Thickness = 111 feet
Spacing = 640 acres

FIGURE 12.

TABLE V

NORMALIZED PERMEABILITIES AND VISCOSITIES

p	$p_{confining}$	k_r	$k_p = \frac{k_r}{k_r \text{ @ } 2600}$	μ	$\mu_{k_p} = \frac{\mu}{k_p}$
2600	3003	.0775	1.0	.0183	.0183
2500	3103	.0690	.952	.0180	.0189
2400	3203	.0665	.918	.0178	.0194
2300	3303	.0635	.876	.0175	.0200
2200	3403	.0605	.834	.0173	.0207
2100	3503	.0578	.798	.0171	.0214
2000	3603	.0550	.758	.0169	.0223
1900	3703	.0525	.724	.0166	.0229
1800	3803	.0502	.692	.0164	.0237
1700	3903	.0480	.662	.0162	.0245
1600	4003	.0460	.634	.0160	.0252
1500	4103	.0441	.608	.0158	.0260
1400	4203	.0422	.583	.0156	.0268
1300	4303	.0405	.559	.0154	.0275
1200	4403	.0389	.537	.0152	.0283
1100	4503	.0374	.516	.0151	.0293
1000	4603	.0359	.495	.0149	.0301
900	4703	.0343	.473	.0148	.0313
800	4803	.0332	.458	.0146	.0319
700	4903	.0317	.437	.0145	.0331
600	5003	.0305	.422	.0144	.0341
500	5103	.0293	.405	.0142	.0351
400	5203	.0282	.389	.0141	.0362
300	5303	.0269	.371	.0140	.0377
200	5403	.0260	.359	.0140	.0390
100	5503	.0249	.343	.0139	.0405

APPENDIX A

Page

BASIC EQUATIONS

I. Units of measurement 34

II. Conversion to "real gas conditions" 35

III. Equations to describe flow of fluids under transient or unsteady state conditions 36

IV. Equations to describe pressure buildup tests under transient or unsteady state conditions 38

V. Other equations in practical units 41

APPENDIX A

BASIC EQUATIONS

I. Units of measurement

Symbol	cgs Units	Practical Units	
		Liquids	Gas
p = pressure	atmosphere	psia	psia
c = compressibility	vol/vol/atm	vol/vol/psi	vol/vol/psi
ϕ = porosity	fraction	fraction	fraction
h = pay thickness	cm	ft	ft
k = permeability	darcy	md	md
μ = viscosity	cp	cp	cp
q = flow rate	cc/sec	B/D	MCF/D
Q = cumulative production	cc	Bbl	MCF
r = radius	cm	ft	ft
ℓ = length	cm	ft	ft
w = width	cm	ft	ft
t = time	sec	hour	hour
A = ℓ x w	cm^2	$(ft)^2$	$(ft)^2$

B = conversion of surface volumes to subsurface volumes, Fraction

II. Conversion to "real gas conditions"

A. Without variation of k with pressure

$$m(p) = 2 \int \frac{p}{\mu z} dp$$

p = pressure, psia

μ = gas viscosity, cp

z = gas deviation factor

B. With variation of k with pressure

$$m'(p) = 2 \int \frac{pk_{r(p)}}{\mu z} dp$$

p = pressure, psia

μ = gas viscosity, cp

z = gas deviation factor

$$k_{r(p)} = \frac{\text{In-situ permeability*}}{\text{Laboratory permeability}}$$

*Laboratory measured permeability for rocks having low actual permeability may require a large correction to be representative of in-situ permeability.

III. Equations to describe flow of fluids under transient or unsteady state conditions

NOTE: These equations are not applicable at early times when r_w is large; use p_D curves when r_w is large.

cgs Units

A. Linear flow when no skin is present

$$p_i - p_w = (2q\mu/kA)\sqrt{kt/\pi\phi\mu c}$$

where

A = fracture length x pay thickness

B. Radial flow

$$p_i - p_w = (q\mu/4\pi kh)\left[\ell n(kt/\phi\mu c r_w^2) + 0.809 + 2s + 2Dq_{sc}\right]$$

where

s is the skin effect

Dq_{sc} represents possible turbulence

$c = S_o c_o + S_g c_g + S_w c_w + c_f$

Practical Units

C. Linear flow

Liquids:

$$p_i - p_w = (16.26q_{sc}B\mu/kA)\sqrt{kt/\phi\mu c}$$

Gases:

$$m(p_i) - m(p_w) = (163.7q_{sc}T/kA)\sqrt{kt/\phi\mu c}$$

Slope of m(p) versus $\sqrt{t}$ curve represents

$m = (163.7q_{sc}T/kA)\sqrt{k/\phi\mu c} = 163.7q_{sc}T/A\sqrt{1/k\phi\mu c}$

D. Radial flow at constant rate

Liquids:

$$p_i - p_w = (162.6)q_{sc}B\mu/kh)\left[\log(kt/\phi\mu cr_w^2) - 3.23 + 0.87s + 0.87Dq_{sc}\right]$$

Slope of the pressure versus log t curve represents

$$m = 162.6lqB\mu/kh$$

$$kh = 162.6lqB\mu/m$$

Gases:

$$m(p_i) - m(p_w) = (1637\ q_{sc}T/kh)\left[\log(kt/\phi\mu cr_w^2) - 3.23 + 0.87s + 0.87\ Dq_{sc}\right]$$

Slope of m(p) versus log t curve represents

$$m = 1637\ q_{sc}T/kh$$

or

$$kh = 1637\ q_{sc}T/m$$

The skin including turbulence may be expressed as

$$s' = 1.15\left[\frac{p_i - p_{1\ hr}}{m} - \log(k/\phi\mu cr_w^2) + 3.23\right]$$

E. Radial flow at constant sand face pressure

Liquids:

$$\frac{1}{q_{sc}} = \frac{162.6B\mu}{(p_i - p_w)kh}\left[\log(kt/\phi\mu cr_w^2) - 3.23 + 0.87s + 0.87Dq\right]$$

Slope of $\frac{1}{q_{sc}}$ versus log t curve represents

$$m = \frac{162.6B\mu}{(p_i - p_w)kh}$$

Gases:

$$\frac{1}{q_{sc}} = 1637 \left(\frac{1}{m(p_i) - m(p_w)}\right)(T/kh)\left[\log(kt/\phi\mu cr_w^2) - 3.23 + 0.87s + 0.87Dq_{sc}\right]$$

Slope of $\frac{1}{q_{sc}}$ versus log t curve represents

$$m = \frac{1637T}{kh\left[m(p_i) - m(p_w)\right]}$$

$$kh = \frac{1637T}{m\left[m(p_i) - m(p_w)\right]}$$

The skin including turbulence may be expressed as

$$s' = 1.151\left[1/q_{sc} @ 1\ hr/m - \log(k/\phi\mu cr_w^2) + 3.23\right]$$

IV. Equations to describe pressure buildup tests transient or unsteady state conditions

cgs Units

A. Linear flow when no skin is present

$$p_i - p_w = (2q\mu/kA)(\sqrt{\pi\phi\mu c/k})(\sqrt{t + \Delta t} - \sqrt{\Delta t})$$

B. Radial flow

$$p_i - p_w = (q\mu/4\pi kh)\ \ell n\left[(t + \Delta t)/\Delta t\right]$$

Practical Units

C. Linear flow

Liquids:

$$p_i - p_w = (16.26qB\mu/kA)(\sqrt{k/\phi\mu c})(\sqrt{t + \Delta t} - \sqrt{\Delta t})$$

and the slope of the pressure versus $(\sqrt{t + \Delta t} - \sqrt{\Delta t})$ curve represents

$$m = (16.26qB\mu/kA)(\sqrt{k/\phi\mu c})$$

Gases:

$$m(p_i) - m(p_w) = (163.72q_{sc}T/kA)(\sqrt{k/\phi\mu c})(\sqrt{t + \Delta t} - \sqrt{\Delta t})$$

and the slope of the m(p) versus $(\sqrt{t + \Delta t} - \sqrt{\Delta t})$ curve is

$$m = (163.72q_{sc}T/kA)(\sqrt{k/\phi\mu c})$$

D. Radial flow

Liquids:

$$p_i - p_w = (162.6q\mu B/kh) \log\left[(t + \Delta t)/\Delta t\right]$$

and the slope of the pressure versus $\log\left[(t + \Delta t)/\Delta t\right]$ curve is

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

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

The skin effect including turbulence when flow rate is constant may be computed as

$$s' = 1.151\left[\frac{P_{1\ hr} - P_w}{m} - \log\left(\frac{k}{\phi\mu c r_w^2}\right) + 3.23\right]$$

also

$$s = \left(\frac{k}{k_1} - 1\right) \ln \frac{r_s}{r_w}$$

where

r_s = radius of area of skin

If r_w' is defined as an effective well radius and r_e is radius being drained

$$\ln \frac{r_e}{r_w'} = \ln \frac{r_e}{r_w} + s$$

$r_w' = r_{we}^{-s}$ = ¼ length of entire vertical fracture

$$\Delta p_{skin} = 0.87sm$$

E. Gases

$$m(p_i) - m(p_w) = 1637\ qT/kh \log\left[(t + \Delta t)/\Delta t\right]$$

and the slope of the m(p) versus $\log\left[(t + \Delta t)/\Delta t\right]$ plot is

$$m = 1637\ qT/kh$$

$$kh = \frac{1637\ qT}{m}$$

The skin including turbulence when flow rate is constant is

$$s' = 1.151\left[\frac{P_{1\ hr} - P_w}{m} - \log\left(\frac{k}{\phi\mu c r_w^2}\right) + 3.23\right]$$

The skin when well face pressure is constant is

$$s' = 1.151\left[1/q_{sc_{(1\ hr)}}/m - \log\left(\frac{k}{\phi\mu c r_w^2}\right) + 3.23\right]$$

V. Other equations in practical units

A. General time equation

$$t_D = 0.000264\ kt/\phi\mu c r^2$$

B. Radius of investigation of the test

$$r_{inv} = \sqrt{0.00105\ kt/\phi\mu c}$$

C. Time when well bore effects in a non-fractured well become negligible and data become amenable to analysis by transient methods

$$t = 2 \times 10^5\ \mu V_w c/kh$$

when

V_w is volume of well bore in barrels

c is compressibility of well bore fluids

k/μ represents total mobility

$$t = 114{,}800\ \mu V_w c/kh$$

when

V_w is in cu ft

Other procedures may include

(1) Plot of BHP - THP versus time should become flat

(2) Plot of p versus $\sqrt{t}$ should change from straight line

(3) Change in slope of plot of $\ell n\ p_D$ versus $\ell n\ t_D$ curve should change from a straight line with slope of one.

D. Time when turbulence might end in a fractured well

$$t = 40{,}000\ \phi\mu c L_f^2/k$$

where

L_f = ½ total fracture length

Early flow in a fractured well gradually changes from a linear-elliptical to a rather radial configuration with time so that an effective well radius, r_w', may be used in radial flow equations. A plot of p versus $\sqrt{t}$ should be a straight line during linear flow, and a plot of $\ell n\ p_D$ versus $\ell n\ t_D$ should have a slope of ½ during linear flow.

Turbulence behaves as a positive skin whereas fracturing usually results in a negative skin. Turbulence does not stabilize during linear flow, but stabilization does occur during radial flow.

E. Time at which data can no longer be analyzed by transient method and data possibly should be analyzed by late transient flow; when $t_{De} = 0.1$

$$t = \phi\mu c r_e^2 / 0.00264k$$

F. Time to end of transient flow and start of semisteady state flow; when $t_{De} = 0.3$

$$t = \phi\mu c r_e^2 / 0.00088k$$

NOTE: The transition period may be lengthy and may be influenced by many variables involving characteristics of the reservoir and its contained fluids.

APPENDIX B

Curves used in analysis of pressure buildup and pressure drawdown analysis:

Well	Zone	Tested Interval feet	Type of Analysis	Date of Test	Type of Curve	Fig. No.
Fawn Creek Government No. 1	1	5747-5792	Buildup #1	06/12/70 06/16/70	$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	13
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	14
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	15
			Buildup #2	07/08/70 08/01/70	$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	16
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	17
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	18
			Drawdown #2	08/01/70 08/16/70	$m(p)$ vs. $\log t$	19
					$m'(p)$ vs. $\log t$	20
					p vs. $\log t$	21
					m vs. $\sqrt{t}$	22
			Buildup #3	08/16/70 10/13/70	$m(p)$ vs. $\log \frac{t^* + \Delta t}{\Delta t}$	23
					$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	24
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	25
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	26
	2	5600-5630	Buildup #1	10/30/70 11/09/70	$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	27
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	28
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	29

APPENDIX B (Cont'd.)

Well	Zone	Tested Interval feet	Type of Analysis	Date of Test	Type of Curve	Fig. No.
	2		Drawdown #1	11/09/70 11/19/70	m(p) vs. log t	30
					m´(p) vs. log t	31
					m(p) vs. $\sqrt{t}$	32
					Two Rate Flow	33
			Buildup #2	11/19/70 02/14/71	m(p) vs. log $\frac{t + \Delta t}{\Delta t}$	34
					m(p) vs. log $\frac{t + \Delta t}{\Delta t}$	35
					m´(p) vs. log $\frac{t + \Delta t}{\Delta t}$	36
					m(p) vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	37
Scandard Draw	1	7181-7212	Buildup #1	06/06/70 06/13/70	m(p) vs. log $\frac{t + \Delta t}{\Delta t}$	38
					m´(p) vs. log $\frac{t + \Delta t}{\Delta t}$	39
					m(p) vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	40
			Drawdown #1	06/13/70 06/20/70	m(p) vs. log t	41
					m´(p) vs. log t	42
					m(p) vs. $\sqrt{t}$	43
			Buildup #2	06/20/70 06/27/70	m(p) vs. log $\frac{t + \Delta t}{\Delta t}$	44
					m´(p) vs. log $\frac{t + \Delta t}{\Delta t}$	45
					m(p) vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	46

APPENDIX B (Cont'd.)

Well	Zone	Tested Interval feet	Type of Analysis	Date of Test	Type of Curve	Fig. No.
	2	6810-6838	Buildup #1	07/22/70 08/03/70	$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	47
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	48
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	49
	3	7454-7456	Buildup #1	09/06/70 10/13/70	$m(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	50
					$m'(p)$ vs. $\log \frac{t + \Delta t}{\Delta t}$	51
					$m(p)$ vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$	52

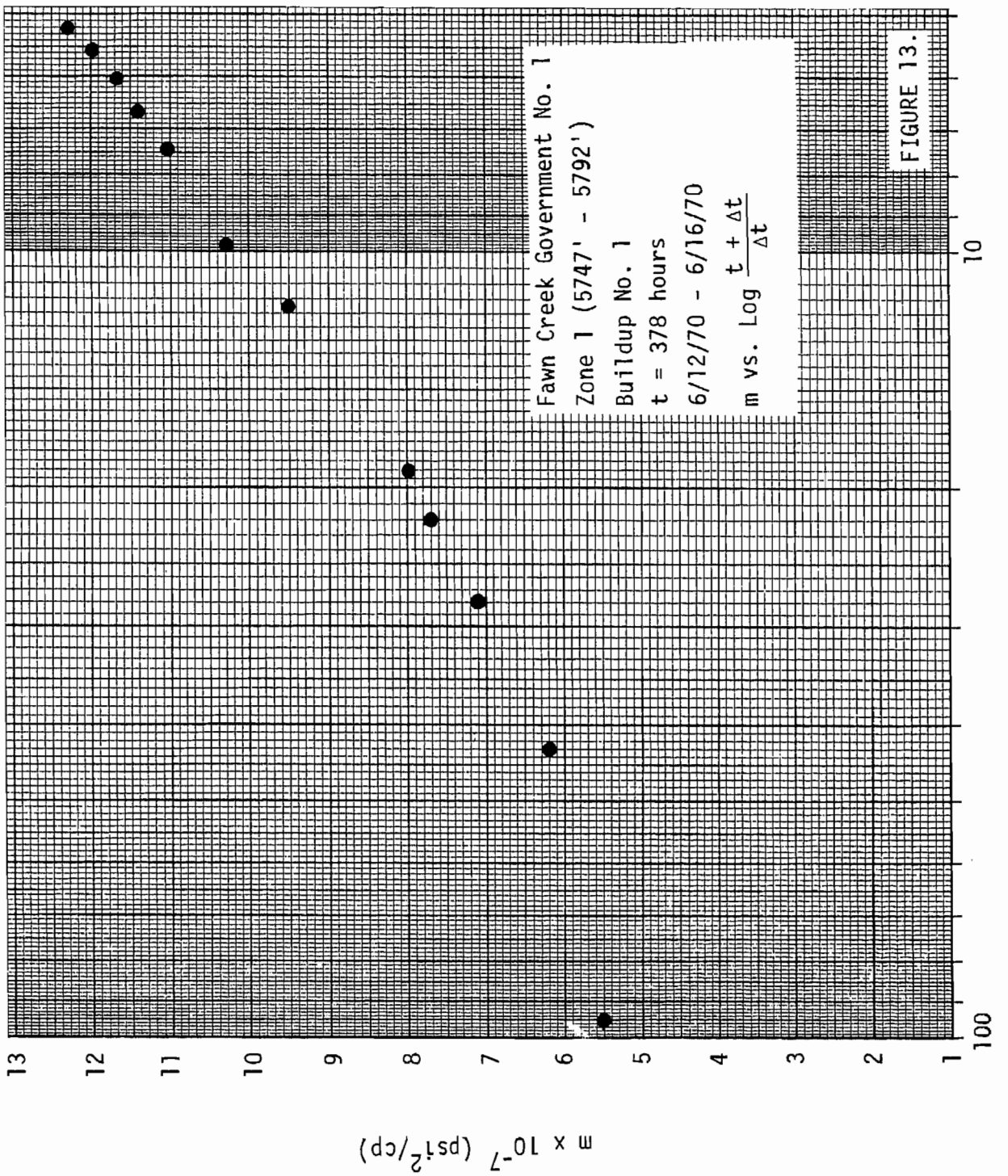

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 1
t = 378 hours
6/12/70 - 6/16/70
m vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} (psi²/cp)
$\frac{t + \Delta t}{\Delta t}$
13
12
11
10
9
8
7
6
5
4
3
2
1
100
10

FIGURE 13.

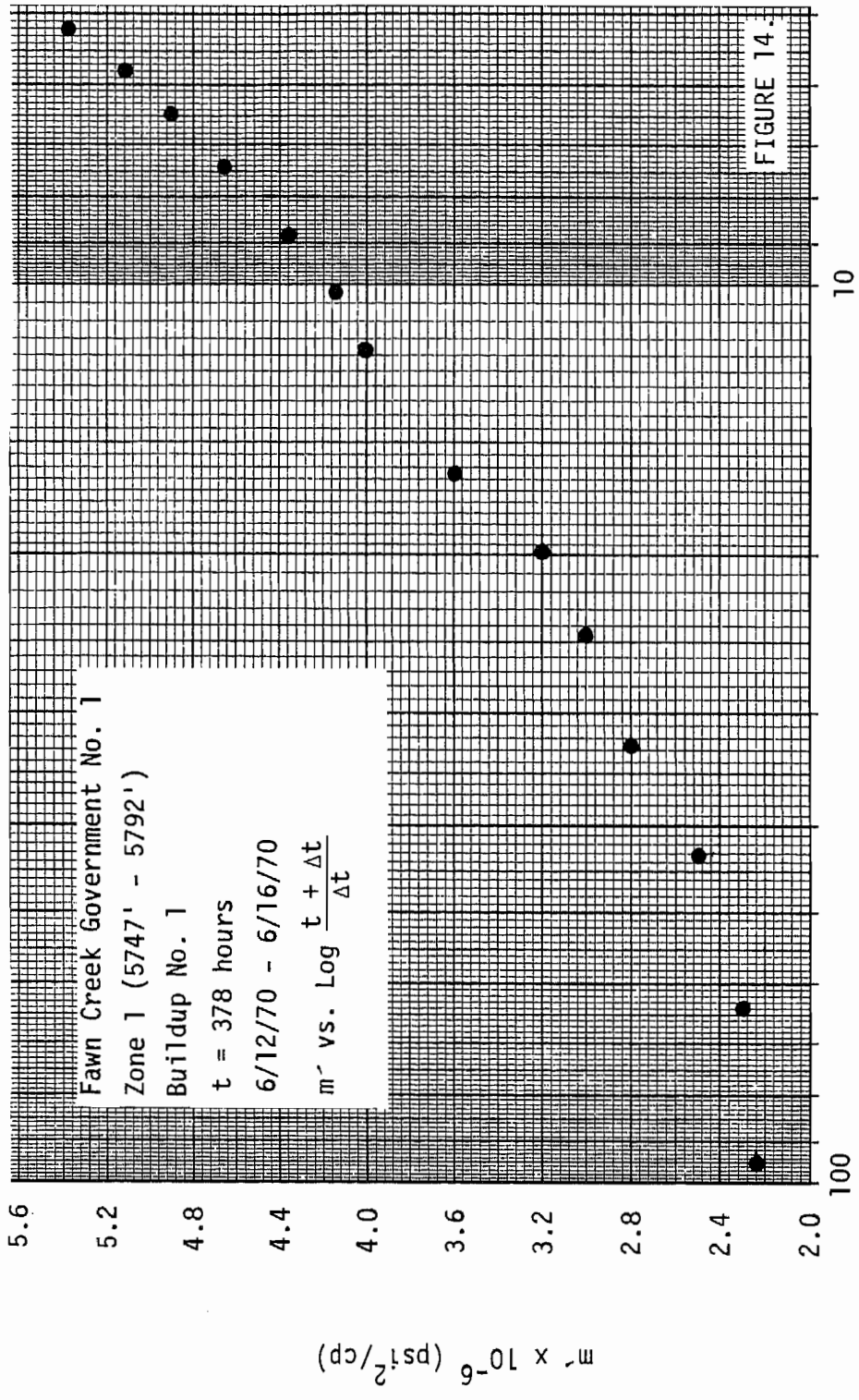

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 1
t = 378 hours
6/12/70 - 6/16/70
m' vs. Log $\frac{t + \Delta t}{\Delta t}$
m' x 10^{-6} (psi^2/cp)
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
100
10
$\frac{t + \Delta t}{\Delta t}$

FIGURE 14.

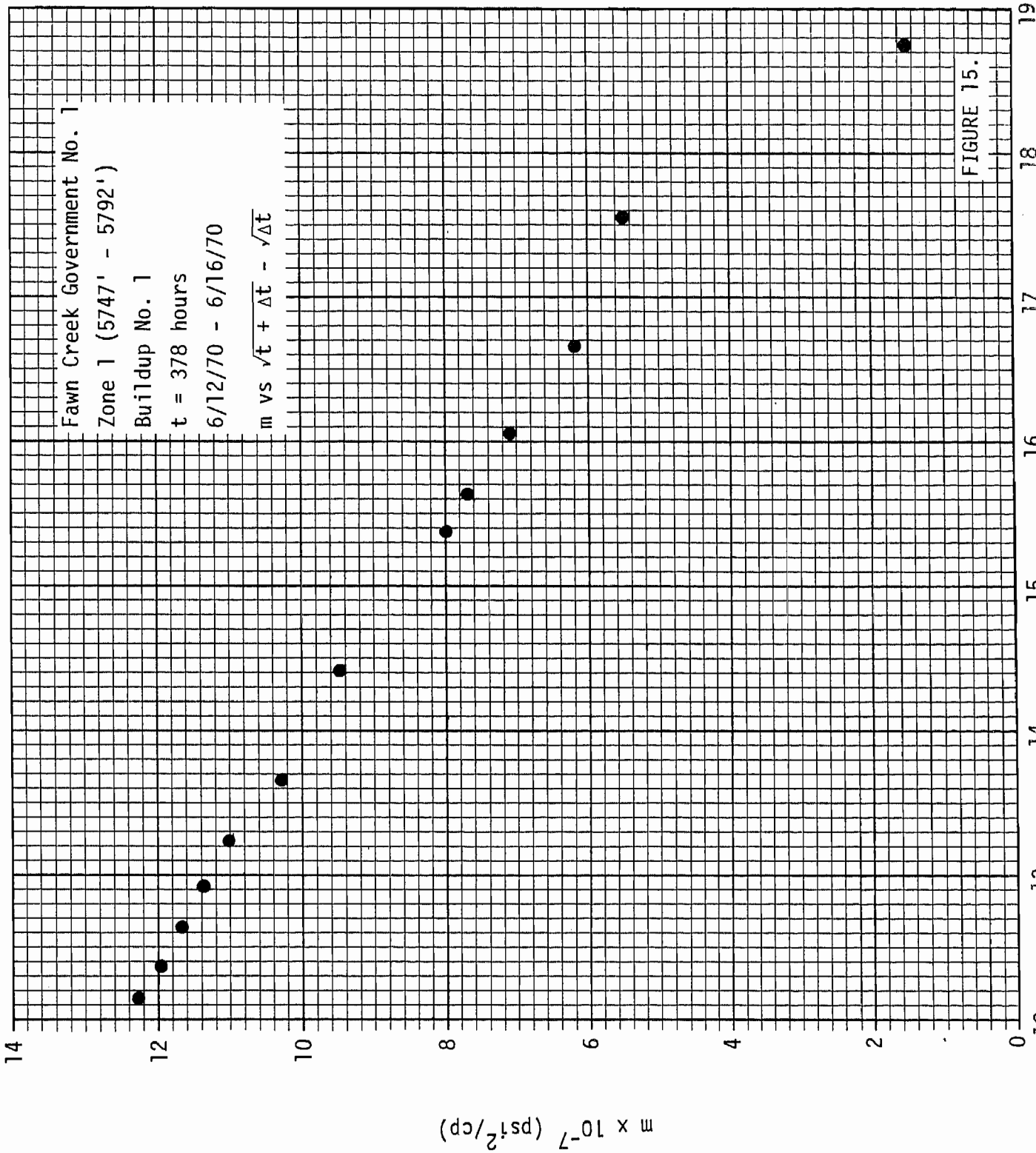

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 1
t = 378 hours
6/12/70 - 6/16/70
m vs $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$
0
2
4
6
8
10
12
14
12
13
14
15
16
17
18
19

FIGURE 15.

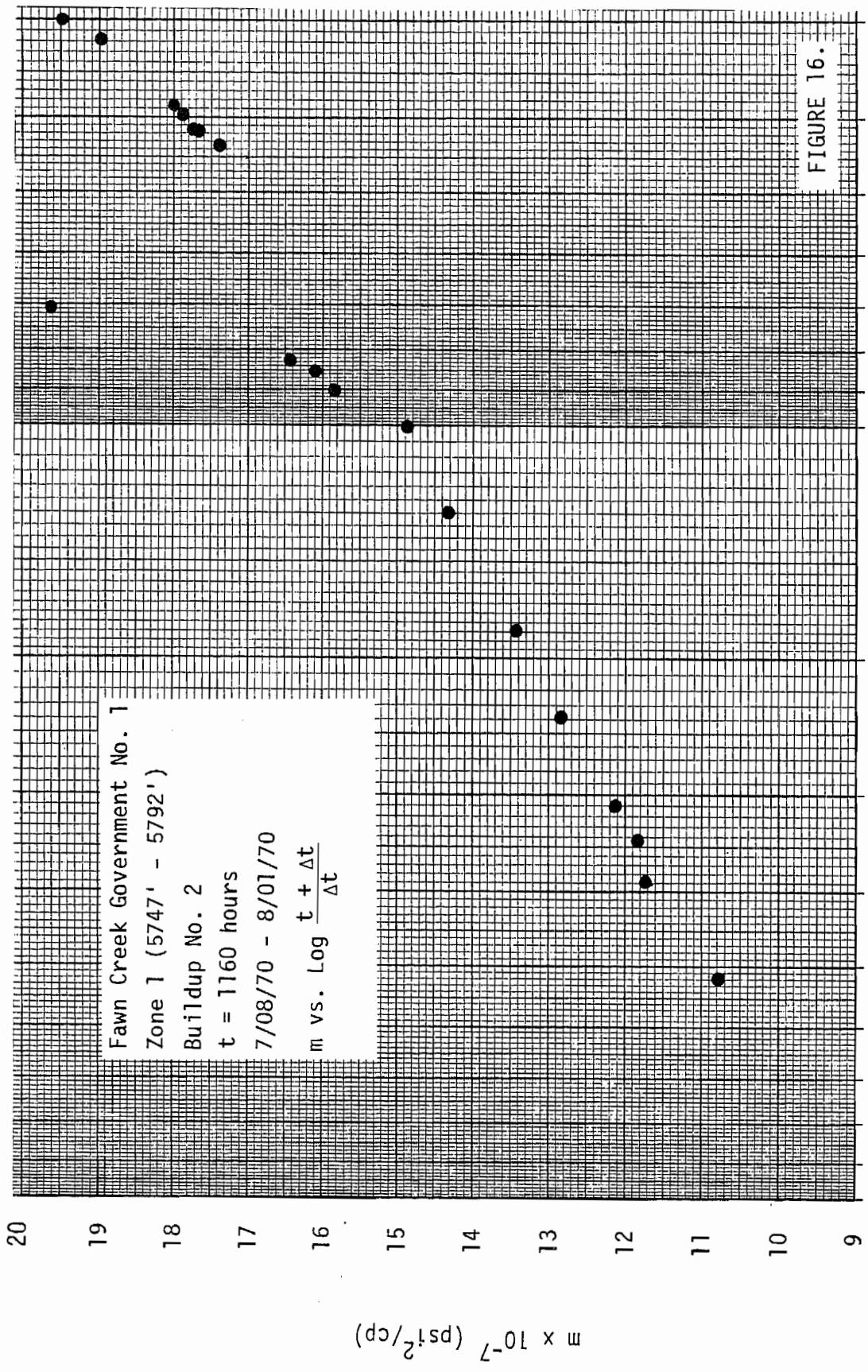

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 2
t = 1160 hours
7/08/70 - 8/01/70
m vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} (psi^2/cp)
20
19
18
17
16
15
14
13
12
11
10
9
100
10
$\frac{t + \Delta t}{\Delta t}$

FIGURE 16.

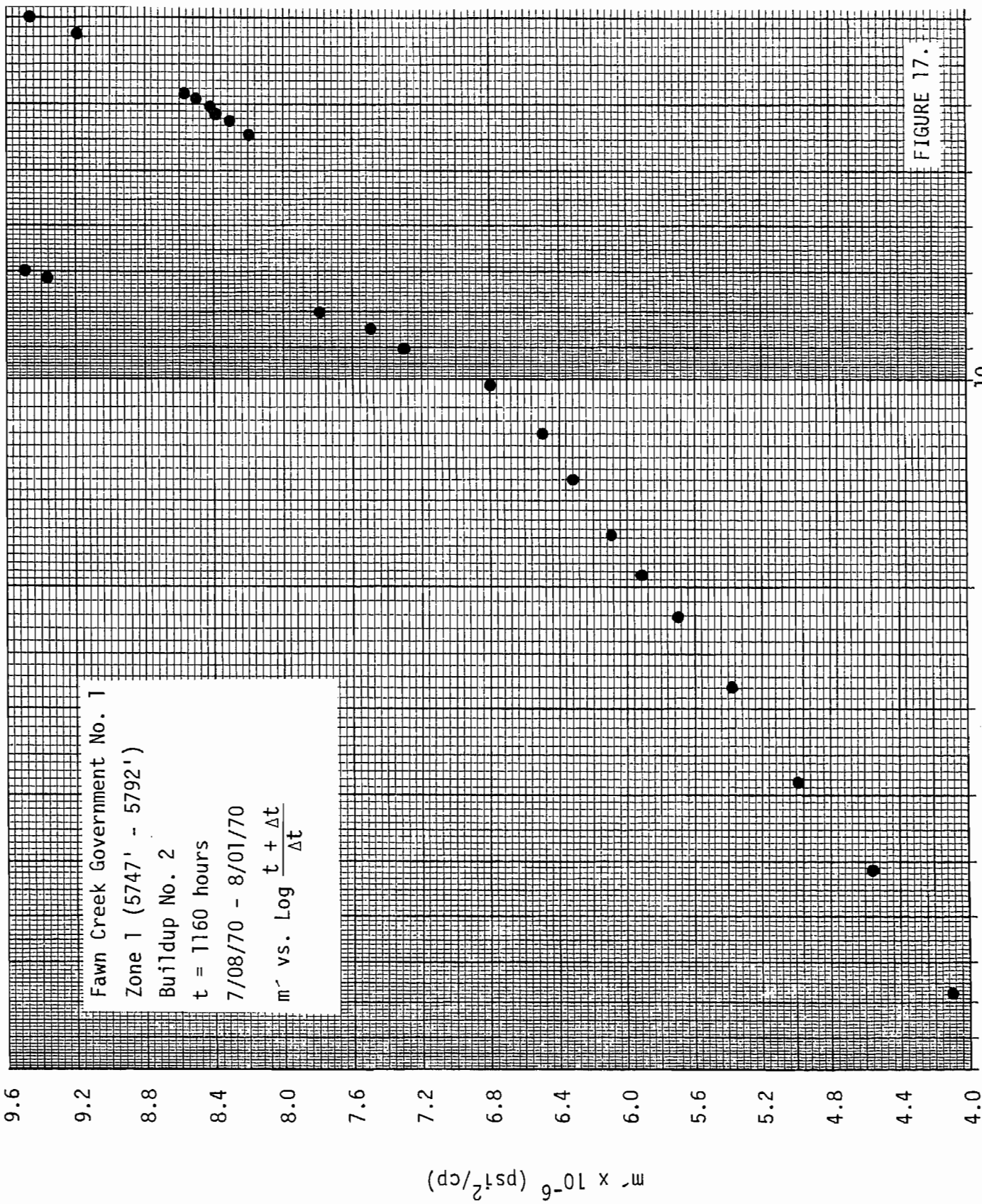

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 2
t = 1160 hours
7/08/70 - 8/01/70
m' vs. Log (t + Δt)/Δt
m' x 10⁻⁶ (psi²/cp)
9.6
9.2
8.8
8.4
8.0
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
100
10
(t + Δt)/Δt

FIGURE 17.

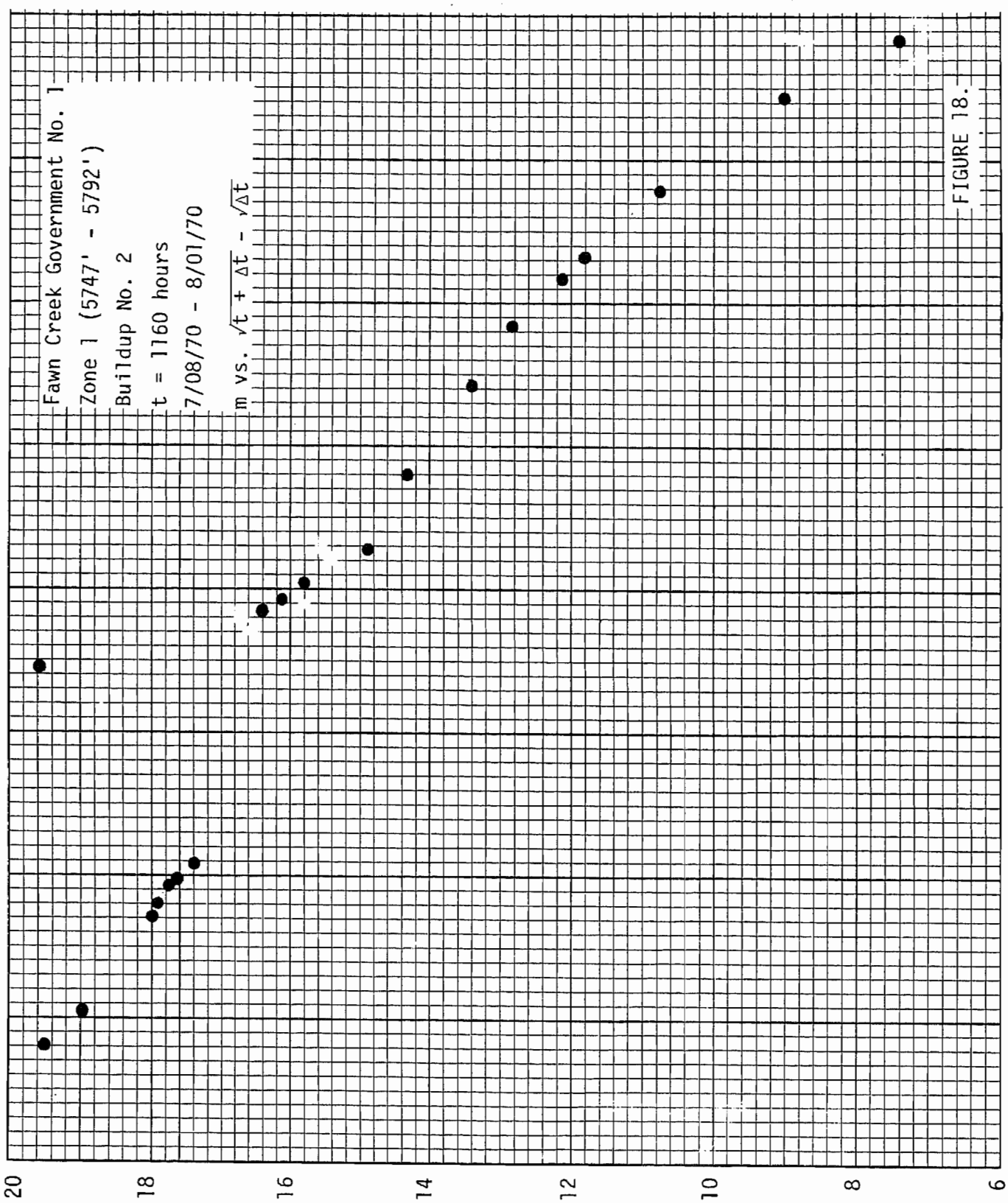

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 2
t = 1160 hours
7/08/70 - 8/01/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$
20
18
16
14
12
10
8
6
16
18
20
22
24
26
28
30
32

FIGURE 18.

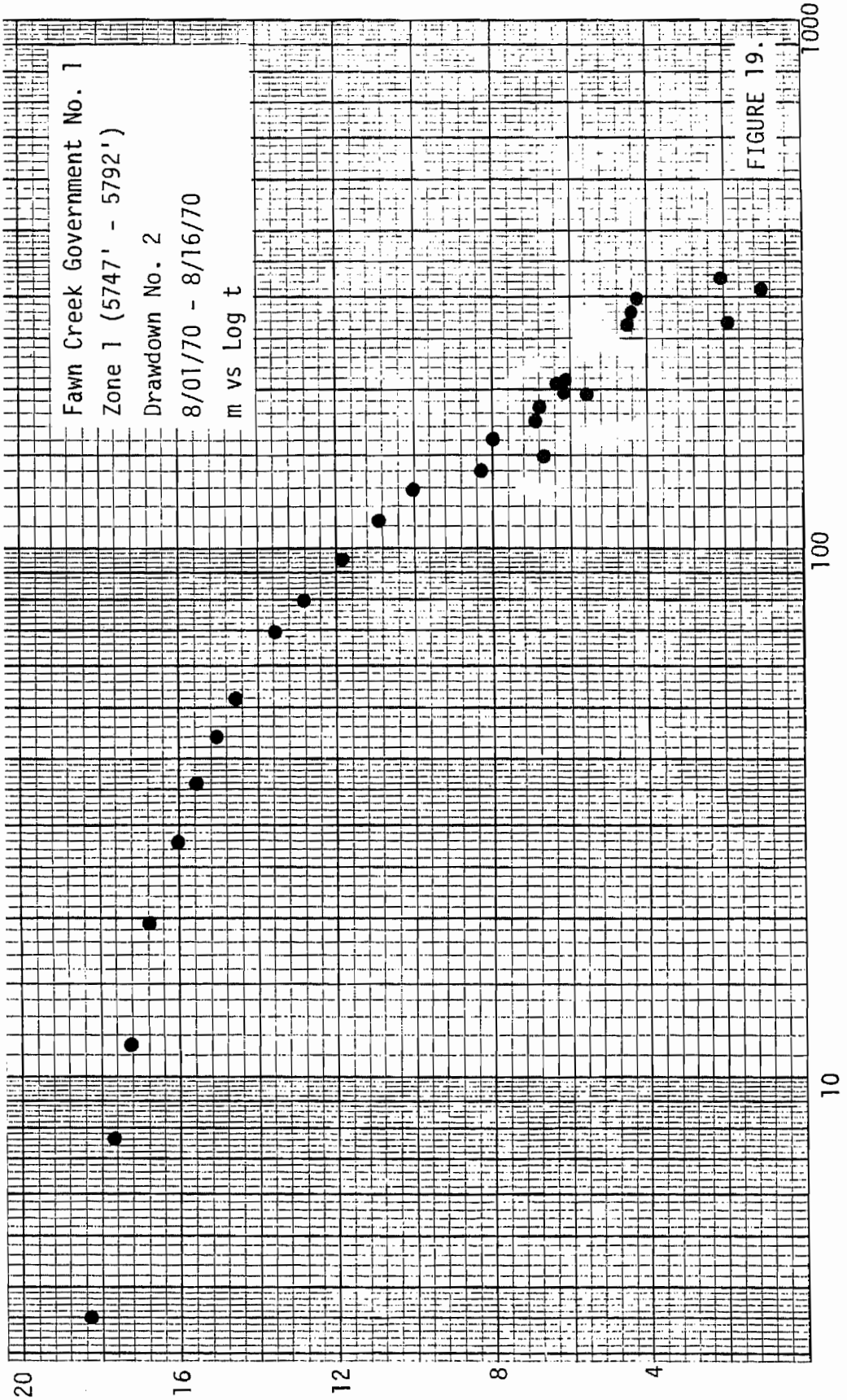

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Drawdown No. 2
8/01/70 - 8/16/70
m vs Log t
m x 10⁻⁷ (psi²/cp)
20
16
12
8
4
10
100
1000
t(hours)

FIGURE 19.

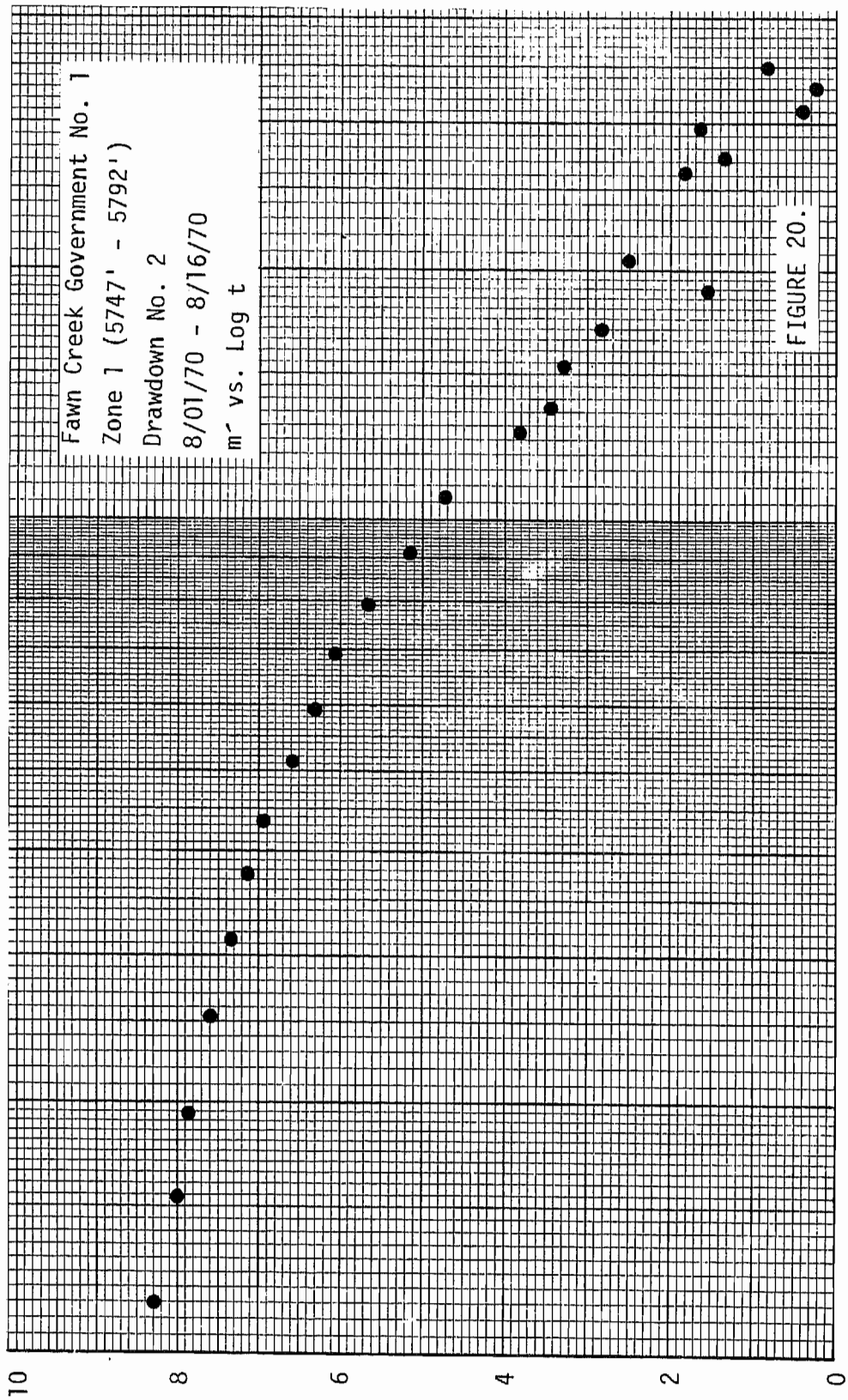
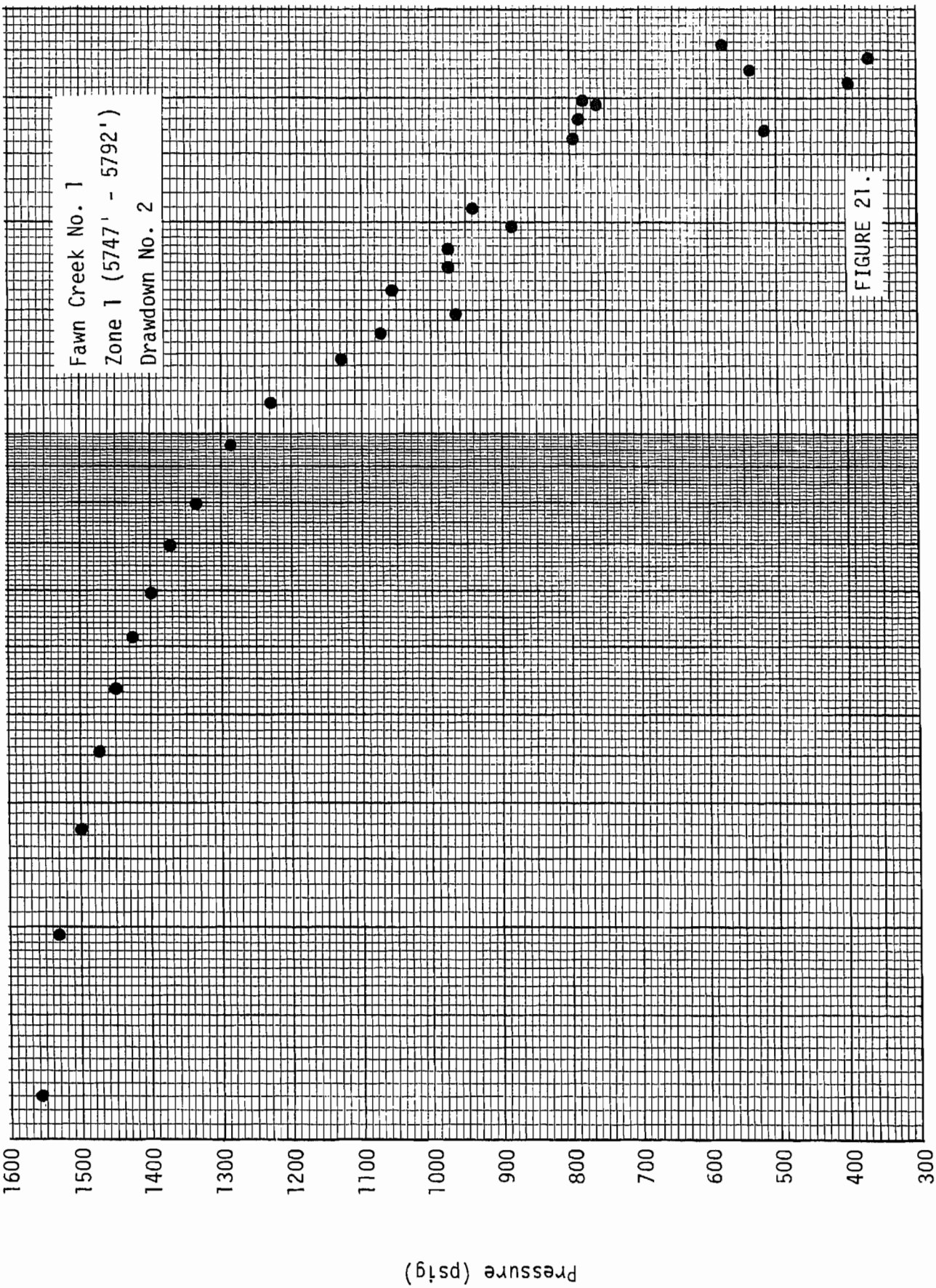

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Drawdown No. 2
8/01/70 - 8/16/70
m' vs. Log t
m' x 10⁻⁶ (psi²/cp)
0
2
4
6
8
10
10
100
t(hours)

FIGURE 20.


Fawn Creek No. 1
Zone 1 (5747' - 5792')
Drawdown No. 2
FIGURE 21.
Pressure (psig)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
10
100
t, hours

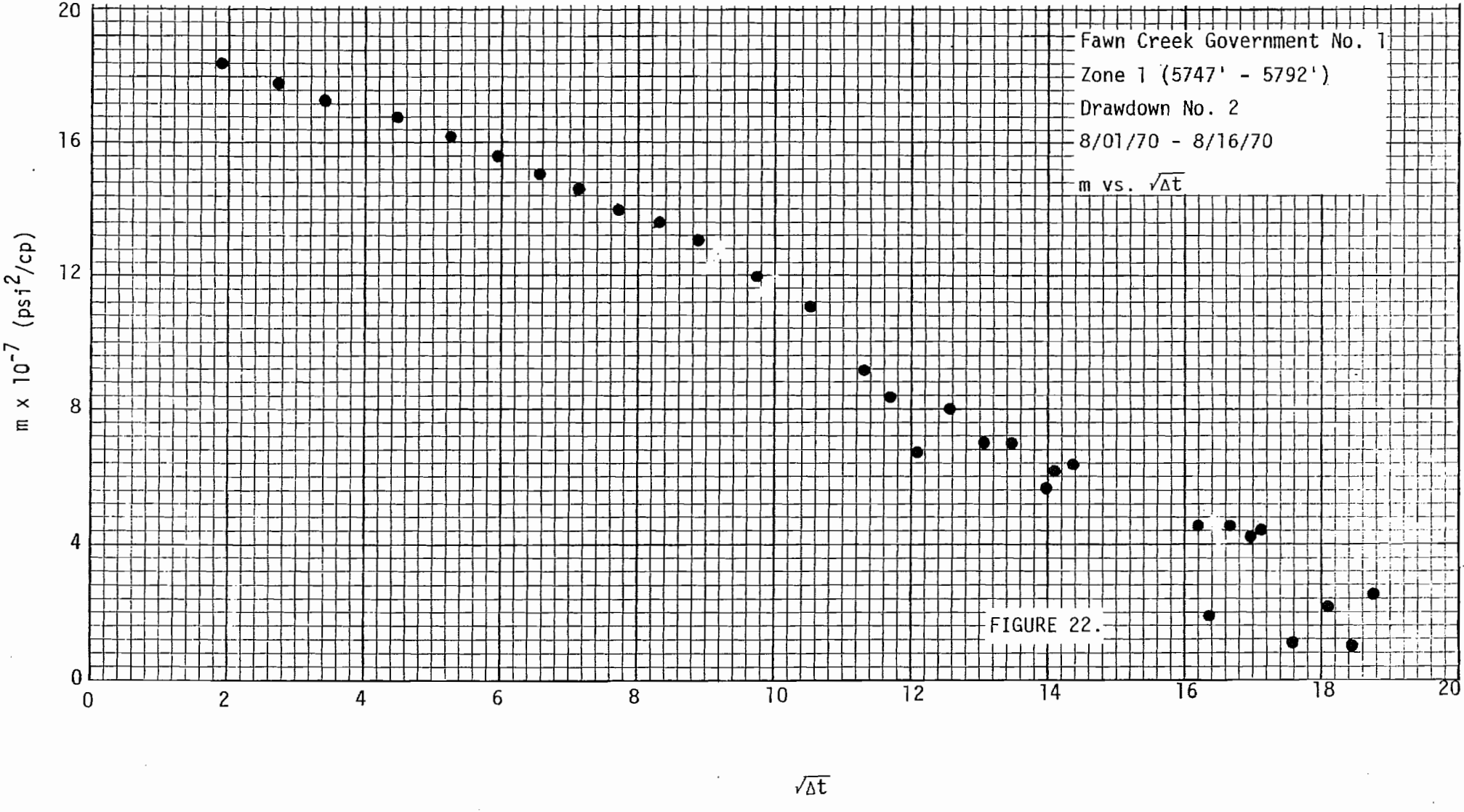

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Drawdown No. 2
8/01/70 - 8/16/70
m vs. $\sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{\Delta t}$
0
4
8
12
16
20
0
2
4
6
8
10
12
14
16
18
20

FIGURE 22.

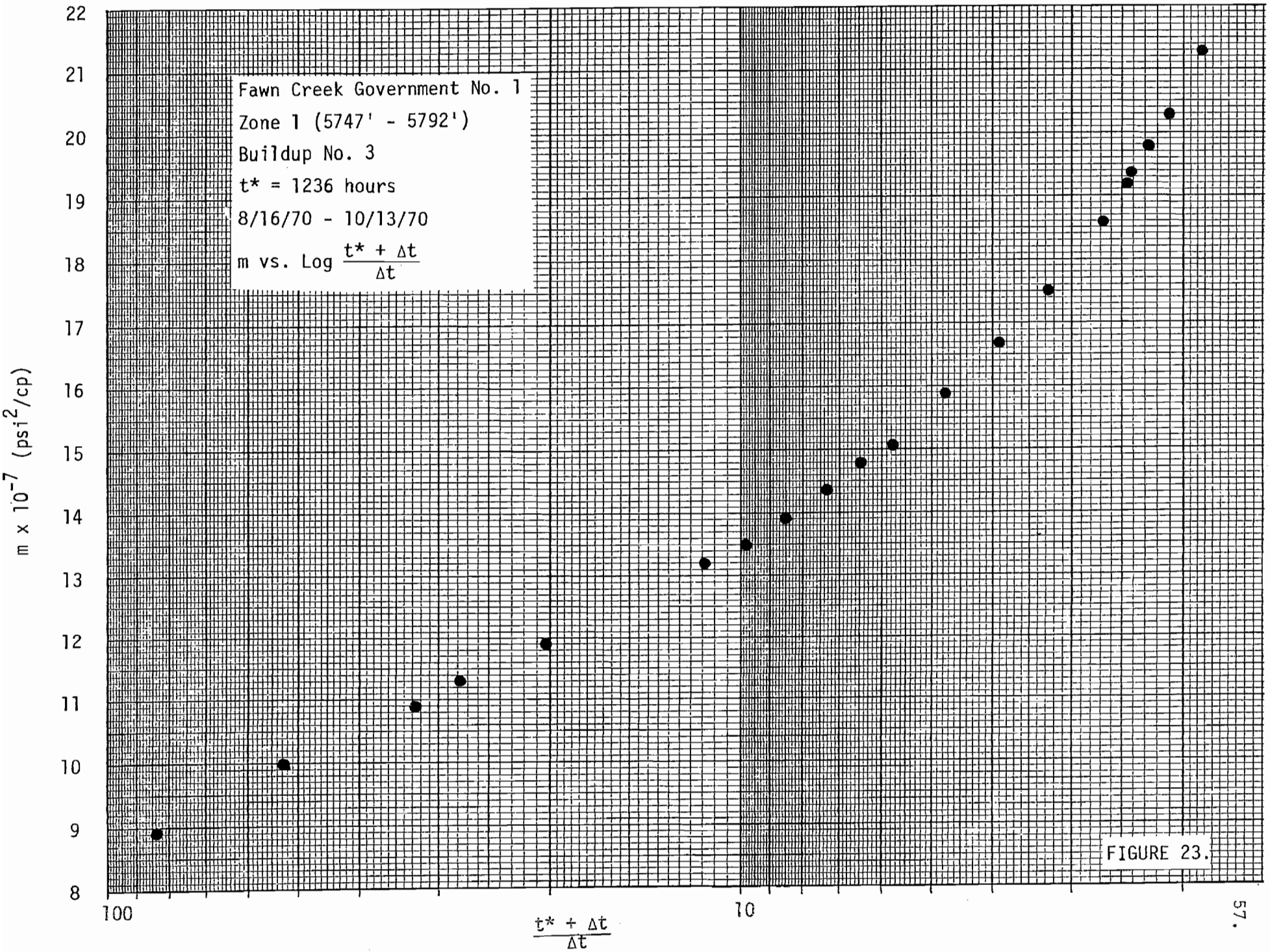

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 3
t* = 1236 hours
8/16/70 - 10/13/70
m vs. Log (t* + Δt)/Δt
m x 10^-7 (psi^2/cp)
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
100
10
(t* + Δt)/Δt

FIGURE 23.

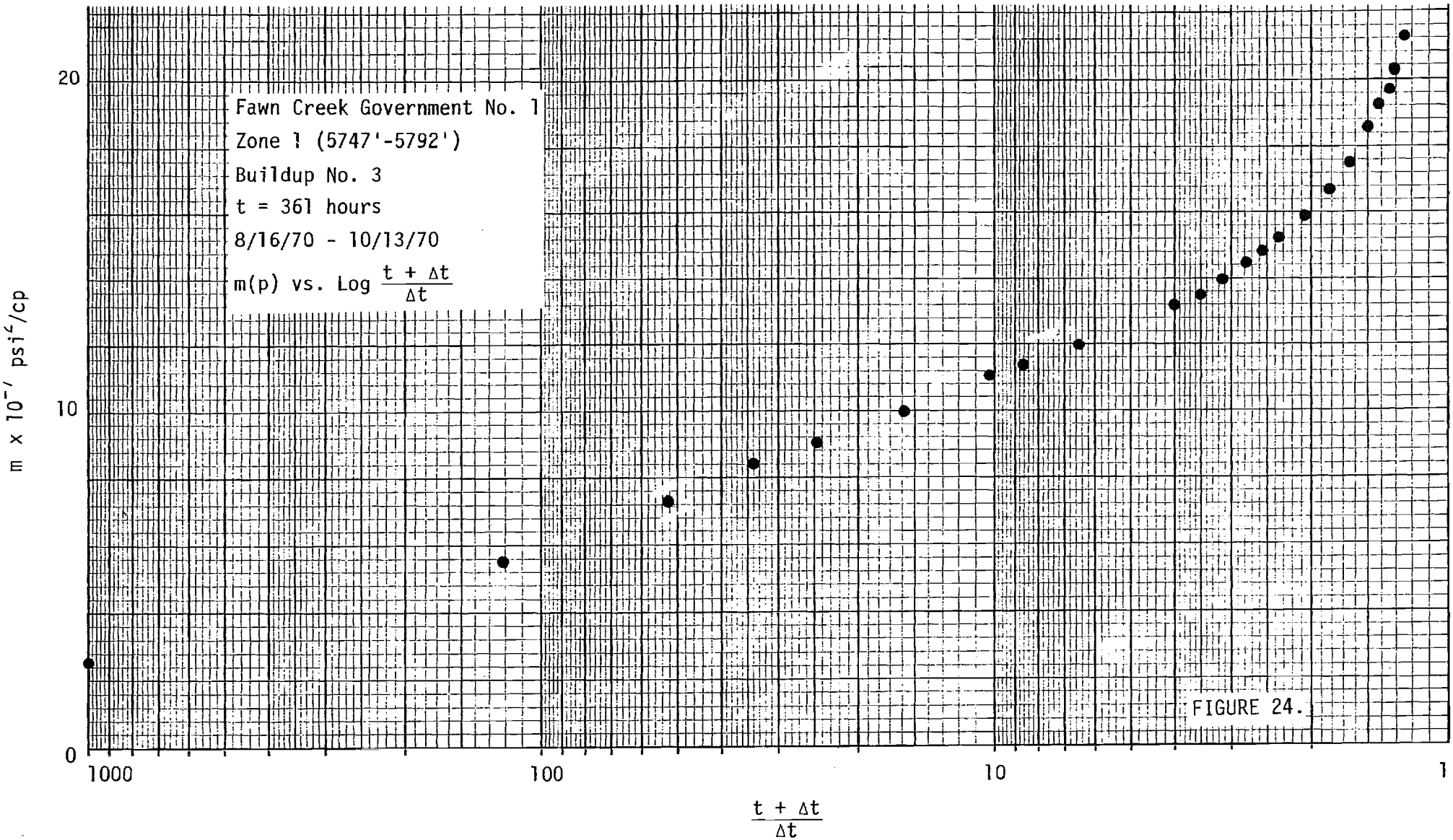

Fawn Creek Government No. 1
Zone 1 (5747'-5792')
Buildup No. 3
t = 361 hours
8/16/70 - 10/13/70
m(p) vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} psi^4/cp
20
10
0
1000
100
10
1
$\frac{t + \Delta t}{\Delta t}$

FIGURE 24.

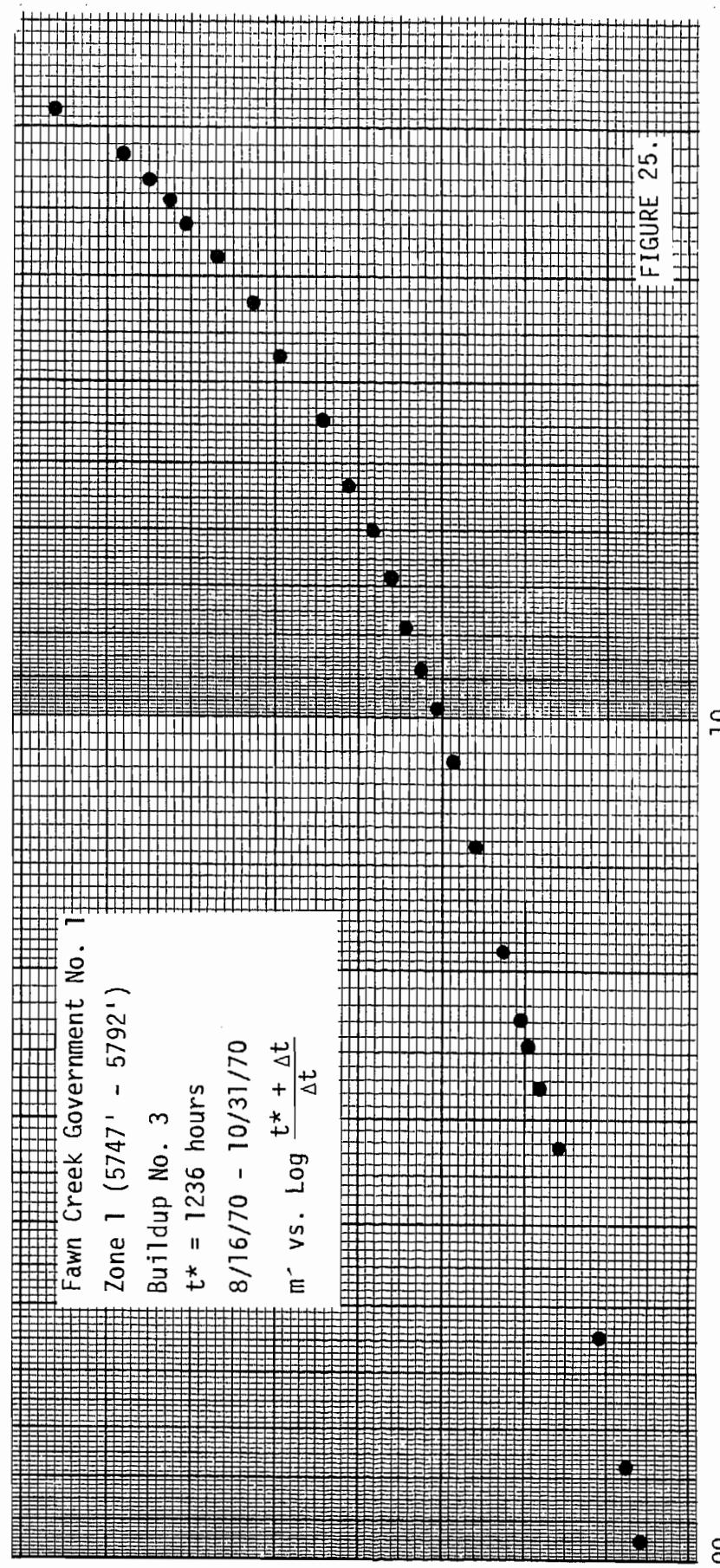

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 3
t* = 1236 hours
8/16/70 - 10/31/70
m' vs. Log (t* + Δt)/Δt
m' x 10⁻⁶ (psi²/cp)
11
10
9
8
7
6
5
4
3
100
10
(t* + Δt)/Δt

FIGURE 25.

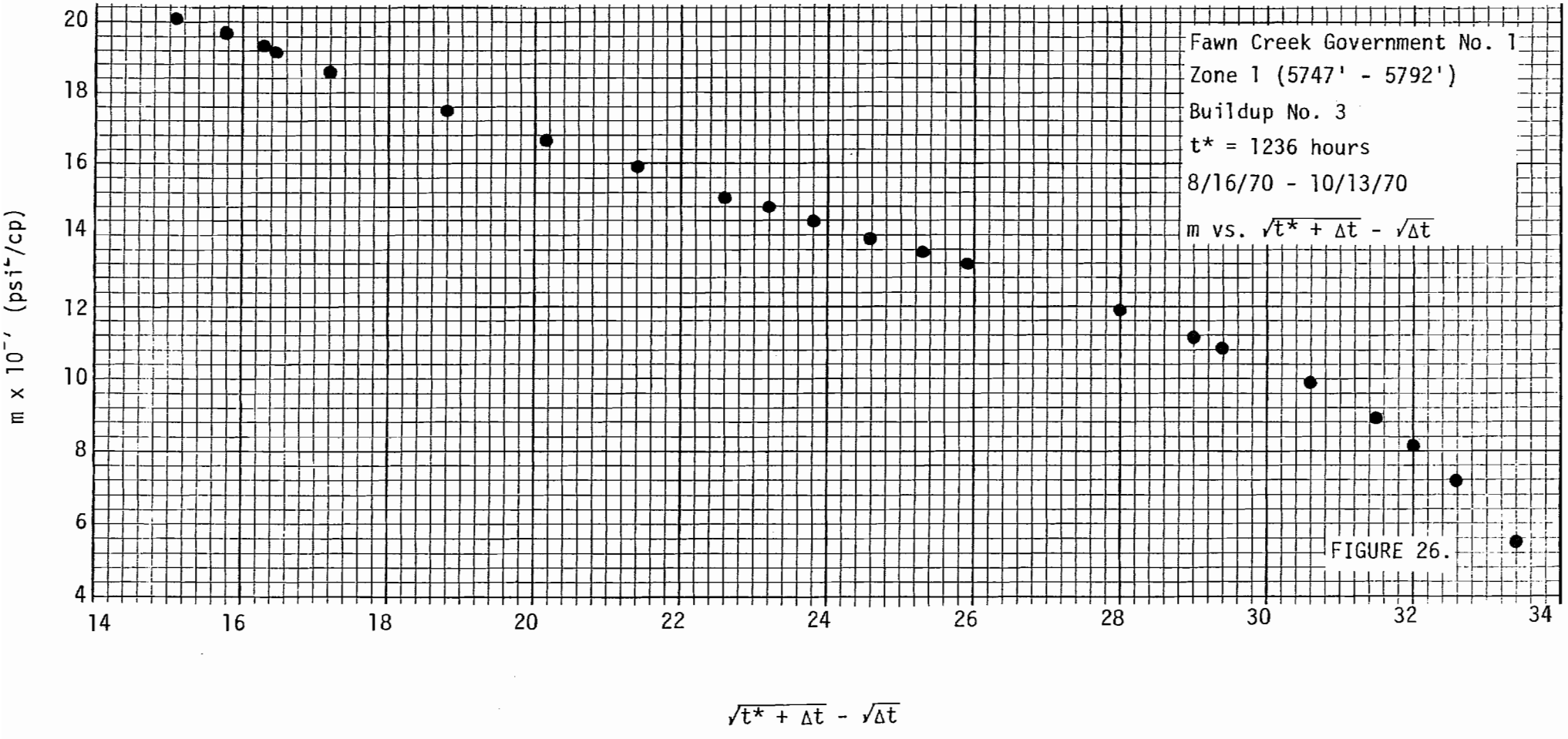

Fawn Creek Government No. 1
Zone 1 (5747' - 5792')
Buildup No. 3
t* = 1236 hours
8/16/70 - 10/13/70
m vs. $\sqrt{t^* + \Delta t} - \sqrt{\Delta t}$
m x 10^{-1} (psi²/cp)
$\sqrt{t^* + \Delta t} - \sqrt{\Delta t}$
20
18
16
14
12
10
8
6
4
14
16
18
20
22
24
26
28
30
32
34

FIGURE 26.

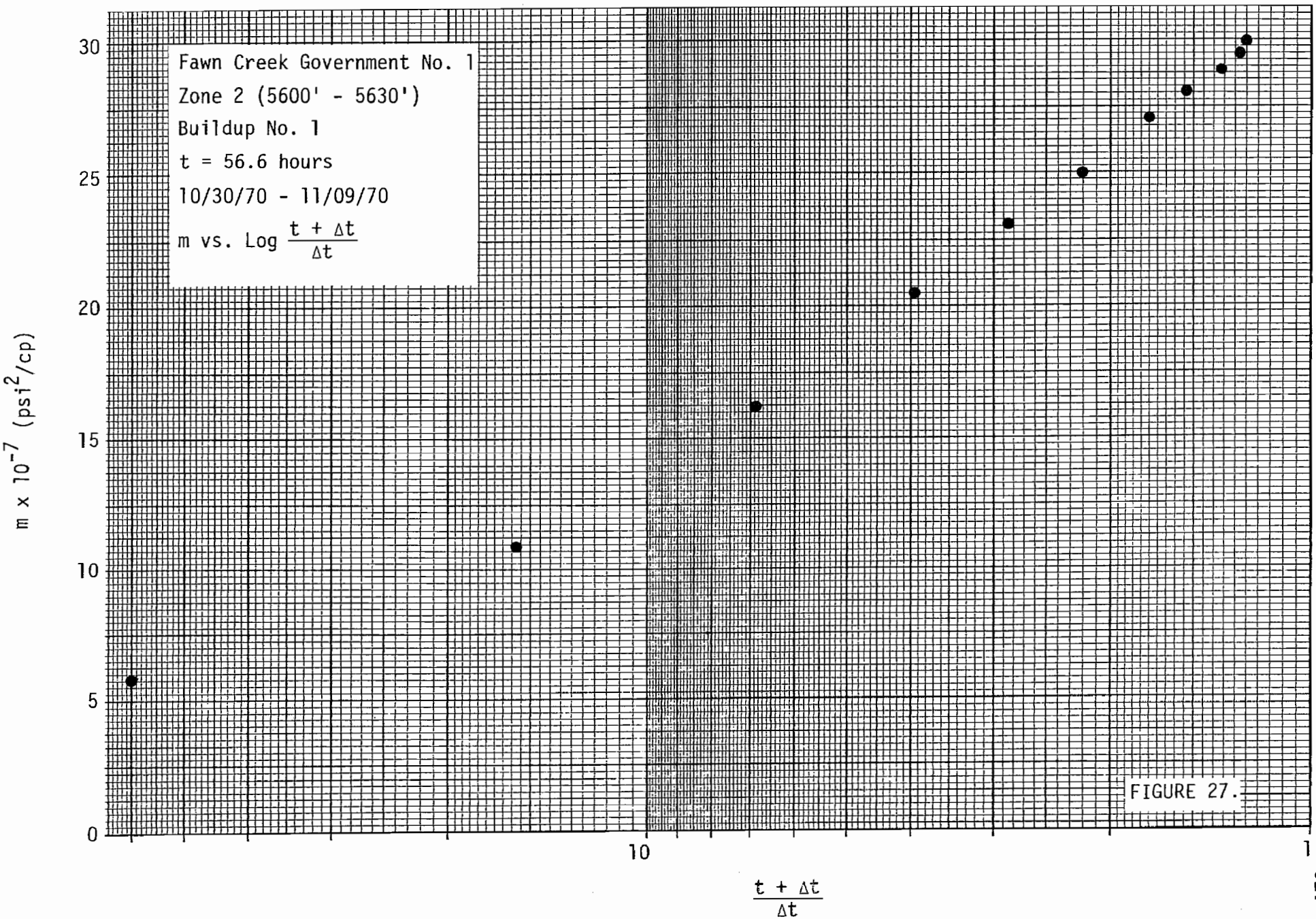

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 1
t = 56.6 hours
10/30/70 - 11/09/70
m vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} (psi^2/cp)
30
25
20
15
10
5
0
10
1
$\frac{t + \Delta t}{\Delta t}$

FIGURE 27.

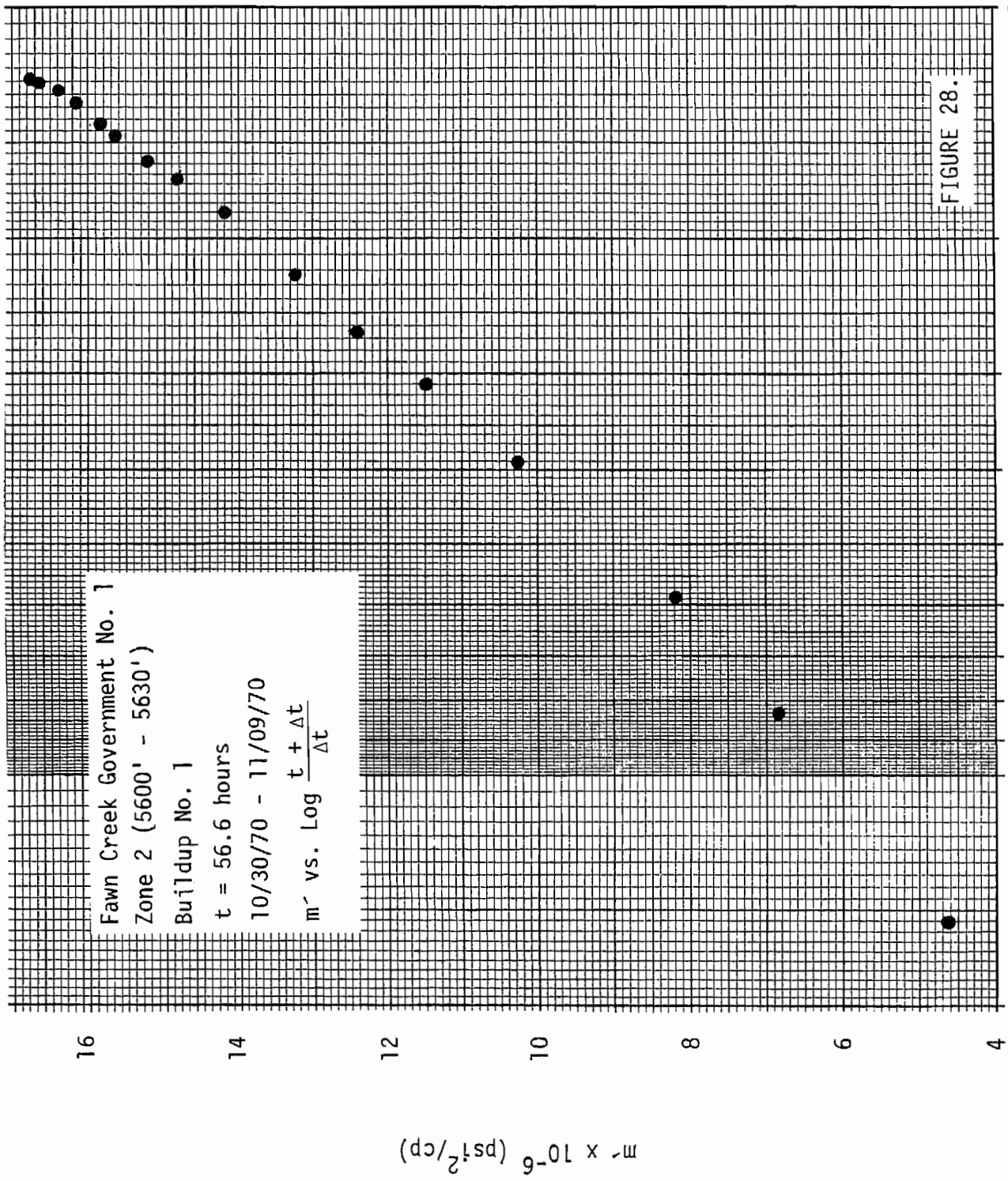

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 1
t = 56.6 hours
10/30/70 - 11/09/70
m´ vs. Log (t + Δt)/Δt
m´ x 10⁻⁶ (psi²/cp)
16
14
12
10
8
6
4
10
1
(t + Δt)/Δt

FIGURE 28.

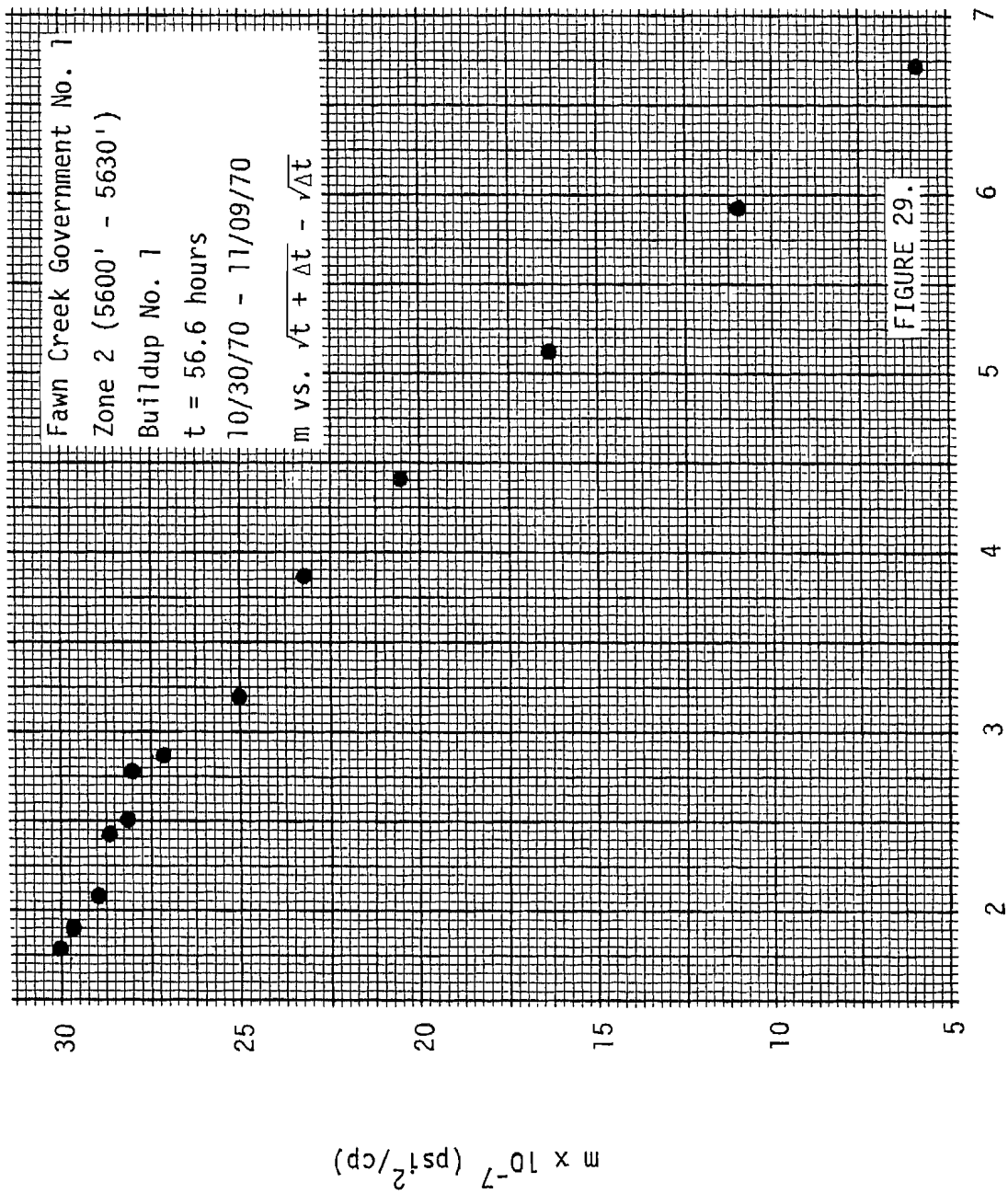

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 1
t = 56.6 hours
10/30/70 - 11/09/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
30
25
20
15
10
5
2
3
4
5
6
7
$m \times 10^{-7}$ (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$

FIGURE 29.

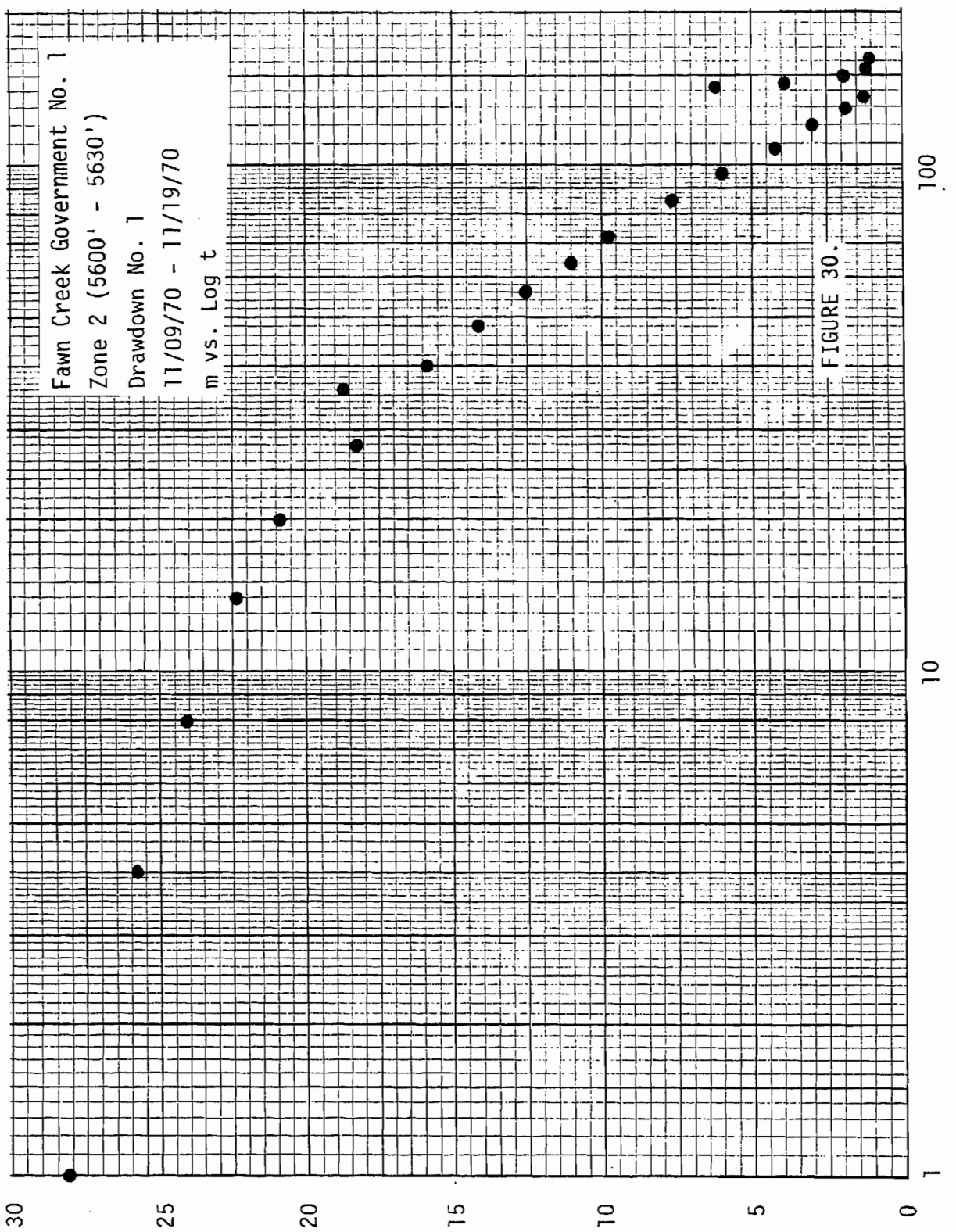

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Drawdown No. 1
11/09/70 - 11/19/70
m vs. Log t
m x 10-7 (psi2/cp)
t(hours)
0
5
10
15
20
25
30
1
10
100

FIGURE 30.

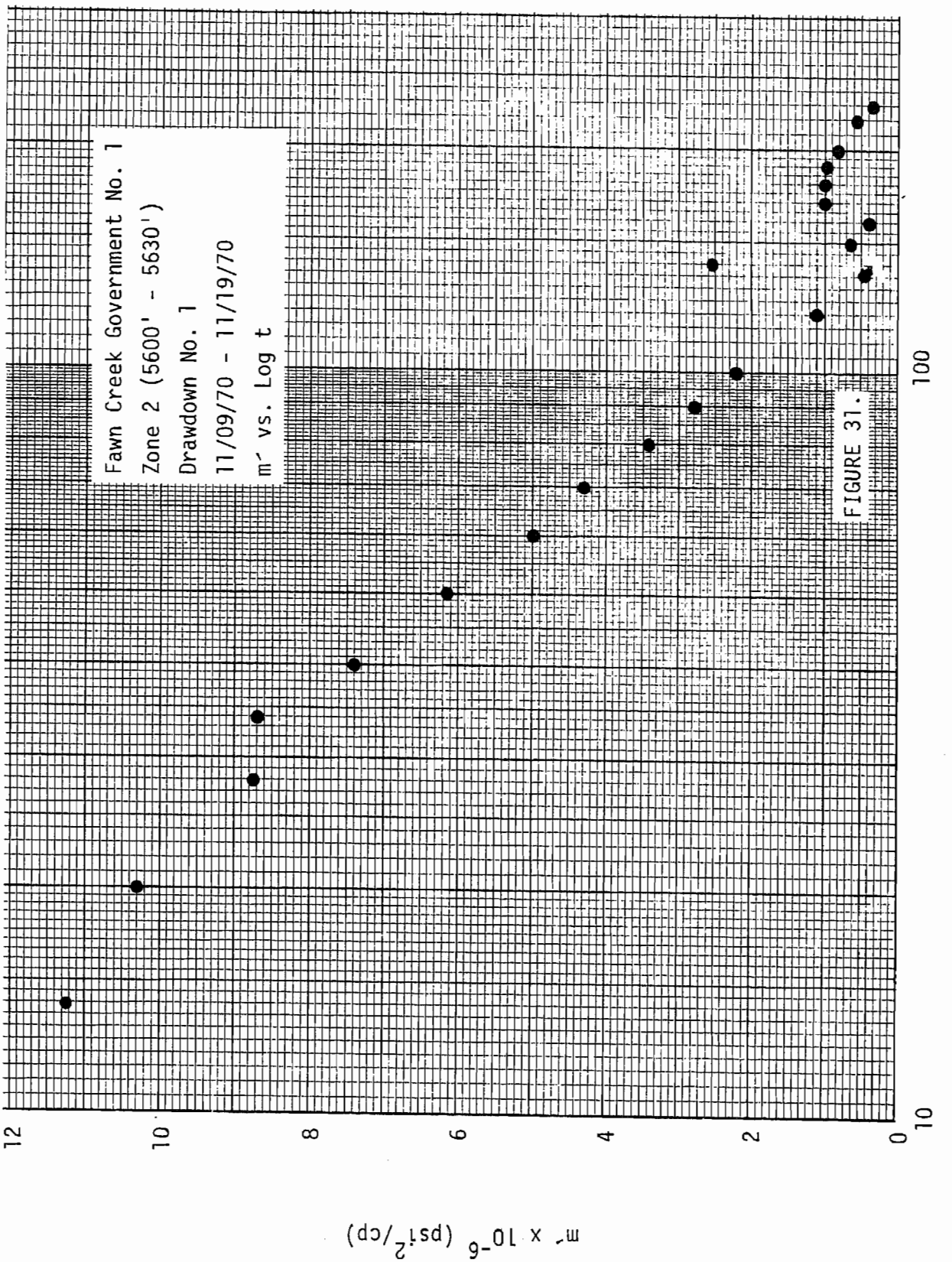

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Drawdown No. 1
11/09/70 - 11/19/70
m' vs. Log t
m' x 10⁻⁶ (psi²/cp)
t(hours)
0
2
4
6
8
10
12
10
100

FIGURE 31.

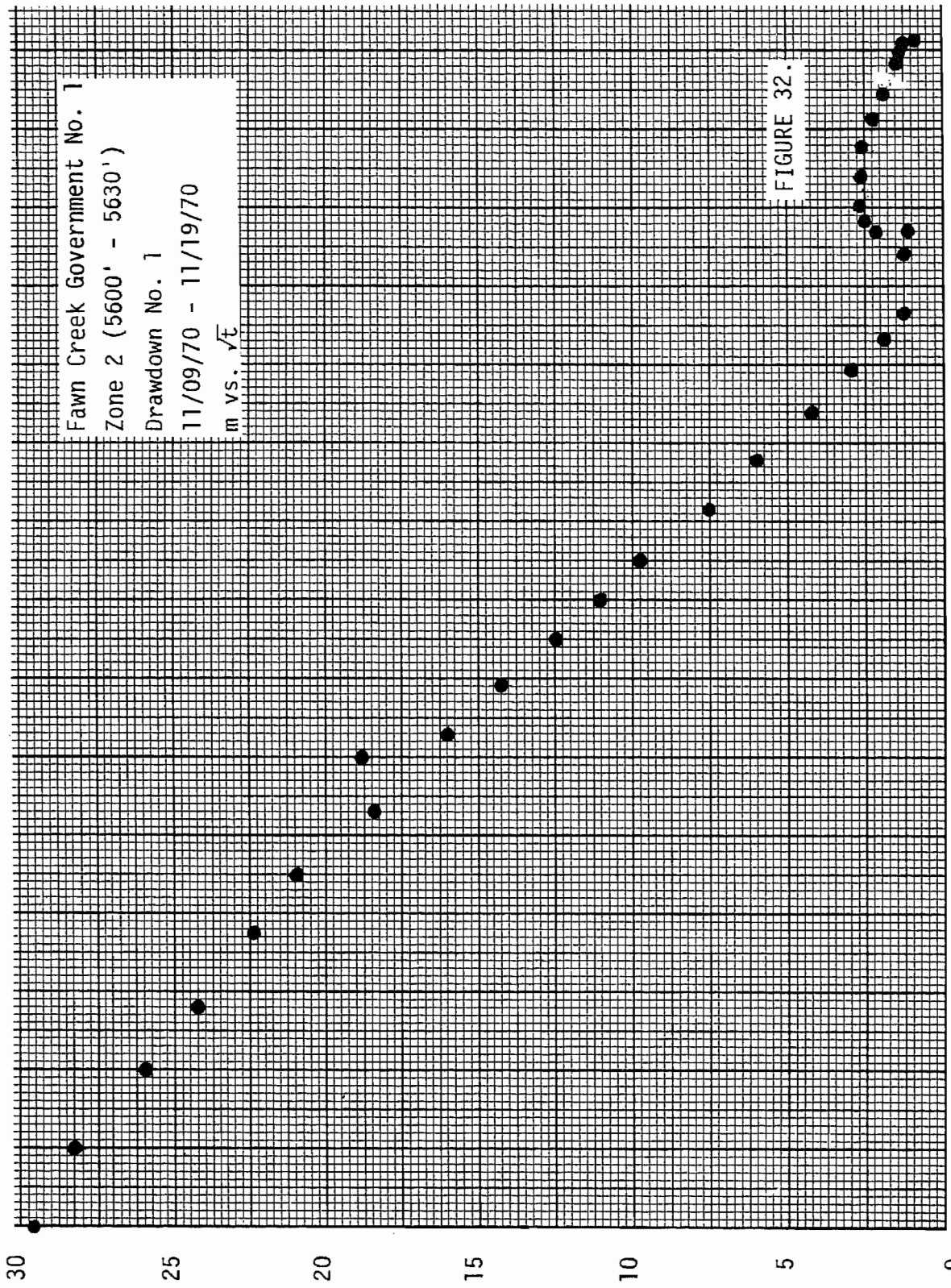

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Drawdown No. 1
11/09/70 - 11/19/70
m vs. $\sqrt{t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t}$
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

FIGURE 32.

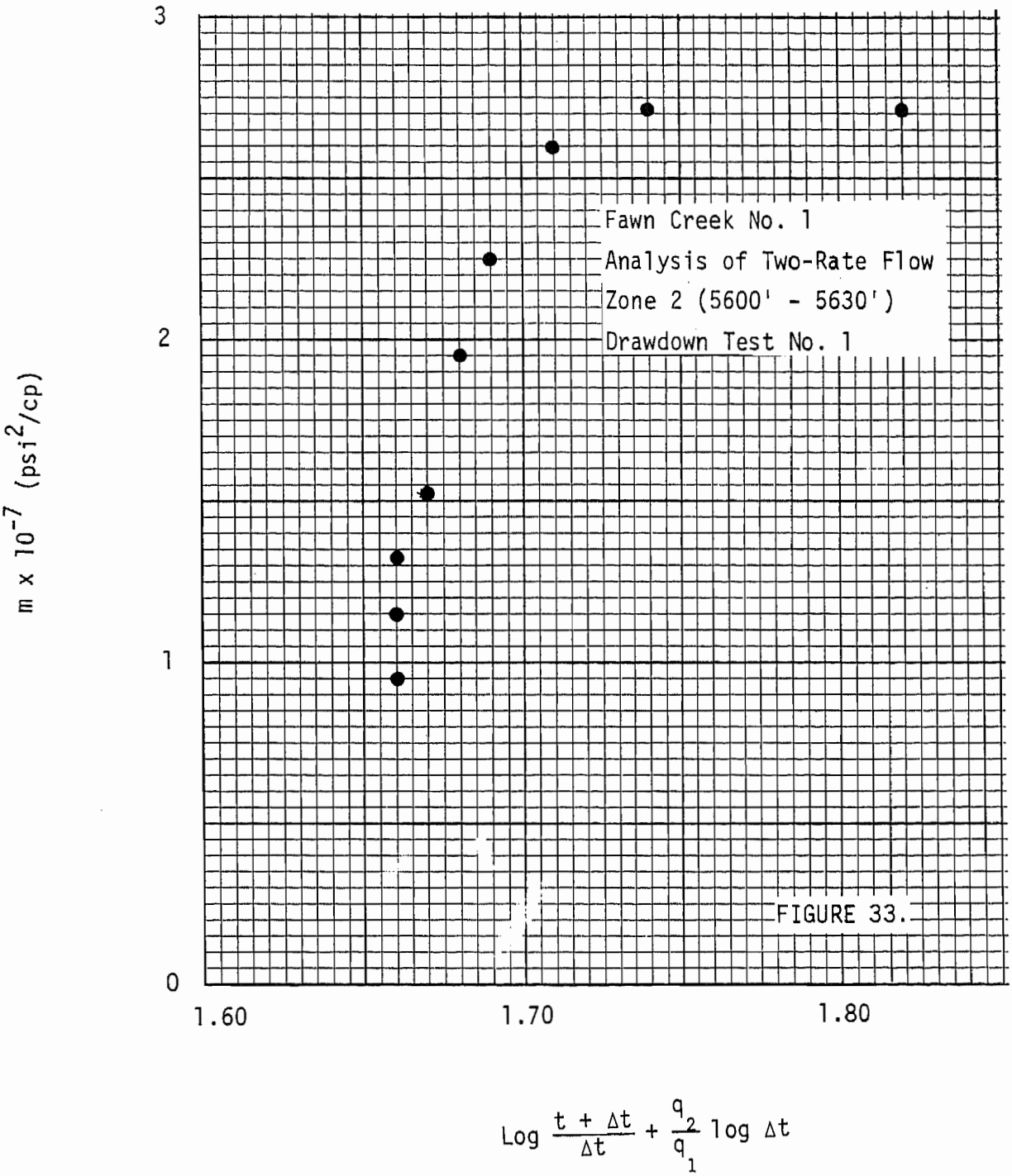

Fawn Creek No. 1
Analysis of Two-Rate Flow
Zone 2 (5600' - 5630')
Drawdown Test No. 1
3
2
1
0
1.60
1.70
1.80
m x 10^-7 (psi^2/cp)
Log (t + Δt)/Δt + q2/q1 log Δt

FIGURE 33.

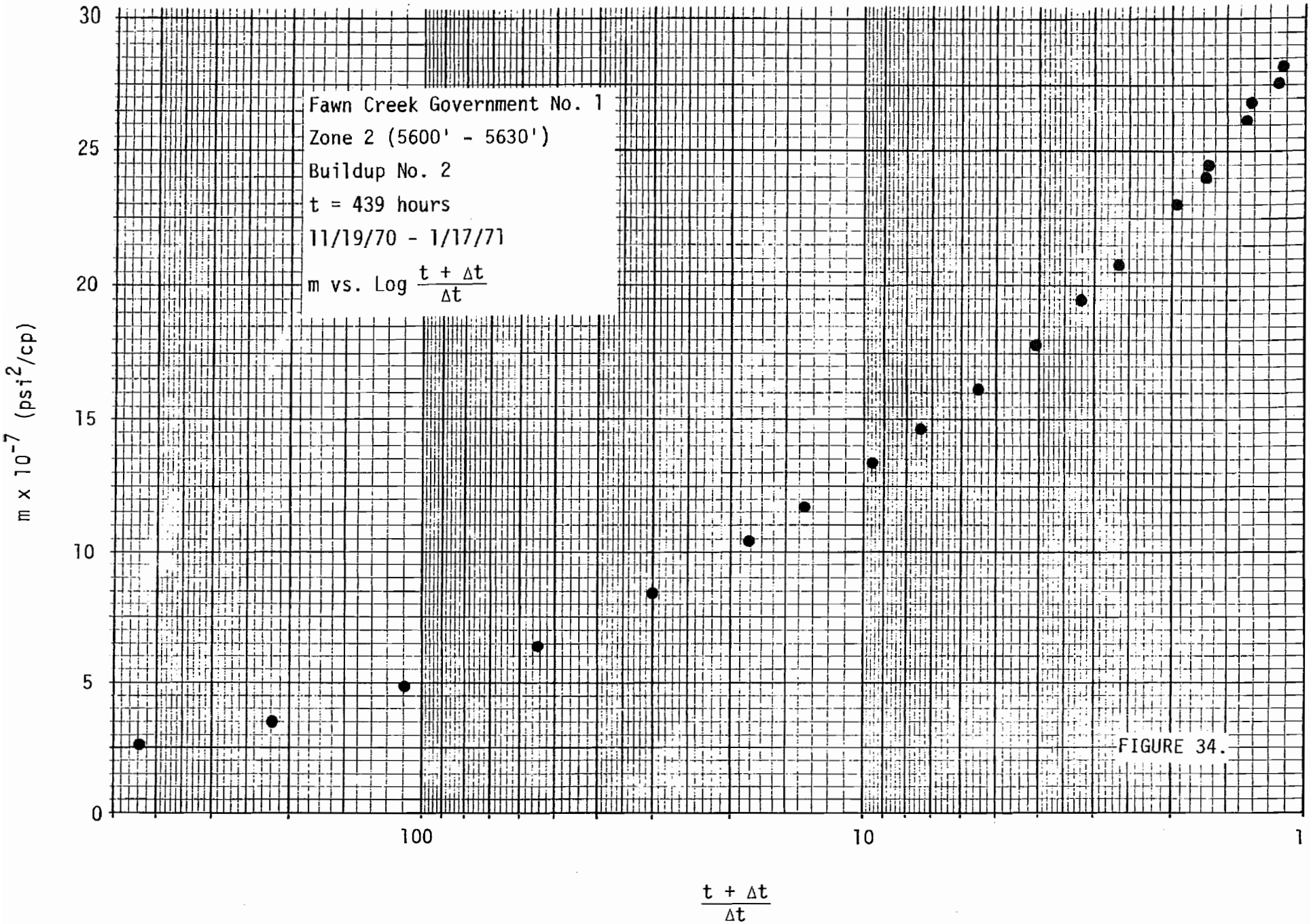

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 2
t = 439 hours
11/19/70 - 1/17/71
m vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} (psi^2/cp)
30
25
20
15
10
5
0
100
10
1
$\frac{t + \Delta t}{\Delta t}$

FIGURE 34.

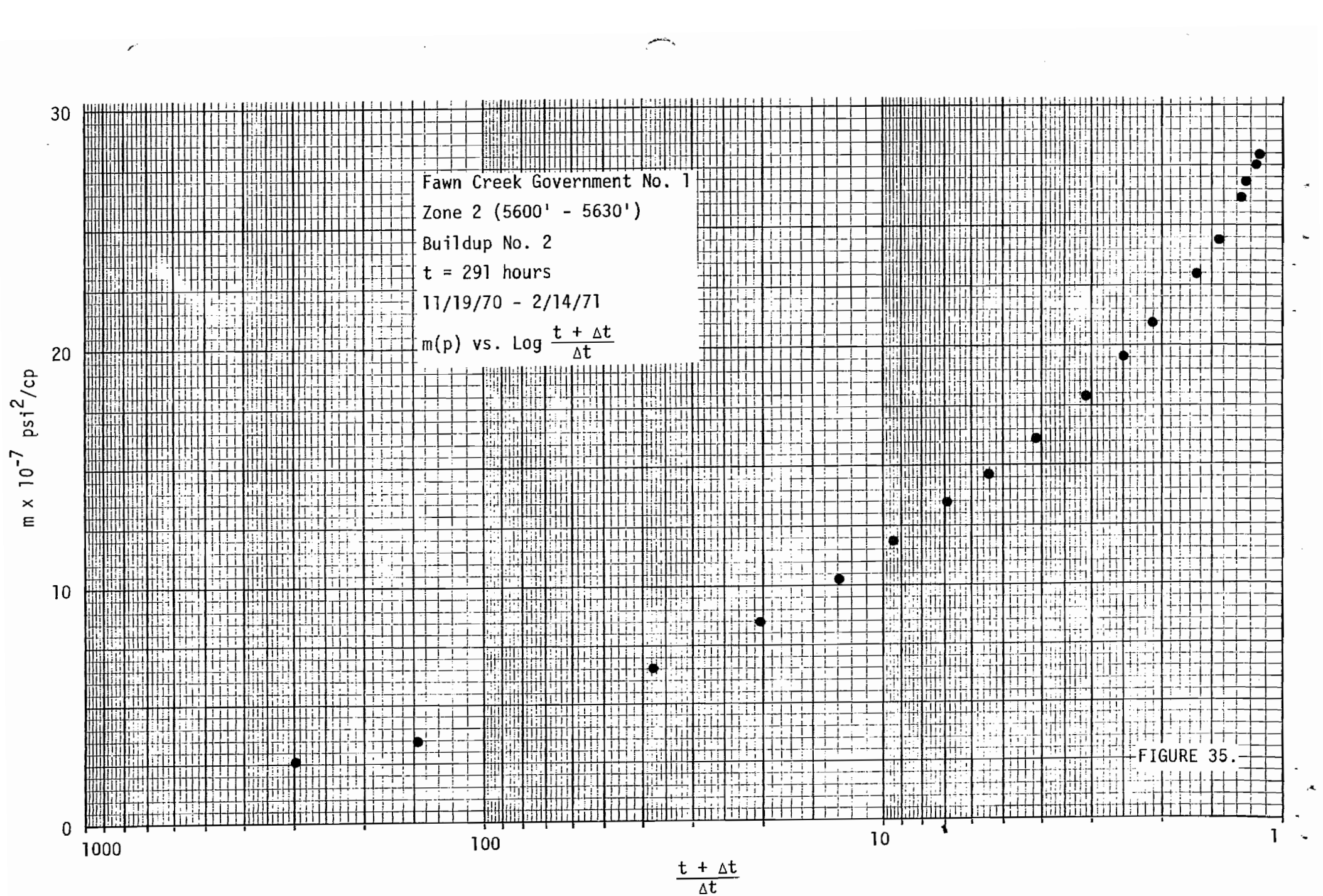

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 2
t = 291 hours
11/19/70 - 2/14/71
m(p) vs. Log (t + Δt)/Δt
m x 10^-7 psi^2/cp
30
20
10
0
1000
100
10
1
(t + Δt)/Δt

FIGURE 35.

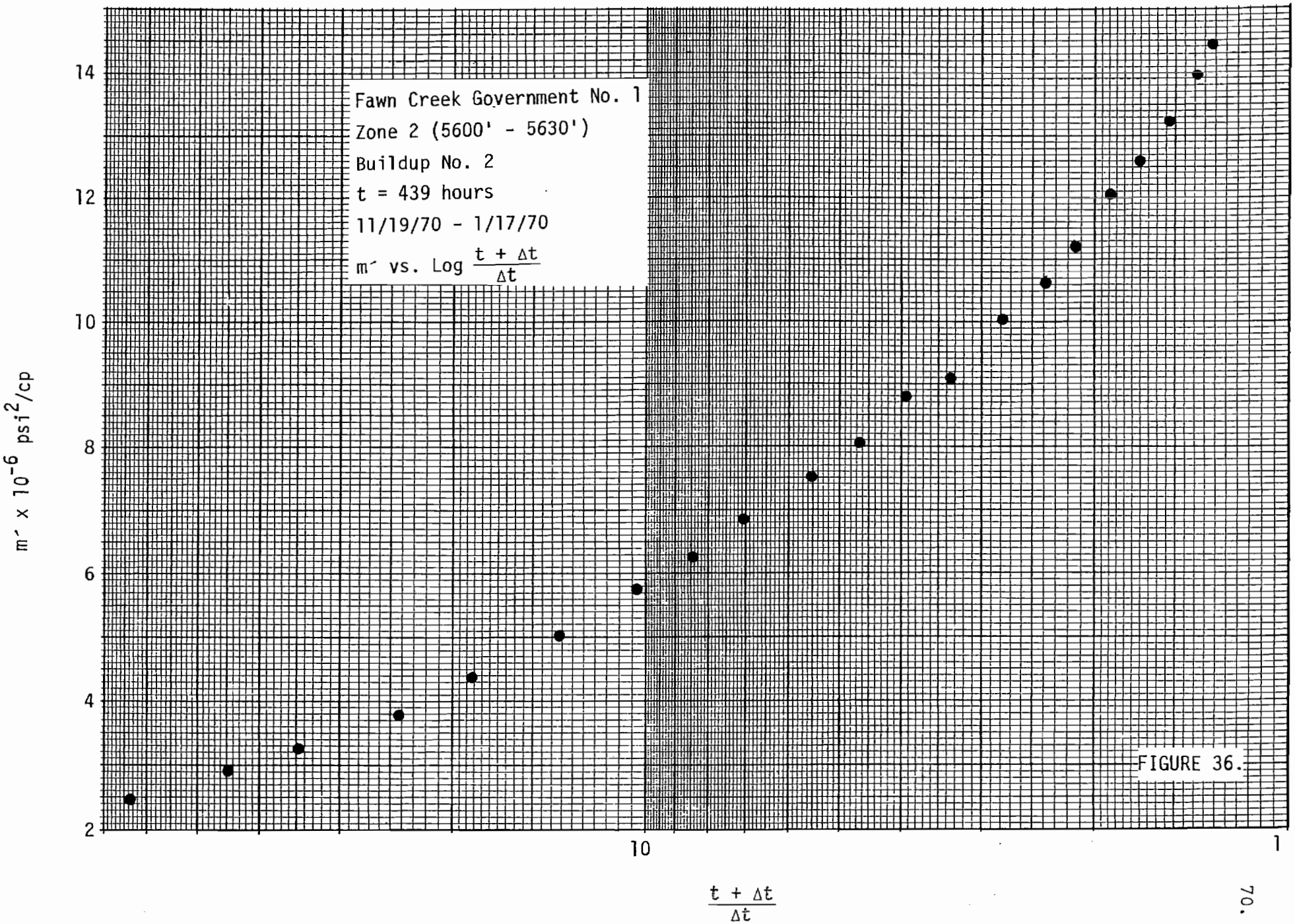

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 2
t = 439 hours
11/19/70 - 1/17/70
m´ vs. Log (t + Δt)/Δt
m´ x 10^-6 psi^2/cp
14
12
10
8
6
4
2
10
1
(t + Δt)/Δt

FIGURE 36.

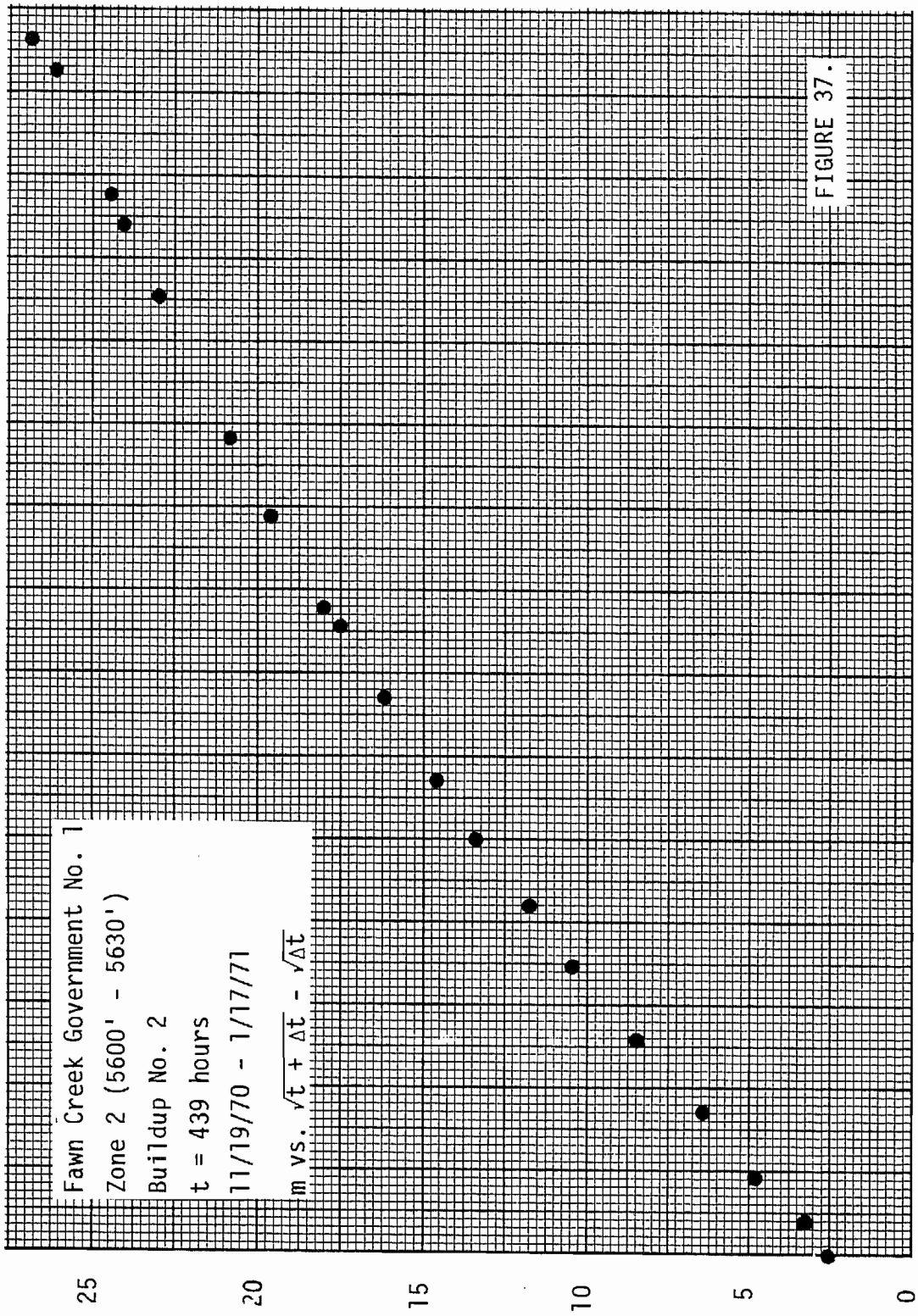

Fawn Creek Government No. 1
Zone 2 (5600' - 5630')
Buildup No. 2
t = 439 hours
11/19/70 - 1/17/71
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$
0
5
10
15
20
25
6
8
10
12
14
16
18
20

FIGURE 37.

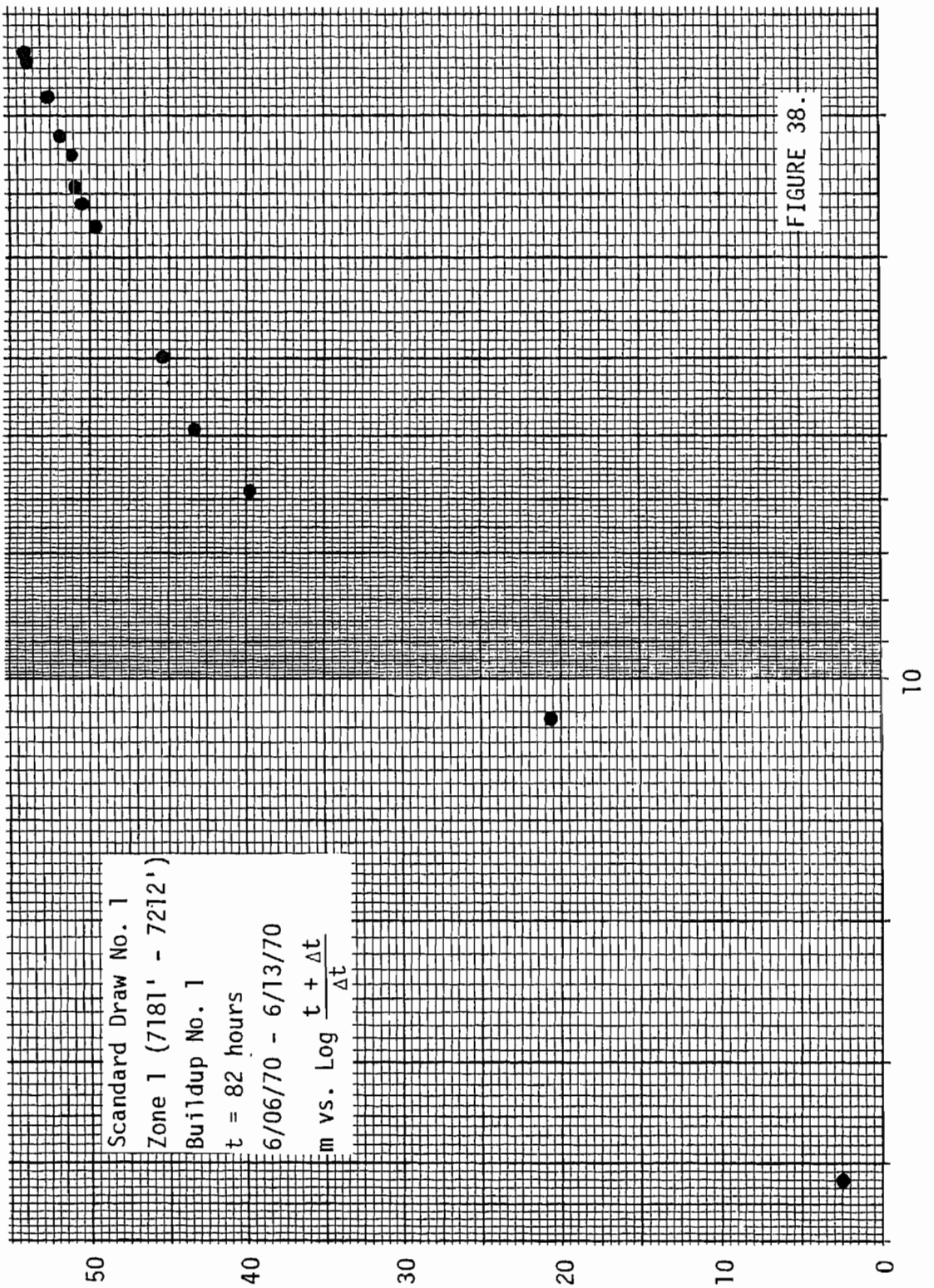

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 1
t = 82 hours
6/06/70 - 6/13/70
m vs. Log $\frac{t + \Delta t}{\Delta t}$
50
40
30
20
10
0
10
$m \times 10^{-7}$ (psi^2/cp)
$\frac{t + \Delta t}{\Delta t}$

FIGURE 38.

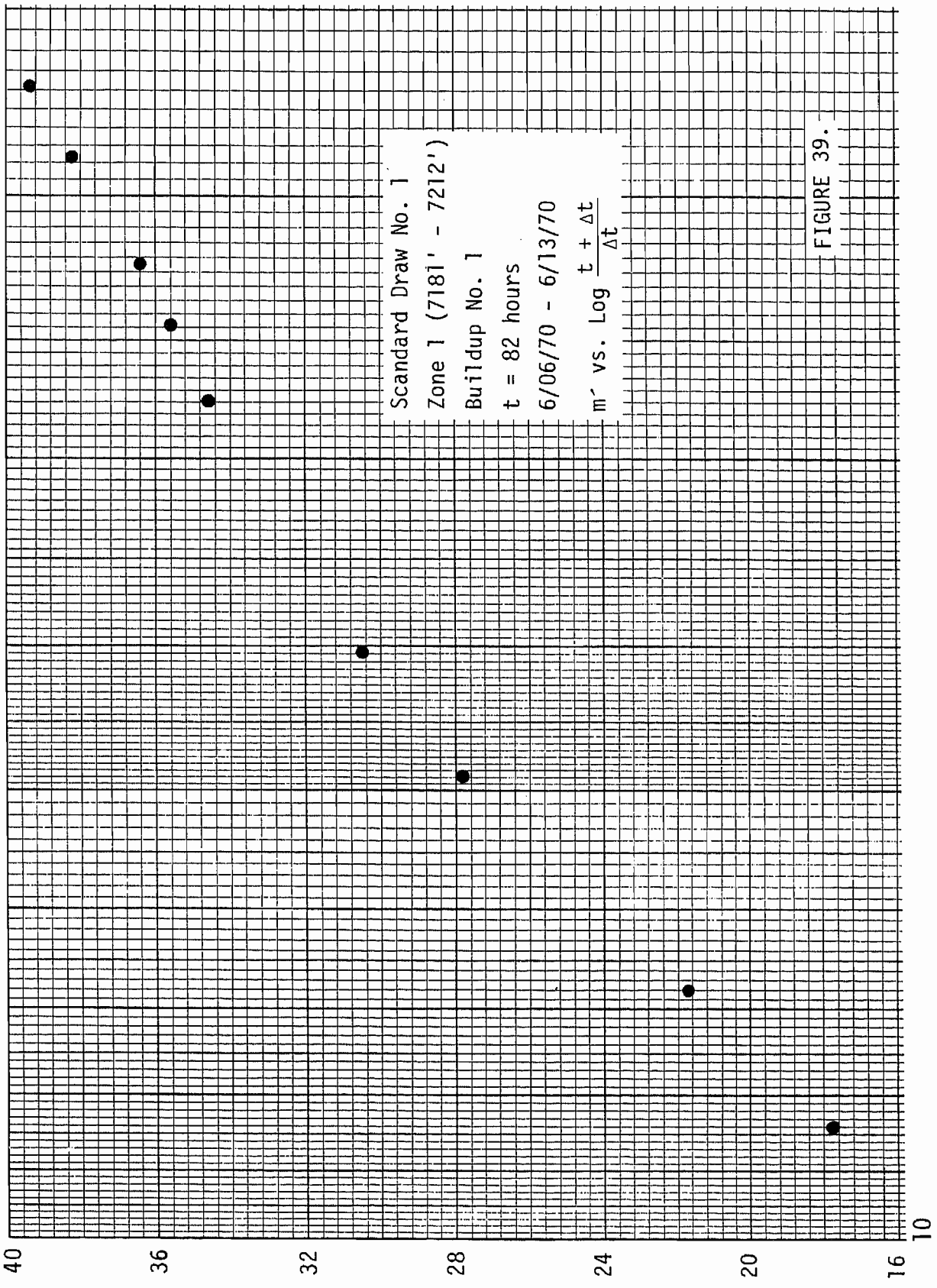

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 1
t = 82 hours
6/06/70 - 6/13/70
m' vs. Log $\frac{t + \Delta t}{\Delta t}$
m' x 10^{-6} (psi²/cp)
40
36
32
28
24
20
16
10
$\frac{t + \Delta t}{\Delta t}$

FIGURE 39.

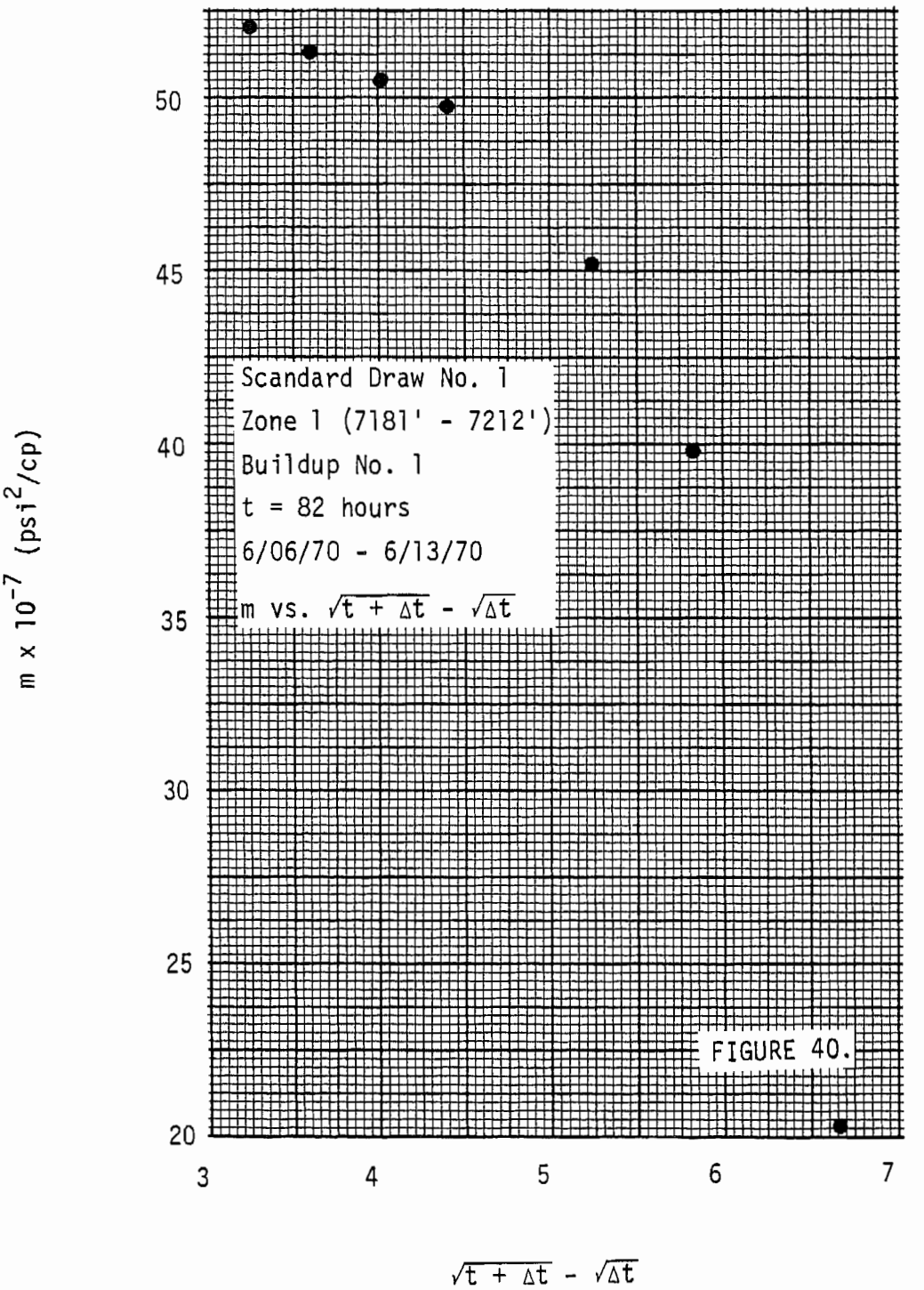

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 1
t = 82 hours
6/06/70 - 6/13/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
50
45
40
35
30
25
20
3
4
5
6
7
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$

FIGURE 40.

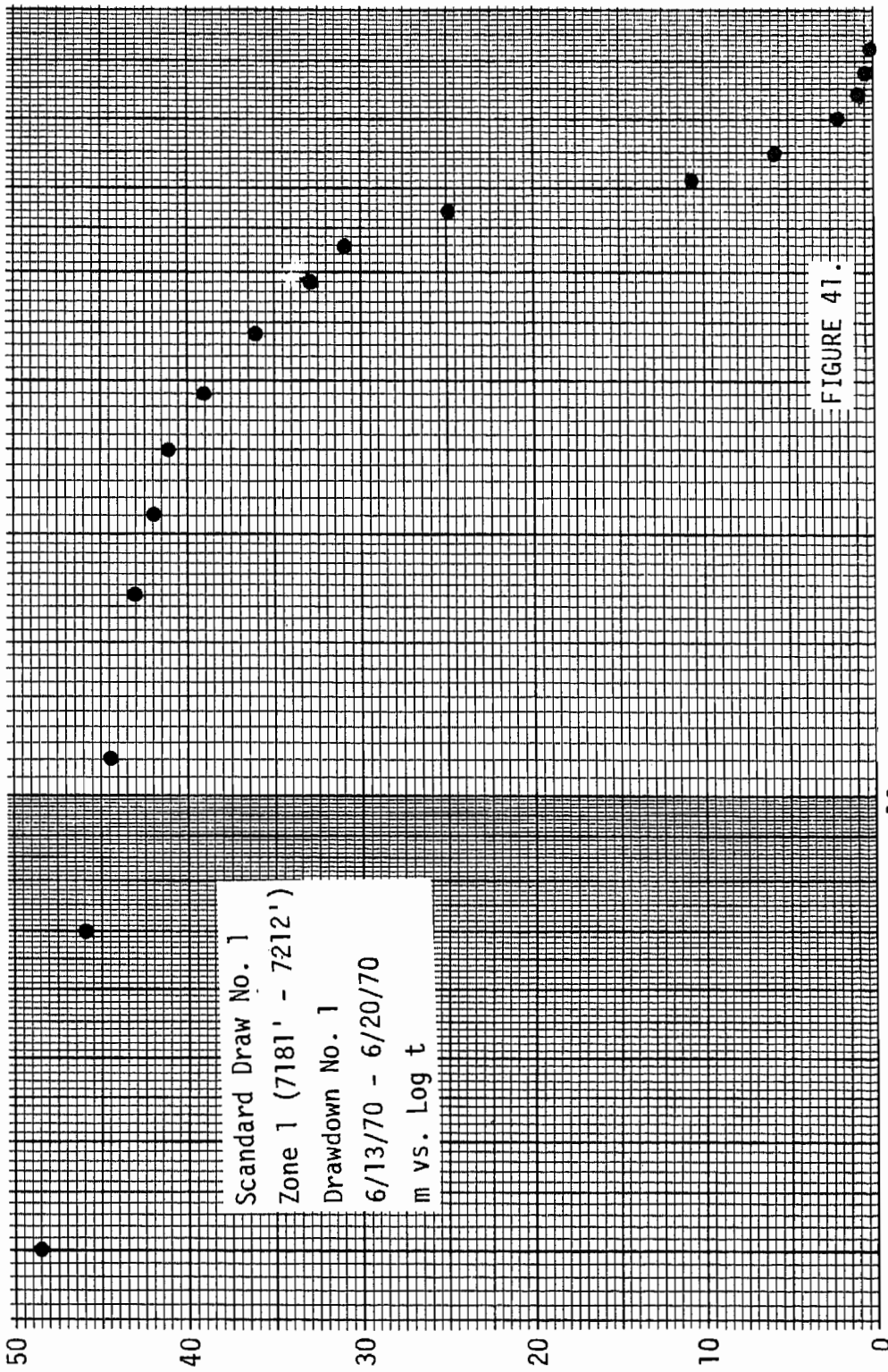

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Drawdown No. 1
6/13/70 - 6/20/70
m vs. Log t
m x 10-7 (psi2/cp)
50
40
30
20
10
0
10
t(hours)

FIGURE 41.

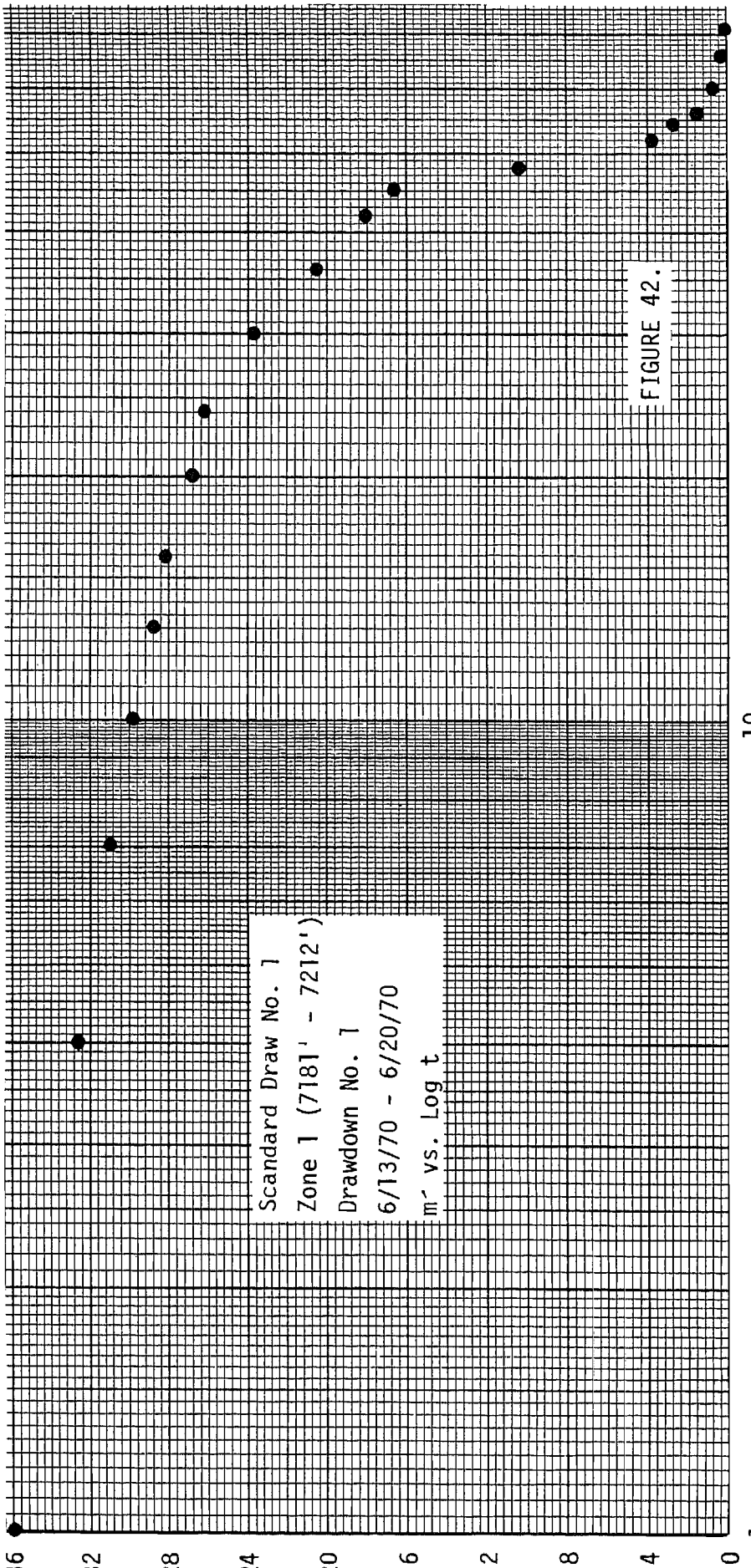

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Drawdown No. 1
6/13/70 - 6/20/70
m' vs. Log t
m' x 10⁻⁶ (psi²/cp)
36
32
28
24
20
16
12
8
4
0
1
10
t(hours)

FIGURE 42.

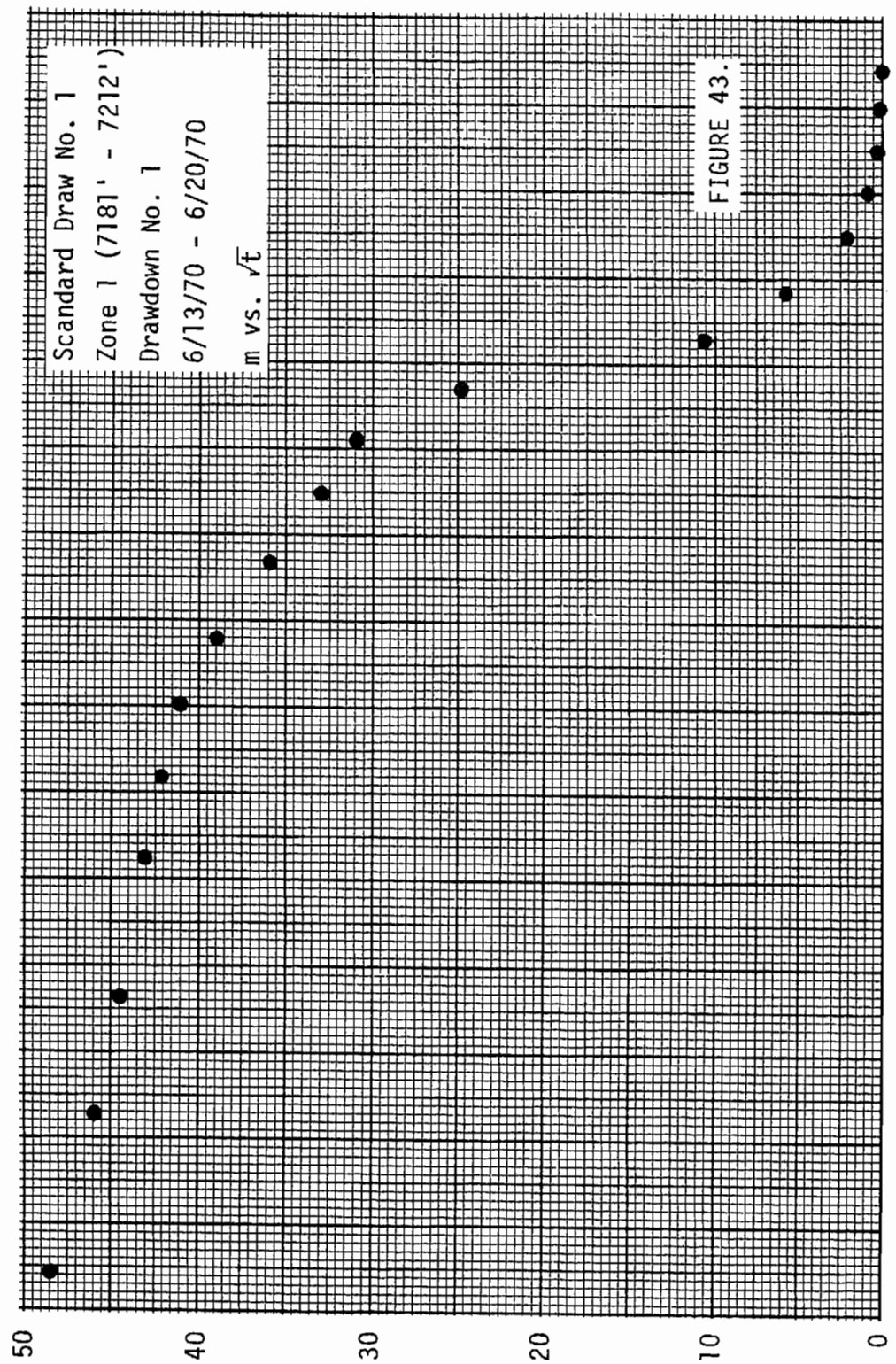

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Drawdown No. 1
6/13/70 - 6/20/70
m vs. $\sqrt{t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t}$
0
10
20
30
40
50
2
3
4
5
6
7
8
9

FIGURE 43.

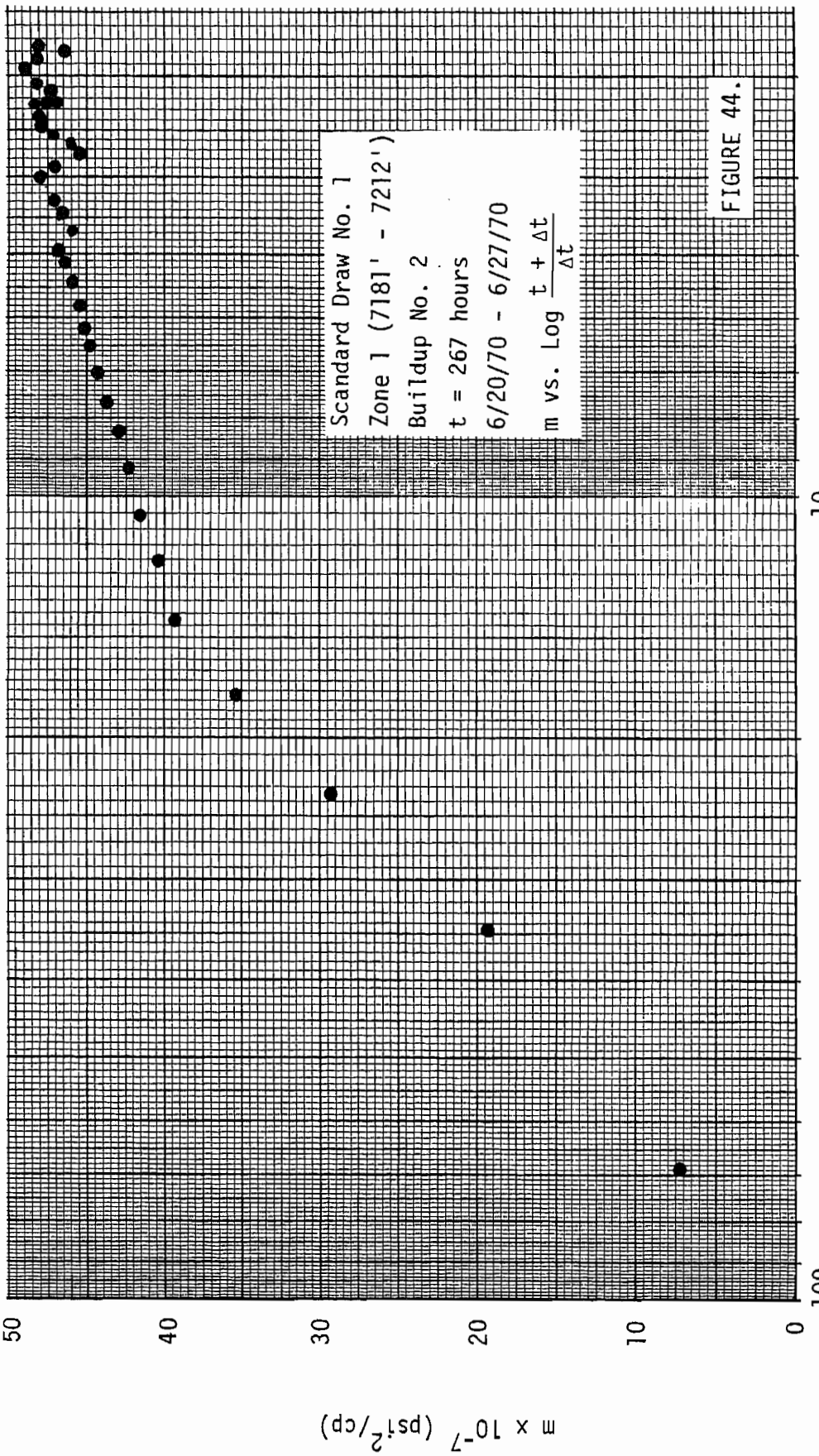

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 2
t = 267 hours
6/20/70 - 6/27/70
m vs. Log (t + Δt)/Δt
m x 10⁻⁷ (psi²/cp)
50
40
30
20
10
0
10
100
(t + Δt)/Δt

FIGURE 44.

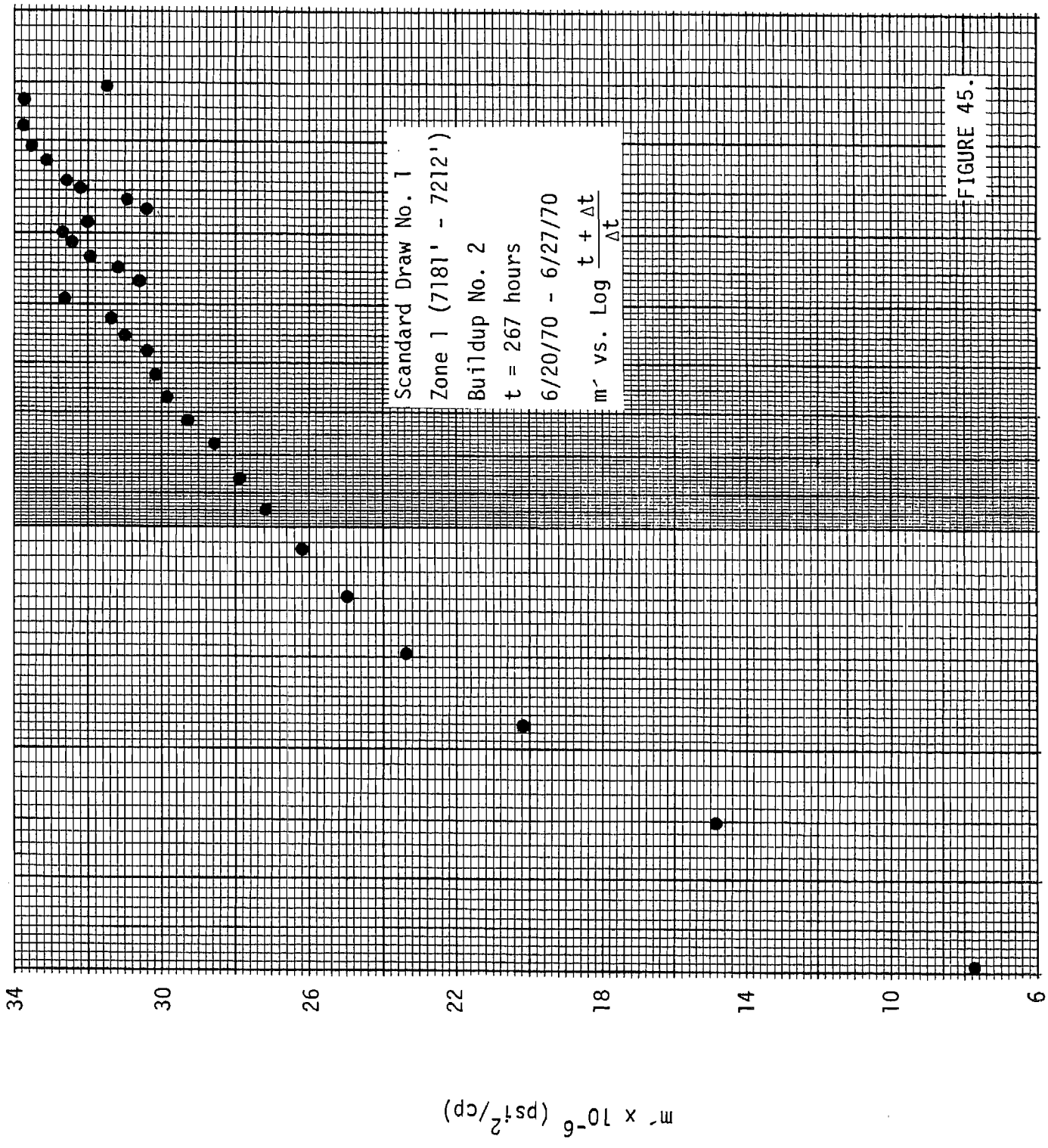

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 2
t = 267 hours
6/20/70 - 6/27/70
m' vs. Log $\frac{t + \Delta t}{\Delta t}$
34
30
26
22
18
14
10
6
10
$m' \times 10^{-6}$ (psi^2/cp)
$\frac{t + \Delta t}{\Delta t}$

FIGURE 45.

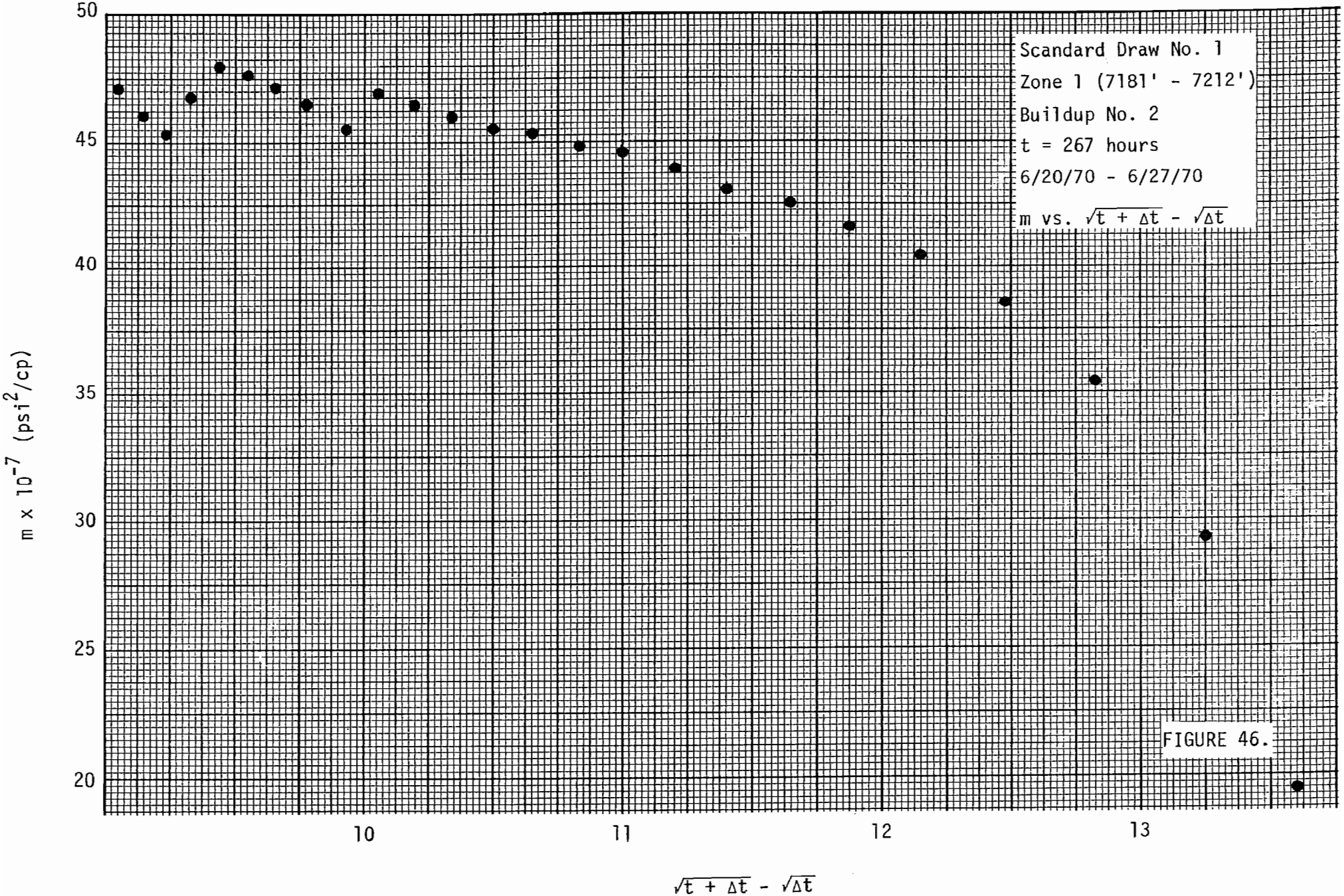

Scandard Draw No. 1
Zone 1 (7181' - 7212')
Buildup No. 2
t = 267 hours
6/20/70 - 6/27/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
50
45
40
35
30
25
20
10
11
12
13
m x 10^{-7} (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$

FIGURE 46.

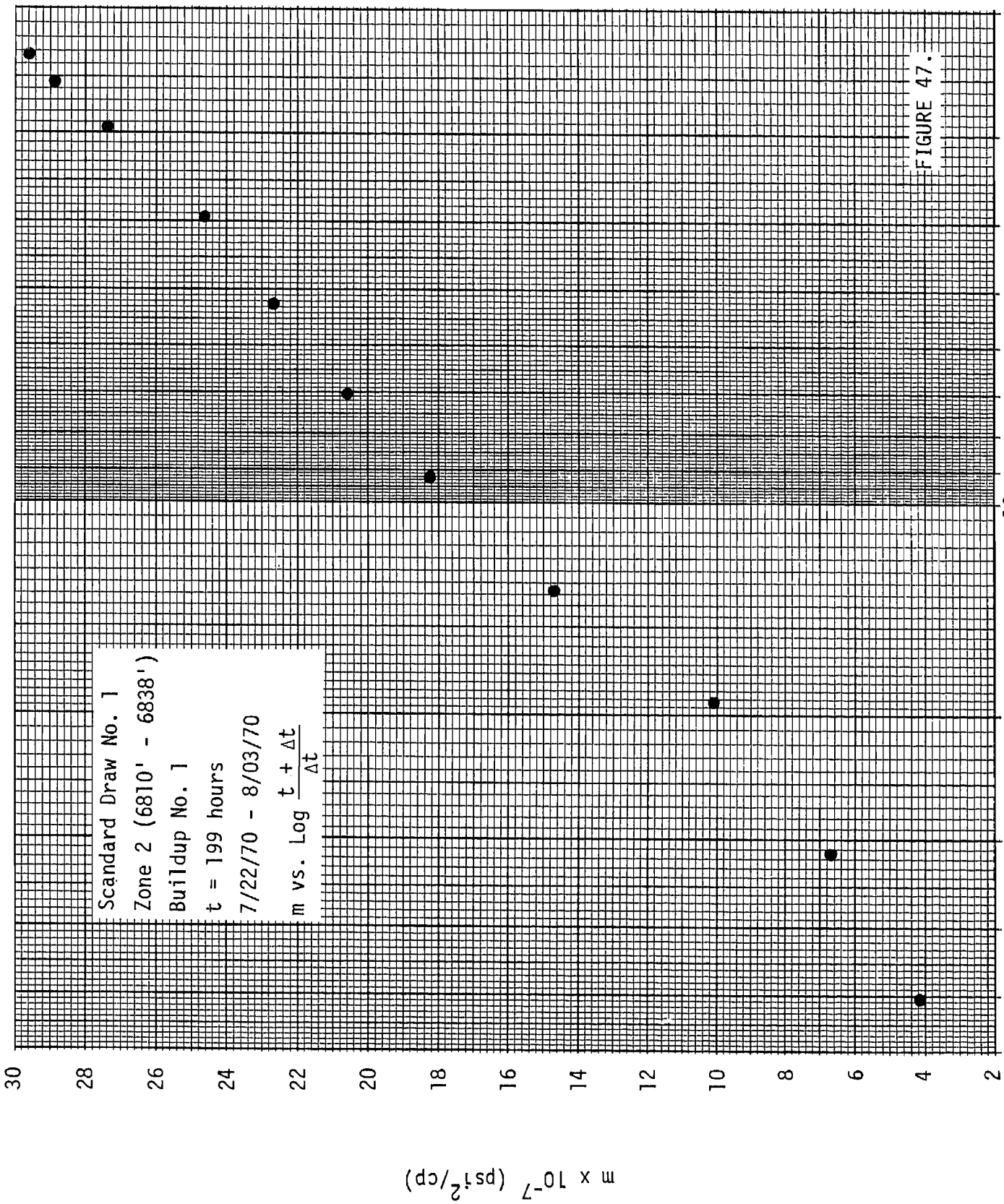

Scandard Draw No. 1
Zone 2 (6810' - 6838')
Buildup No. 1
t = 199 hours
7/22/70 - 8/03/70
m vs. Log $\frac{t + \Delta t}{\Delta t}$
m x 10^{-7} (psi²/cp)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
10
$\frac{t + \Delta t}{\Delta t}$

FIGURE 47.

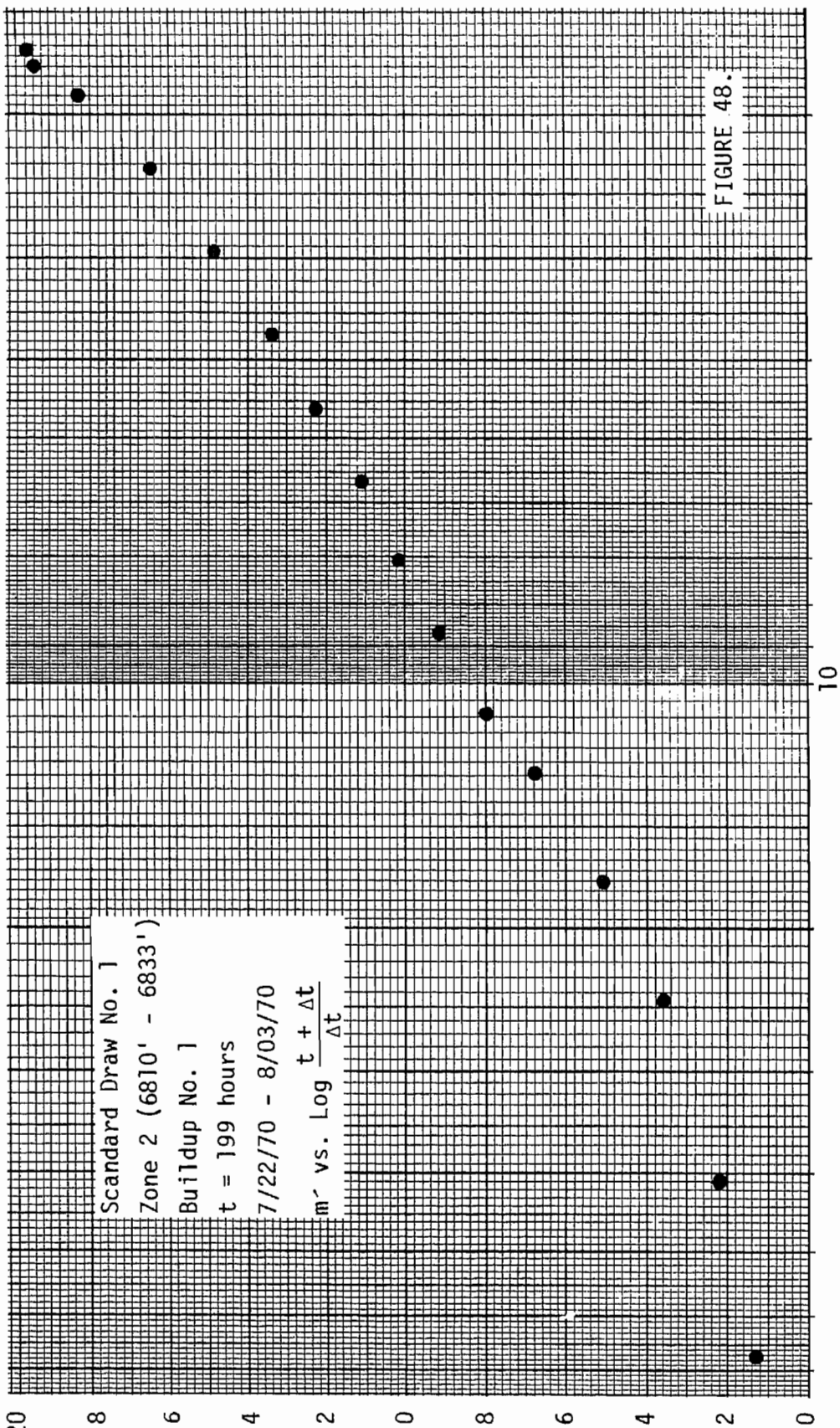

Scandard Draw No. 1
Zone 2 (6810' - 6833')
Buildup No. 1
t = 199 hours
7/22/70 - 8/03/70
m' vs. Log $\frac{t + \Delta t}{\Delta t}$
m' x 10^{-6} (psi²/cp)
0
2
4
6
8
10
12
14
16
18
20
10
$\frac{t + \Delta t}{\Delta t}$

FIGURE 48.

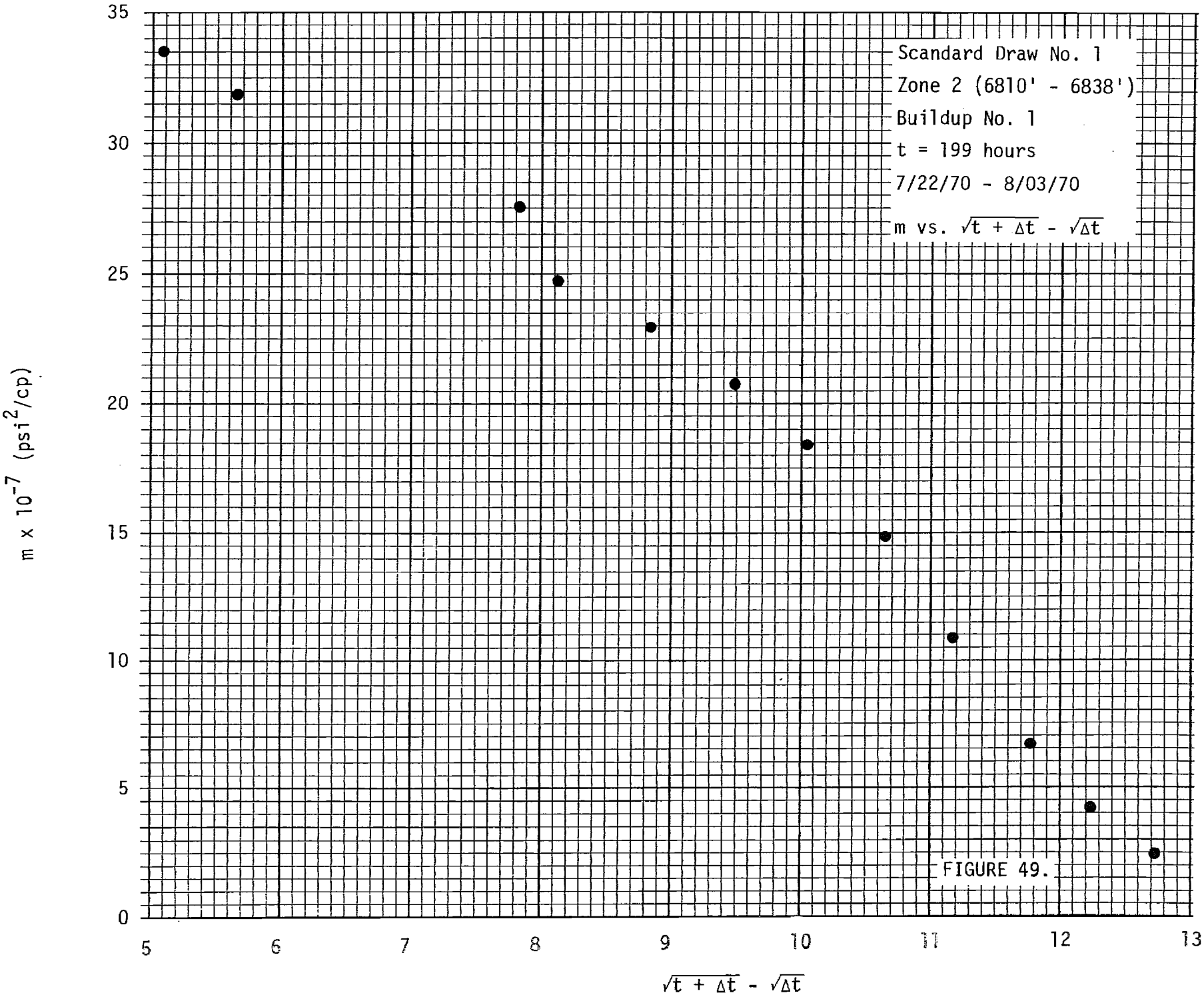

Scandard Draw No. 1
Zone 2 (6810' - 6838')
Buildup No. 1
t = 199 hours
7/22/70 - 8/03/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
$m \times 10^{-7}$ (psi^2/cp)
35
30
25
20
15
10
5
0
5
6
7
8
9
10
11
12
13
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$

FIGURE 49.

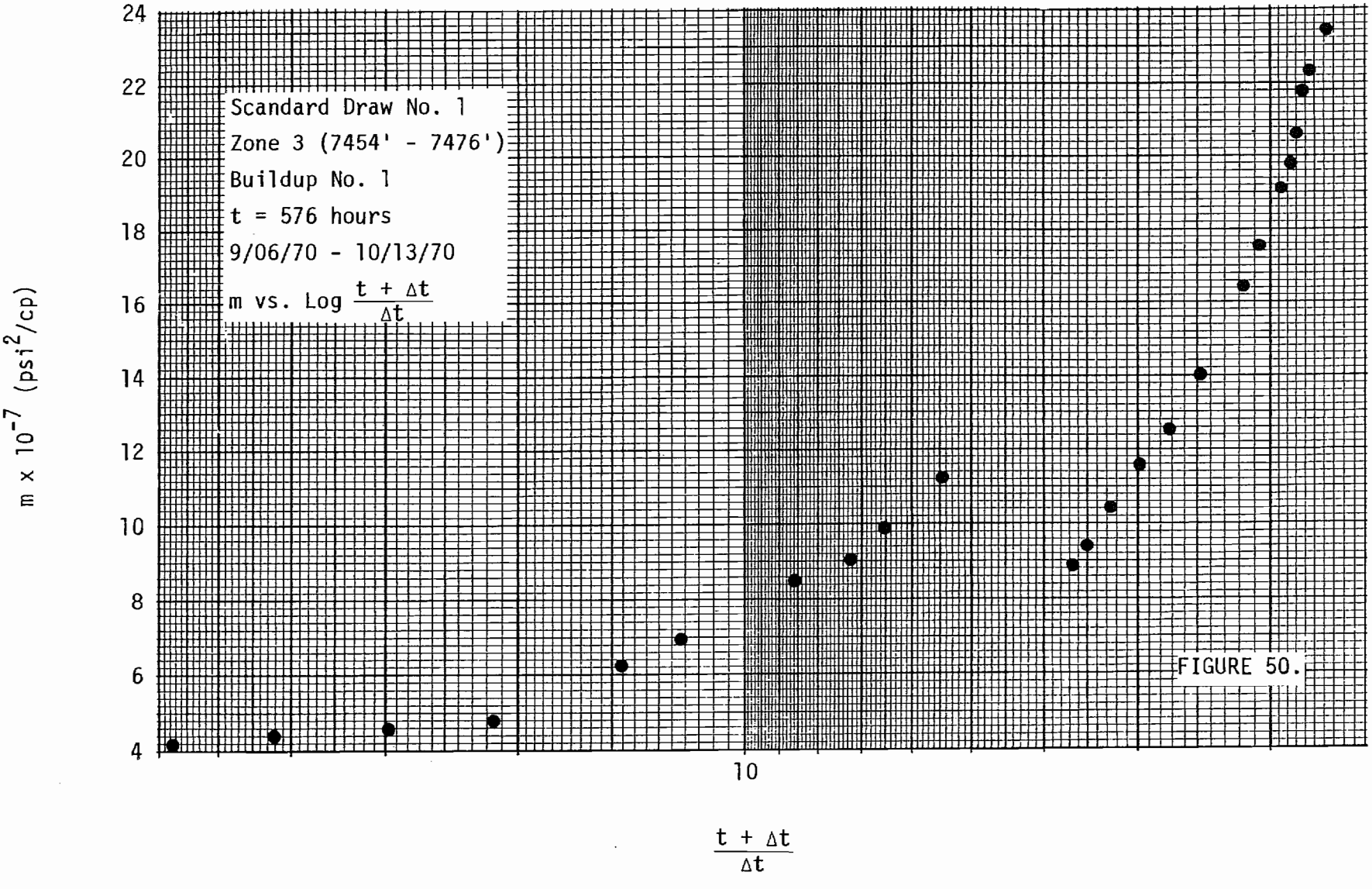

Scandard Draw No. 1
Zone 3 (7454' - 7476')
Buildup No. 1
t = 576 hours
9/06/70 - 10/13/70
m vs. Log (t + Δt)/Δt
m x 10^-7 (psi^2/cp)
24
22
20
18
16
14
12
10
8
6
4
10
(t + Δt)/Δt

FIGURE 50.

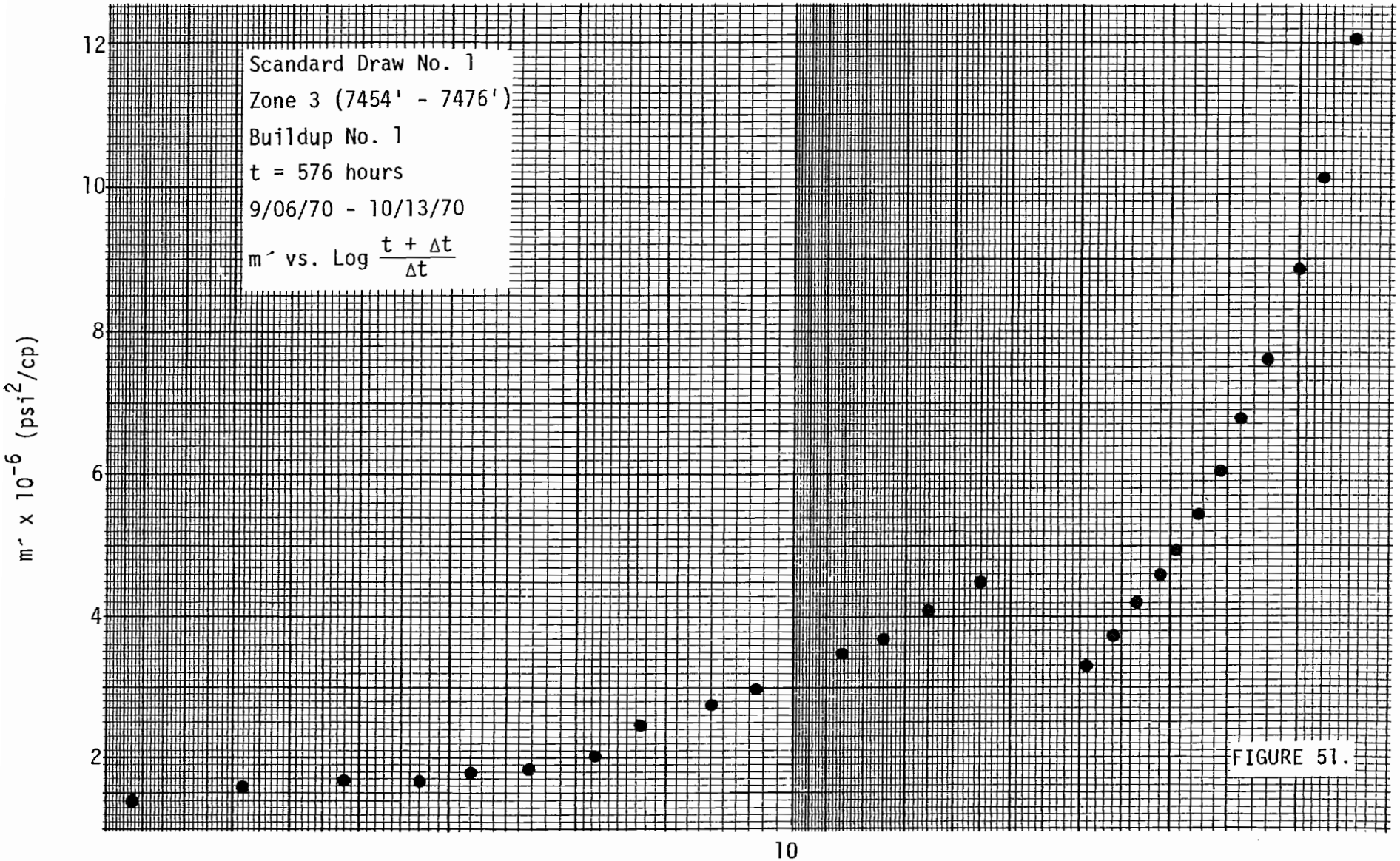

Scandard Draw No. 1
Zone 3 (7454' - 7476')
Buildup No. 1
t = 576 hours
9/06/70 - 10/13/70
m´ vs. Log (t + Δt)/Δt
m´ x 10^-6 (psi^2/cp)
12
10
8
6
4
2
10
(t + Δt)/Δt

FIGURE 51.

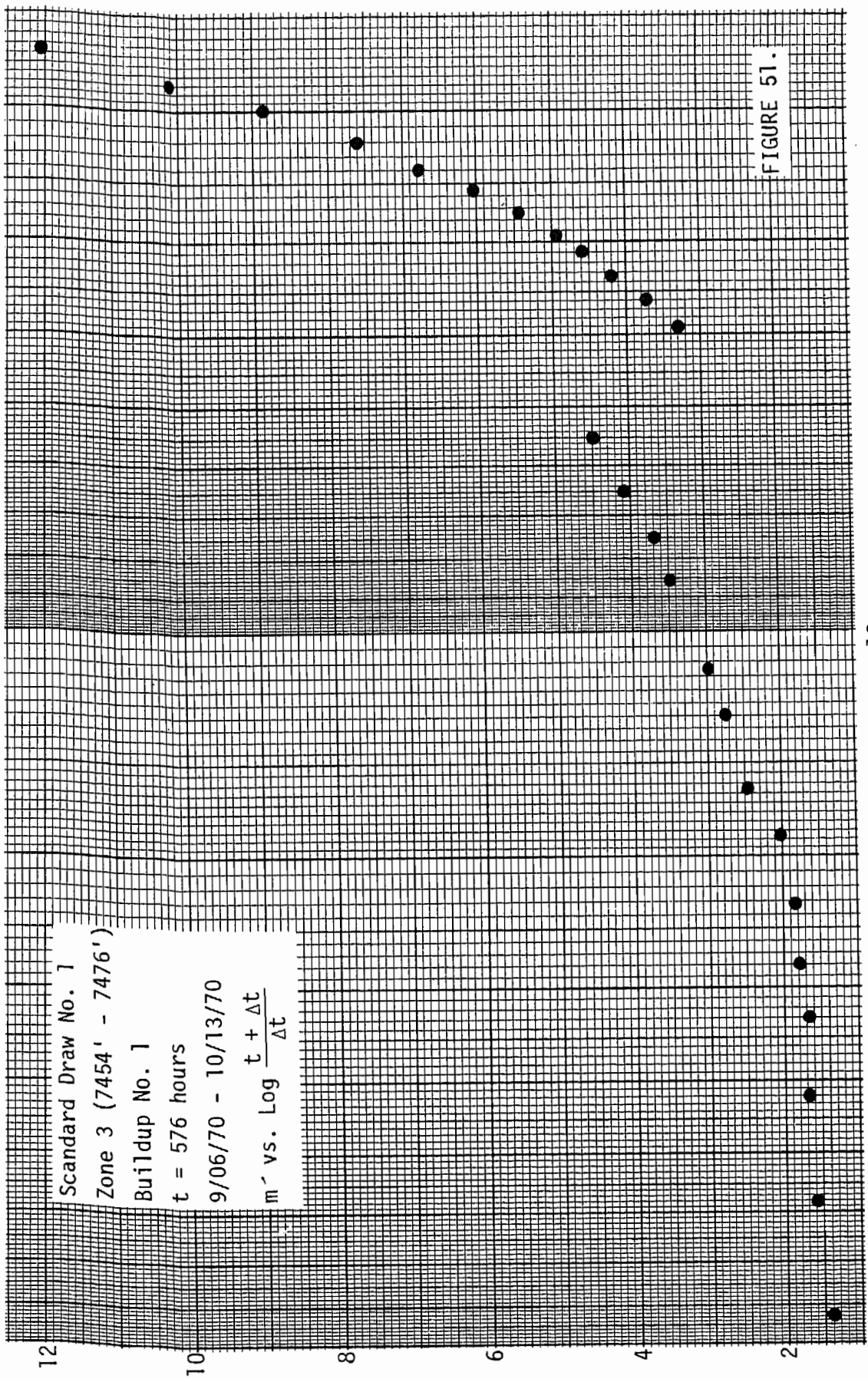

Scandard Draw No. 1
Zone 3 (7454' - 7476')
Buildup No. 1
t = 576 hours
9/06/70 - 10/13/70
m' vs. Log $\frac{t + \Delta t}{\Delta t}$
12
10
8
6
4
2
10
$\frac{t + \Delta t}{\Delta t}$
m' x 10^{-6} (psi^2/cp)

FIGURE 51.

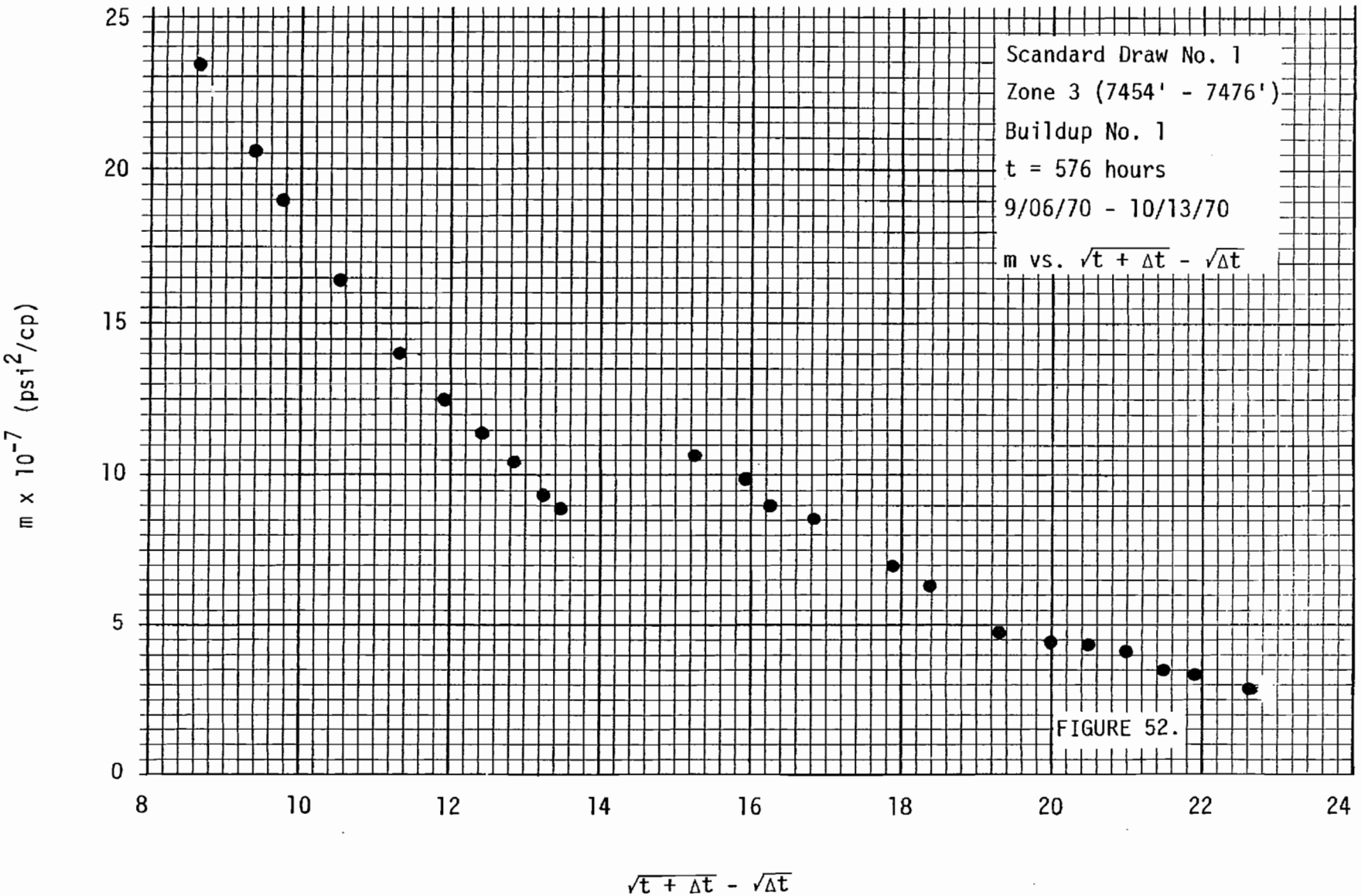

Scandard Draw No. 1
Zone 3 (7454' - 7476')
Buildup No. 1
t = 576 hours
9/06/70 - 10/13/70
m vs. $\sqrt{t + \Delta t} - \sqrt{\Delta t}$
m x 10^{-7} (psi^2/cp)
$\sqrt{t + \Delta t} - \sqrt{\Delta t}$
0
5
10
15
20
25
8
10
12
14
16
18
20
22
24

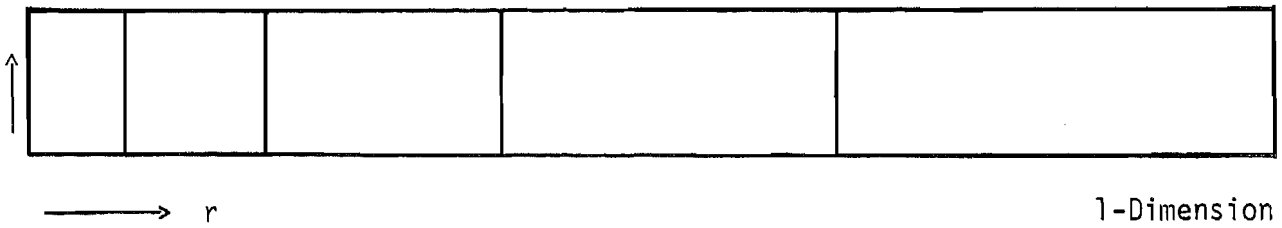
FIGURE 52.

APPENDIX C

DESCRIPTION OF RESERVOIR MODEL

APPENDIX C

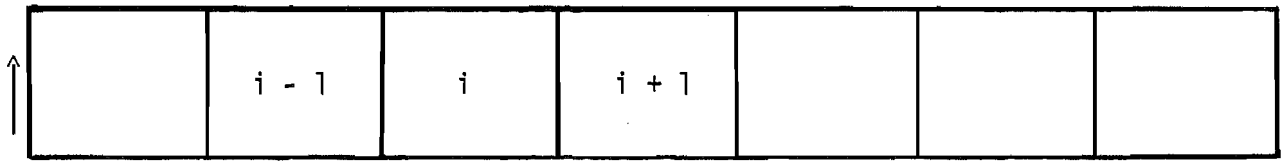
DESCRIPTION OF RESERVOIR MODEL



r

1-Dimension

Radial transformation using shape factors, which allow the system to be evaluated as a linear system



X

1-Dimension

Partial differential equation for a linear system using real gas potential, m or m´, can be written as follows:

$$\frac{\partial k \frac{\partial m}{\partial x}}{\partial x} - q_g = \phi c \frac{\partial m}{\partial t}$$

$$\phi_i^{n+1} = \phi_{i\ orig}\left[1 + c_{i\ rock}\left(p_i^{n+1} - p_{i\ orig}\right)\right]$$

$$m = 2 \int \frac{p}{\mu z}\, dp$$

or

$$m' = 2 \int \frac{p k_r}{\mu z}\, dp$$

In finite difference form, using implicit technique:

$$\frac{m_{i-1}^{n+1} - 2\,m_i^{n+1} + m_{i+1}^{n+1}}{\Delta x_i^{\,2}} = \frac{\phi_i^{n+1}\, c_i^{n+1}}{k_i} \frac{\left(m_i^{n+1} - m_i^{n}\right)}{\Delta t}$$

where

n = time step

i = cell block designation

m = real gas potential, psi^2/cp

m' = real gas potential including pressure dependent permeability, psi^2/cp

z = deviation factor, fractional

μ = gas viscosity, cp

k_r = permeability, fractional

c_{rock} = rock compressibility, psi^{-1}

ϕ = porosity, fractional

ϕ_{orig} = original porosity, fractional

q_g = flow

c = total compressibility, psi^{-1}

p = reservoir pressure, psi