Generic In situ Copper Mine Design Manual
Volume 5. Field Testing at the Santa Cruz Site

Science Applications International Corp.
McLean, VA

Prepared for

Bureau of Mines, Minneapolis, MN

30 Apr 88

Preceding page blank

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO. OFR 4(5)89

2.

3. PB89-153308

4. Title and Subtitle

Generic In Situ Copper Mine Design Manual - Volume V, Field Testing at the Santa Cruz Site

5. Report Date

April 30, 1988

6.

7. Author(s) Donald H. Davidson, Ray V. Huff (RVH), Ralph E. Weeks (SHB), and John F. Edwards (DMC).

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Science Applications International Corporation
8400 Westpark Drive
McLean, VA 22102

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C) J0267001

(G)

12. Sponsoring Organization Name and Address

Mining Technology
U.S. Bureau of Mines
Twin Cities Research Center
65629 Minnehaha Ave. South, Minneapolis, Minnesota 55417

13. Type of Report & Period Covered

9/30/86-4/30/88

14.

15. Supplementary Notes

Prepared in cooperation with: Ray V. Huff and Associates, Inc., (RHA), Golden, CO; Davy McKee Corporation (DMC), San Ramon, California; and Sergent, Hauskins & Beckwith (SHB), Phoenix, Arizona.

16. Abstract (Limit: 200 words)

This report describes the field tests conducted at the Santa Cruz Joint Venture Site (jointly owned by ASARCO Santa Cruz Incorporated and Freeport Copper Company) in Casa Grande, Arizona. These tests were carried out in existing core holes SC-46 and SC-19 and include: coring, water injection permeability measurements; geophysical wireline logging measurements of initial water saturation, porosity, and flow profile; and laboratory core leaching. The purpose of these tests is to provide supporting data for the commercial scale operation and experiment designs. Coring and testing in SC-46 was conducted over the interval 1,436 feet to 1,685 feet, and in SC-19 1,249 feet to 1,461 feet. Field test results indicate the following average properties: 1 md in SC-46 and 4 md in SC-19 with mud damage in the test interval, and 20 to 30 md in SC-19 where the test interval did not have mud damge; 8% porosity in SC-46 and 9% in SC-19; 100% water saturation in SC-46 and in SC-19. Preliminary laboratory core leaching data indicate that a 50 gpl sulfuric acid strength that 10 gpl copper loadings are achieved at a net acid consumption of less than 3½ lb acid per lb copper. These data are within the range of input parameters used to calculate the economics for the best mining scenario for the commercial design in Volume IV.

17. Document Analysis a. Descriptors

In situ leaching, copper mining, field test, coring, logging, permeability testing, core leaching

b. Identifiers/Open-Ended Terms

True In Situ Copper Mining

c. COSATI Field/Group

18. Availability Statement

Release Unlimited

19. Security Class (This Report)

Unclassified

20. Security Class (This Page)

Unclassified

21. No. of Pages

115

22. Price

PC

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

This report was prepared by Science Applications International Corporation, Environmental Technology Group, McLean, Virginia, under USBM Contract number J0267001. The contract was initiated under the Mining Technology Program. It was administered under the technical direction of Twin Cities Research Center with Mr. Jon K. Ahlness acting as Technical Project Officer. Mr. David J. Askin was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period 3/1/87 to 1/11/88. This report was submitted by the authors on 1/11/88.

Science Applications International Corporation was the prime Contractor for this work. Ray V. Huff and Associates, Inc., Davy McKee Corporation, and Sergent Hauskins, & Beckwith were subcontractors. Those who made direct input are:

Science Applications International Corporation
- Donald H. Davidson
- Hunter J. Loftin
- Alfred N. Wickline

Ray V. Huff and Associates, Inc.
- Ray V. Huff
- Steven G. Axen
- David R. Baughman

Davy McKee Corporation
- John F. Edwards

Sergent, Hauskins & Beckwith
- Ralph E. Weeks
- Paul V. Smith
- Lori C. Robison

Special appreciation is accorded to Mr. William Larson, Mr. Daniel Millenacker, Mr. Sterling Cook, Ms. Linda Dahl, and Mr. Steve Paulson of the U.S. Bureau of Mines Twin Cities Research Center.

ABSTRACT

This report describes the field tests conducted at the Santa Cruz Joint Venture Site (jointly owned [50/50] by ASARCO Santa Cruz Incorporated and Freeport Copper Company) in Casa Grande, Arizona. These tests were carried out in existing core holes SC-46 and SC-19 and include: coring; water injection permeability measurements; geophysical wireline logging measurements of initial water saturation, porosity, and flow profile; and laboratory core leaching. The purpose of these tests is to provide supporting data for the commercial scale operation and field experiment designs. Coring and testing in SC-46 were conducted over the interval 1,426 feet to 1,685 feet, and in SC-19 1,249 feet to 1,461 feet. Field test results indicate the following average properties: Permeability of 1 md in SC-46 and 4 md in SC-19 both with mud damage in the test interval, and 20 to 30 md in SC-19 where the test interval did not have mud damage; 8% porosity in SC-46 and 9% in SC-19; 100% water saturation in SC-46 and SC-19. Preliminary laboratory core leaching data indicate that at 50 gpl sulfuric acid strength that 10 gpl copper loadings are achieved at a net acid consumption of less than 3 1/2 lb acid per lb copper. These field test results are within the range of input parameters used to determine the economics of the best mining scenario for the commercial design described in Volume VI.

TABLE OF CONTENTS

	Page
FOREWORD	4
ABSTRACT	5
CHAPTER 1. EXECUTIVE SUMMARY	12
1.1 OBJECTIVE	12
1.2 RESULTS AND CONCLUSIONS	12
1.3 RECOMMENDATIONS	13
CHAPTER 2. DESCRIPTION OF FIELD TEST ACTIVITIES	15
2.1 GENERAL APPROACH	15
2.2 SELECTING TEST HOLE LOCATIONS	15
2.3 ACQUISITION OF CASING DIMENSIONS	17
2.4 TEST PLAN AND SPECIFICATIONS	20
2.4.1 Test Activity Plan	20
2.4.2 Purchased Equipment	20
2.4.3 Drilling Contractor Requirements	29
2.4.4 Logging Contractor Requirements	35
CHAPTER 3. FIELD TEST OPERATIONS	37
3.1 SUMMARY OF TEST OPERATIONS SCHEDULE	37
3.1.1 Hole SC-46	37
3.1.2 Hole SC-19	38
3.2 HOLE INSPECTION AND REPAIR	41
3.2.1 Hole SC-46	41
3.2.2 Hole SC-19	41
3.3 HOLE RE-ENTRY	41
3.3.1 Hole SC-46	41
3.3.2 Hole SC-19	41
3.4 PLUGGING AND WEDGING	42
3.4.1 Hole SC-46	42
3.4.2 Hole SC-19	42
3.5 CORING	43
3.5.1 Hole SC-46	43
3.5.2 Hole SC-19	43

TABLE OF CONTENTS
(Continued)

Page

3.6 LOGGING. 43

3.6.1 Hole SC-46. 43
3.6.2 Hole SC-19. 44

3.7 PRESSURE TRANSIENT TESTING 44

3.7.1 General Discussion. 44
3.7.2 Hole SC-46. 50
3.7.3 Hole SC-19. 51

3.8 FLOW PROFILING 53

3.8.1 General Discussion. 53
3.8.2 Hole SC-46. 54
3.8.3 Hole SC-19. 54

3.9 WELL ABANDONMENT 55

3.9.1 Hole SC-46. 55
3.9.2 Hole SC-19. 55

CHAPTER 4. RESULTS AND CONCLUSIONS. 56

4.1 FLOW TESTS 56

4.1.1 Pressure Transient Testing. 56
4.1.2 Flow Profile. 62

4.2 CORING 62

4.2.1 SC-46 63
4.2.2 SC-19 63

4.3 LOGGING. 64

4.3.1 Porosity. 64
4.3.2 Initial Water Saturation. 65
4.3.3 Hole Diameter 65
4.3.4 Flow Profile. 65

4.4 ASSESSMENT OF EQUIPMENT REQUIREMENTS 65

TABLE OF CONTENTS
(Continued)

CHAPTER 5. LABORATORY CORE LEACHING TESTS 67

5.1 TEST PLAN. 67

5.2 CORE LEACHING TESTING. 68

5.3 RESULTS AND CONCLUSIONS. 69

APPENDIX A - ANALYSIS OF PRESSURE TRANSIENT DATA 71

A.1 TEST PROCEDURE 71

A.2 METHOD OF DATA ANALYSIS. 71

A.2.1 Possible Flow Regimes 71
A.2.2 Data Plotting 72
A.2.3 Data Interpretation 74

LIST OF TABLES

Table		Page
2-1	Core Hole Data.	16
2-2	Test Hole Data Versus Commercial Ore Block.	18
2-3	Estimates of Time Required for Test on Santa Cruz Hole SC-46. .	21
2-4	Estimates of Time Required for Test on Santa Cruz Hole SC-19. .	24
2-5	Purchased Equipment Inventory	27
2-6	Items to be Included in Drilling Contractor Rig Inventory . . .	30
2-7	Crew Report	34
2-8	Wireline Logs to be Run and Equipment to be Provided by Contractor.	36
4-1	Flow Test Summary	57
4-2	Summary of Specific Injectivity Data SC-46 and SC-19.	58
4-3	Summary of Pressure Transient Analysis for Radial Flow Geometry	60
4-4	Summary of Pressure Transient Analysis for Spherical Flow Geometry.	61
5-1	Description of TCRC Core Samples and Tests.	69
A-1	Summary of Flow Regime Data Plots	114

LIST OF FIGURES

Figure		Page
3-1	Diagram for Piping and Meter Manifold for Water Injection Test.	45
3-2	Downhole Tubing String and Equipment.	47
3-3	Bottom Hole Shut-In Plug.	49
A-1	SC 46 Test 2, Build-Up, Radial.	75
A-2	SC 46 Test 2, Build-Up, Linear.	76
A-3	SC 46 Test 2, Build-Up, Spherical	77
A-4	SC 46 Test 2, Fall-Off, Log-Log	78
A-5	SC 46 Test 2, Fall-Off, Radial.	79
A-6	SC 46 Test 2, Fall-Off, Linear.	80
A-7	SC 46 Test 2, Fall-Off, Spherical	81
A-8	SC 46 Test 3, Build-Up, Radial.	82
A-9	SC 46 Test 3, Build-Up, Linear.	83
A-10	SC 46 Test 3, Build-Up, Spherical	84
A-11	SC 46 Test 3, Fall-Off, Log-Log	85
A-12	SC 46 Test 3, Fall-Off, Radial.	86
A-13	SC 46 Test 3, Fall-Off, Linear.	87
A-14	SC 46 Test 3, Fall-Off, Spherical	88
A-15	SC-19 Test 1A, Build-Up, Radial	89
A-16	SC-19 Test 1A, Build-Up, Radial	90
A-17	SC-19 Test 1A, Build-Up, Radial	91
A-18	SC-19 Test 1B, Build-Up, Radial	92
A-19	SC-19 Test 2, Build-Up, Radial.	93
A-20	SC-19 Test 2, Build-Up, Linear.	94
A-21	SC-19 Test 2, Build-Up, Spherical	95
A-22	SC-19 Test 2, Fall-Off, Log-Log	96

LIST OF FIGURES
(Continued)

Figure	Page
A-23 SC-19 Test 2, Fall-Off, Radial.	97
A-24 SC-19 Test 2, Fall-Off, Linear.	98
A-25 SC-19 Test 2, Fall-Off, Spherical	99
A-26 SC-19 Test 3, Build-Up, Radial.	100
A-27 SC-19 Test 3, Build-Up, Linear.	101
A-28 SC-19 Test 3, Build-Up, Spherical	102
A-29 SC-19 Test 3, Fall-Off, Log-Log	103
A-30 SC-19 Test 3, Fall-Off, Radial.	104
A-31 SC-19 Test 3, Fall-Off, Linear.	105
A-32 SC-19 Test 3, Fall-Off, Spherical	106
A-33 SC-19 Test 4, Build-Up, Radial.	107
A-34 SC-19 Test 4, Build-Up, Linear.	108
A-35 SC-19 Test 4, Build-Up, Spherical	109
A-36 SC-19 Test 4, Fall-Off, Log-Log	110
A-37 SC-19 Test 4, Fall-Off, Radial.	111
A-38 SC-19 Test 4, Fall-Off, Linear.	112
A-39 SC-19 Test 4, Fall-Off, Spherical	113

CHAPTER 1

EXECUTIVE SUMMARY

1.1 OBJECTIVE

The purpose of this work was to obtain data at the Santa Cruz site to support the design of a commercial scale operation and a field experiment.

Field testing is directed at obtaining in situ measurements of permeability, porosity, vertical flow profiles, initial water saturation, and coring in the mineralized zone. Design data pertaining to effluent copper loading, gangue acid consumption, and copper recovery, are obtained by conducting laboratory acid core leaching tests.

To minimize costs, the field tests are conducted by entering existing core holes, wedging off, and coring. The in situ measurements are obtained in the cored section. Holes SC-46 and SC-19 were selected, SC-46 represents a porphyry host rock, and SC-19 a granite host rock. In each hole approximately 200 feet of core is obtained.

1.2 RESULTS AND CONCLUSIONS

The field test began on October 8, 1987 and ended on November 9, 1987, a total of 33 days. The significant results and conclusions are summarized below.

- No significant operational problems were encountered by working in the old core holes and wedging off to: obtain new core; conduct water injection tests; and obtain geophysical wireline logs.
- Comparison of permeability data obtained in the old and new SC-19 core hole indicates a 5-to-1 higher permeability in the old core hole. Since both intervals tested are at approximately the same locations, and geological inspection of core from both intervals did not show significant variation, it is likely this difference is attributed to mud damage in the new core hole. Any mud that was used in the old core hole had years to break down.
- Permeabilities measured in the new core hole sections of SC-46 and SC-19, where mud damage existed, were 1 md and 4 md respectively. A 20-to-35 md permeability was measured in the old core hole section of SC-19 where mud damage was least. Assuming a 5-to-1 damage effect due

to mud, these initial tests indicate a range of 5-to-20 md in permeability at Santa Cruz.

- o The density log provides the most direct measure of porosity. Based on grain density of 2.65 gram per cc, the average porosity in SC-46 is calculated as 8% with a range of 4% to 15%. In SC-19 the average value is 9% with a range of 5% to 15%. These values and ranges can be refined when the mineral content (type and level) is determined.

- o The assumption of 100% water saturation in the mineralized zone was confirmed by the following observations and measurements.

  - + Piping placed in the holes during field testing shows wetting of the pipe surface at water levels corresponding to 400 and 500 feet below the surface.

  - + Downhole pressure measurements at the end of the fall-off tests in SC-46 and SC-19 indicate static water levels of 416 feet below the surface in SC-46 and 480 feet in SC-19.

- o Preliminary laboratory core leach tests conducted on core obtained from the old SC-19 core hole indicate that at sulfuric acid concentrations of 50 gpl that copper loadings of 10 gpl can be achieved at a net acid consumption of less than 3 1/2 lb acid per lb copper.

1.3 RECOMMENDATIONS

The following recommendations are based on work conducted at the Santa Cruz site for field tests conducted from 10/8/87 to 11/9/87.

- o The technique of working in an existing core hole to obtain: additional core; permeability data; and geophysical logs can be useful in obtaining preliminary data for the assessment of in situ leach potential. Specific changes recommended are as follows:

  - + Avoid permeability testing in the new core hole section to avoid mud damage effects.

  - + The above can be achieved by air hammer drilling a section of the mineralized zone for permeability testing after wedging and initiating the new hole with mud drilling. Core would be obtained below the interval tested for permeability.

  - + An alternative to air hammer drilling in the wedged off hole would be to clean out the old core hole and conduct a permeability test before wedging off to obtain additional core.

  - + Purchase a string of 2 3/8 inch diameter non-upset standard API thread and coupled tubing with turned down couplings for any work in small diameter 2.98 inch diameter holes.

- To confirm the impact of drilling mud on permeability testing conduct an additional test by re-entering SC-46, setting and drilling off the wedge 30 feet, then air hammer a section through the ore zone, and then conduct a water injection test. Based on the data obtained in the SC-19 old core hole, this proposed permeability test should provide a higher injection rate than that obtained in the test conducted in the new core hole section of SC-46.

- Conduct an expanded analysis of the geophysical logs for the determination of porosity when data pertaining to grain density and mineral content of the entire cored intervals in SC-46 and SC-19 become available. These data enable the "bound" hydrogen ion component of the logs to be removed, thus correcting the log signal for true porosity.

CHAPTER 2

DESCRIPTION OF FIELD TEST ACTIVITIES

2.1 GENERAL APPROACH

Contractor experience on two previous in situ copper field experiments demonstrated that preliminary permeability tests, well logging, and coring can be conducted by re-entry of existing mineral exploration holes of nominal 3-inch diameter. This represents a significant savings over drilling new core holes from the surface. The sequence of field activities is discussed below.

- o Rig-up over the hole, clean hole to the top of the ore zone, set a wedge, and core 200 feet.
- o Conduct wireline geophysical logging of the holes to obtain data on porosity, water saturation, hole irregularity, and flow profile. Specific logs to be run include gamma density, thermal neutron, induction, sonic veolocity, caliper, temperature, differential temperature, and spinner.
- o Conduct permeability tests in the cored ore interval using constant rate or constant pressure water injection through packer equipment installed in the hole. The procedure used to conduct the test is the pressure transient method.

2.2 SELECTION OF TEST HOLE LOCATIONS

The following factors were considered in the test hole selections:

- o Mechanical condition of the hole, as related to re-entry.
- o Test interval characteristics, including:
  - + Depth of interval below casing point.
  - + Ore interval length suitable for test work.
  - + Ore grade, mineralogy, and continuity.
- o Proximity to selected pilot test site.
- o Host rock mineralogy.

Parameters for 14 core holes were evaluated for the above criteria. See Table 2-1. Mechanical conditions for four of the holes were specified by the site operator, and were unknown for the others. Holes SC-19 and SC-46 best

TABLE 2-1. CORE HOLE DATA

Hole	A	B	C	D	E	F	G	Mechanical Condition/Comments
SC35	100	1,898	2,220	100	100/0	P		NQ rods stuck 800′ to 2,296 - not useable
SC46	400	1,476	1,800	100	75/25	P	392	4" I.D. casg. (cemented) to 1,084′ - useable HQ hole (3.79" diam) to 2,325′; 470 ft @ 0.92%
SC38	600	1,150	1,318	100	100/0	P	20 (?)	Unknown - 168 ft. @ 0.29%
SC24	550	1,550	1,820	70	70/30	M	497 (?)	Unknown - 270 ft. @ 0.69%
SC19	650	1,193	1,460	75	60/40	G	0	3.5" I.D. casg. (cemented) to 1,205; NX hole open to 2,340 ft. - useable; 255 ft @ 0.63%
SC36	800	1,269	1,355	100	75/25	G	463 (?)	Unknown - 86 ft @ 0.39%
SC39	1,100	1,775	2,019	80	100/0	M	768 (?)	Unknown - 244 ft @ 0.42%; some chalcocite
SC52	1,200	1,870	2,030	100	100/0	P	1,112	4" I.D. casg. (cemented) to 758′ - open HQ (3.79") hole to 2,040′; useable - 160 ft @ 0.53% + shorter intervals
SC60	4,200	2,018	2,515	100	20/80	G	0 (?)	Unknown - 497 ft @ 0.34%
SC61	4,400	1,973	2,199	100	60/40	G	0 (?)	Unknown - 226 ft @ 0.90%
SC58	4,650	2,021	2,614	100	15/85	G	140 (?)	Unknown - 593 ft @ 0.65%
SC64	4,950	2,184	2,273	100	0/100	P	180 (?)	Unknown - 89 ft @ 0.90%
SC49		Insufficient oxide ore						
SC59	1,900	1,456	1,672	100	70/30	M	280 (?)	Unknown - 216 ft @ 0.61%

Notes:

1. "Unknown" mechanical condition will require study of drillers logs.

2. Above ore intervals selected based on ≥0.20% oxide cu., interval approaching 200+ ft. in length, closest proximity to casing point and pilot test site.

A = Distance to test site, ft.
B = Depth of top of ore interval, ft.
C = Depth to bottom of ore interval, ft.

D = % ore in interval
E = % chrysocolla to % atacamite
F = Host rock type

G = Depth of ore below casing, ft.
- P - Porphyry
- G - Granite
- M - Mixture of P and G

met the selection criteria, including mechanical condition. Table 2-2 compares test hole data with average properties of the commercial ore block.

- o Core hole SC-46, collar location 64,483 N., 49,496 E. The test interval is located in the depth interval between 1,476 ft. and 1,800 ft., includes both chrysocolla and atacamite mineralization, is contained within porphyry type host rock, and begins about 392 ft. below the existing well casing point.

- o Core hole SC-19, collar location 65,520 N., 49,459 E. The test interval is located in the depth interval between 1,193 ft. and 1,460 ft., includes both chrysocolla and atacamite mineralization, is contained within granite type host rock, and begins immediately below the existing casing point.

2.3 ACQUISITION OF CASING DIMENSIONS

The casing dimensions of the existing core holes SC-46 and SC-19 are required to write specifications for purchasing of well heads. Inspection of these core holes by ASARCO revealed that the existing physical conditions of these holes would not permit making the required measurements without conducting mechanical work. Remedial work was also performed in SC-52 and SC-39. Holes SC-24, SC-59, SC-35, SC-49, SC-36, SC-38, SC-37, and SC-40 were inspected and marked.

- o SC-46

  - + Existing 4 1/2 inch o.d. (4 inch i.d.) casing had been torch-cut and bent shut as an expedient method of plugging the casing. External casing threads were visible only where core rod wear had parted the casing; apparently abrasion between the well casing and the surface casing during drilling operations had worn off most of the casing threads, thus preventing use of a capped coupling to plug the well. The threads observed suggest that the next casing coupling is at about 20 ft. depth. The casing coupling o.d. is 5 inches. The annulus between the surface casing and the well casing was open.

  - + The well was excavated to a depth of about 5 ft., the 7 inch surface casing was cut off, and the damaged upper portion (about 3 ft.) of 4 1/2 inch o.d. well casing was cut off. A section of new 4 1/2 inch o.d., 4 inch i.d. schedule 40 black iron pipe was welded on; a threaded end with a coupling now extends about 6 inches above ground level. A 1 ft. long section of similar pipe was threaded into the coupling, and a cap welded on it. This cap may be removed, and a wellhead may be welded onto the short nipple. The well number was marked on the casing and the excavation was backfilled.

TABLE 2-2. TEST HOLE DATA VERSUS COMMERCIAL ORE BLOCK

Parameter	Commercial Ore Block	S.C.-19	S.C.-46
% atacamite	34%	40%	25%
% Chrysocolla	53%	60%	75%
Oxide grade	.73%	.63%	.92%
Ore thickness	344 ft.	255 ft.	470 ft.
Ore bottom depth	2129 ft.	1460 ft.	1800 ft.

+ Since the annulus between the surface and well casings is open, it is recommended that this annulus be cement-filled prior to drilling operations, to meet well abandonment requirements. This will save the time (proposed in the original plan), required to drill out this annulus.

o SC 19

+ Existing 4 inch o.d. (3 1/2 inch i.d.) casing has a coupling at ground level, with a 41 inch long capped casing section threaded into it. Welded to this cap is a 1 ft. section of 2 inch galvanized pipe, which acts as a holder for a 4 ft. long piece of P.V.C. pipe, which apparently is used as a location marker. No surface casing was observed, but no excavation was made. The next casing coupling should be at about 20 ft. depth; the 3 1/2 inch casing coupling o.d. is 4 5/8 inches.

+ An attempt to unscrew the upper (capped) casing section was unsuccessful, so the casing was cut about 8 inches above the coupling for inspection. The casing is obstructed by 1 or 1 1/2 inch P.V.C. pipe cemented into the center of the casing. The P.V. C. pipe is also plugged, possibly with cement, so no determination of the depth of this plug could be made; pounding on the plug with a digging bar had no effect. The original capped casing was replaced, tack welded in place and the well number marked on the casing.

+ Recommendation is to attempt to drill out the cement and pipe, since there is no obvious reason for the cement to extend to depth.

o SC 52

+ The existing 4 1/2 inch o.d. (4 inch i.d.) casing had been plugged by cutting and bending, similar to well SC 46. Minor excavation revealed remnants of badly rusted surface casing, and an open annular space between the casings.

+ The top was cut off and the casing inspected visually. No problems were observed, and thread remnants on the casing top suggest that the next lower joint is at about 20 ft. depth. A short (28 inch long) 4 1/2 inch o.d. casing section was welded on and now extends above ground level. This casing section was plugged by a welded cap. The casing was marked with the well number.

o SC 39

+ Existing 4 inch o.d. (3 1/2 inch i.d.) casing and capped coupling extended about 8 inches above ground level. One side of the casing had been worn through by drill rods. The next lower casing joint should be located at about 20 ft. depth.

+ The casing was excavated to about 4 ft. depth, and the damaged portion cut off about 20 inches below ground level. No evidence of surface casing was found. A 4 1/2 inch o.d. (4 inch i.d.) section 60 inches long was welded to the casing, and a capped thread protector was threaded onto the top end. The casing was marked with the well number, and the excavation backfilled.

o SC 24

The only evidence found of the hole was a 4 ft. section of small diameter P.V.C. pipe sticking out of the ground at the hole location, adjacent to a 4 ft. wooden stake similar to other hole markers in the area. No excavation was done.

o SC 59

Existing casing is 4 inch o.d. (3 1/2 inch i.d.), with coupling and cap, extending about 6 inches above ground level. Due to the apparent good integrity of the casing and cap, and the large (1900 ft.) distance from the proposed test site, no further inspection was made.

o Other Holes

During the course of the above work, the following holes were located and marked with the appropriate numbers: SC 35, 49, 36, 38, 37, and 40.

2.4 TEST PLAN AND SPECIFICATIONS

2.4.1 Test Activity Plan

The test plan of individual activities with associated time estimates are listed in Table 2-3 for hole SC-46 and Table 2-4 for SC-19. A total of 37 1/2 days of testing was estimated. One mineral drilling contractor is utilized for coring, service work in support of geophysical wireline logging, and water injection permeability testing. One logging contractor is utilized to obtain the required logs.

2.4.2 Purchased Equipment

Equipment purchased to support the field tests consists of inflatable packers and support materials and flow meters. Table 2-5 is an inventory list of purchased equipment.

TABLE 2-3. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-46 (TO BE CONDUCTED FIRST)

Activities*	Time**
1. Mobilize drill rig. Rig up over hole.	1 day
2. Check all equipment and assemble.	1 day
3. Remove wellhead.	--
4. Pick up washover pipe with bit. Deepen annulus between existing surface casing and hole to 20 ft. Pull out of hole.	1/2 d
5. Install rag packer at 20 ft. Mix cement and cement annulus from rag packer to surface.	1/2 d
6. Pick up bit and run in hole on drill rods.	1/2 d
7. Hook up circulation system; clean hole to 1,726 ft.	1/2 d
8. Pull out of hole and lay down bit.	1/2 d
9. Run in hole to 1,726 ft. Set mechanical plug. Install Benseal to 1,476 ft. Circulate out excess Benseal at 1,476 ft. Set mechanical plug.	1 day
10. Place 30 ft. of sand on plug.	1/2 d
11. Pull out of hole, pick up wedge, and run in hole.	1/2 d
12. Set wedge on sand plug and cement.	--
13. Pull out of hole, pick up bullnose bit, run in the hole	1/2 d
14. Drill off of wedge 30 ft.	1/2 d
15. Pull out of hole, lay down bullnose bit.	1/2 d
16. Rig up mud system for coring.	--
17. Pick up core bit and barrel, run in the hole.	1/2 d
18. Core until 200 ft. of core is recovered	2 days
19. Photograph, package, and ship core.	--
20. Mobilize logging contractor	--

TABLE 2-3. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-46
(TO BE CONDUCTED FIRST)
(Continued)

Activities*	Time**
21. Condition hole, pull out of the hole, and lay down bit and barrel.	1/2 d
22. Run wireline logs.	1/2 d
23. Run in the hole with bit and condition hole with water.	1/2 d
24. Pull out of hole, lay down bit and rods.	--
25. Pick up packer, rental string, inflation tube. Rig up nitrogen inflation system.	1/2 d
26. Install seating nipple for downhole shut-in valve two joints above packer.	--
27. Run packer to top of ore and inflate packer.	1/2 d
28. Rig up water injection system and connect to tubing (includes w/l lubricator/seal).	1/2 d
29. Run in pressure sensor below shut-in tool on wireline. Tag seating nipple and pull up 5 ft. Activate wireline lubricator.	--
30. Commence water injection. Fill tubing. Establish constant rate. Do not exceed 400 psi surface (if necessary cut rate). Inject water for 6 to 8 hrs. at constant rate. Record pressure and rate.	1/2 d
31. Terminate injection. Close downhole shut-in tool. Record pressure for 16 to 18 hours.	3/4 d
32. Reduce data. Decide if adequate.	--
33. If inadequate, repeat test with necessary modifications.	1 day
34. Pull out wireline with shut-in tool and pressure sensor.	--
35. Release packer and pullout of hole with rental string.	1/2 d
36. Lay down packer and rental string.	--

TABLE 2-3. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-46 (TO BE CONDUCTED SECOND) (Continued)

Activities*	Time**
37. Rig up wellhead with lubricator. Run in spinner tool on wireline. Rig up water injection system to wellhead. Commence injection and run spinner survey.	1/2 d
38. Pull out of hole with spinner and wireline. Remove lubricator and wellhead.	--
39. Install cap on casing.	1/2 d
40. Rig down and move to SC-19.	1/2 d
Total:	17.75 d

Note:

*Only two contractors are expected to be involved in drilling and logging.

**Time is based on a 24 hour a day schedule, e.g., 1 d = 24 hrs., 1/2 d = 12 hrs.

TABLE 2-4. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-19 (TO BE CONDUCTED SECOND)

Activities*	Time**
1. Mobilize drill rig. Rig up over hole.	1 day
2. Check all equipment and assemble.	1 day
3. Remove wellhead. Drill out cement and plastic pipe with air hammer.	2 days
4. Pick up washover pipe with bit. Deepen annulus between existing surface casing and hole to 20 ft. Pull out of hole.	1/2 d
5. Install rag packer at 20 ft. Mix cement and cement annulus from rag packer to surface.	1/2 d
6. Pick up bit and run in hole on drill rods.	1/2 d
7. Hook up circulation system; clean hole to 1,500 ft.	1/2 d
8. Pull out of hole and lay down bit.	1/2 d
9. Run in hole to 1,500 ft. Set mechanical plug. Install Benseal to 1,260 ft. Circulate out excess Benseal at 1,260 ft. Set mechanical plug.	1 day
10. Place 30 ft. of sand on plug.	1/2 d
11. Pull out of hole, pick up wedge, and run in hole.	1/2 d
12. Set wedge on sand plug and cement.	--
13. Pull out of hole, pick up bullnose bit, run in the hole	1/2 d
14. Drill off of wedge 30 ft.	1/2 d
15. Pull out of hole, lay down bullnose bit.	1/2 d
16. Rig up mud system for coring.	--
17. Pick up core bit and barrel, run in the hole.	1/2 d
18. Core until 200 ft. of core is recovered	2 days
19. Photograph, package, and ship core.	--
20. Mobilize logging contractor	--

TABLE 2-4. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-19
(TO BE CONDUCTED SECOND)
(Continued)

Activities*	Time**
21. Condition hole, pull out of the hole, and lay down bit and barrel.	1/2 d
22. Run wireline logs.	1/2 d
23. Run in the hole with bit and condition hole with water.	1/2 d
24. Pull out of hole, lay down bit and rods.	--
25. Pick up packer, rental string, inflation tube. Rig up nitrogen inflation system.	1/2 d
26. Install seating nipple for downhole shut-in valve two joints above packer.	--
27. Run packer to top of ore and inflate packer.	1/2 d
28. Rig up water injection system and connect to tubing (includes w/l lubricator/seal).	1/2 d
29. Run in pressure sensor below shut-in tool on wireline. Tag seating nipple and pull up 5 ft. Activate wireline lubricator.	--
30. Commence water injection. Fill tubing. Establish constant rate. Do not exceed 400 psi surface (if necessary cut rate). Inject water for 6 to 8 hrs. at constant rate. Record pressure and rate.	1/2 d
31. Terminate injection. Close downhole shut-in tool. Record pressure for 16 to 18 hours.	3/4 d
32. Reduce data. Decide if adequate.	--
33. If inadequate, repeat test with necessary modifications.	1 day
34. Pull out wireline with shut-in tool and pressure sensor.	--
35. Release packer and pullout of hole with rental string.	1/2 d
36. Lay down packer and rental string.	--

TABLE 2-4. ESTIMATES OF TIME REQUIRED FOR TEST ON SANTA CRUZ HOLE SC-19 (TO BE CONDUCTED SECOND) (Continued)

Activities*	Time**
37. Rig up wellhead with lubricator. Run in spinner tool on wireline. Rig up water injection system to wellhead. Commence injection and run spinner survey.	1/2 d
38. Pull out of hole with spinner and wireline. Remove lubricator and wellhead.	--
39. Install cap on casing.	1/2 d
40. Rig down and move to SC-19.	1/2 d
Total:	19.75 d

Note:

*Only two contractors are expected to be involved in drilling and logging.

**Time is based on a 24 hour a day schedule, e.g., 1 d = 24 hrs., 1/2 d = 12 hrs.

TABLE 2-5. PURCHASED EQUIPMENT INVENTORY

- o Baski Water Instruments Sliding-End Inflatable Packer. 60 inch element, 2.7 inch o.d.
- o Baski Water Instruments Sliding-End Inflatable Packer. 60 inch element, 2.7 inch o.d.
- o Baski Water Instruments Sliding-End Inflatable Packer. 60 inch element, 3.4 inch o.d.
- o Baski Water Instruments High Pressure Nitrogen Regulator 0-2000 P.S.I. Accu-Trol No. RS-11-20
- o Baski Water Instruments High Pressure Inflation Hose 540 M-B, SE 100 RT, 3/16 inch i.d.
- o Baski Water Instruments 3 ea. Pressure Gauges 0-1000 P.S.I. 1/4 inch NPT fitting Weksler No. AA 142
- o Baski Water Instruments 1 ea. Adapter with 3 parts
  - + 1 ea. 1 inch SCH 80 316SS nipple 12 inch length
  - + 1 ea. 1 inch NPT x 1 1/2 inch NPT forged bushing
  - + 1 ea. 1 1/2 inch NPT 3000 P.S.I. coupling
- o Baski Water Instruments Unions/Hose Ends/Adapters for high pressure hose
  - + 10 ea. 3/16 inch high pressure hose ends
  - + 5 ea. 1/8 inch high pressure couplings
  - + 8 ea. 1/8 inch thick wall 316 SS tubing lengths 1/2 to 1 feet
  - + 10 ea. 1/8 inch high pressure ferrule type tube-to hose connectors
  - + 4 ea. 1/8 inch x 1/4 inch NPT forged bushing
- o Baski Water Instruments Adapter of 3 parts
  - + 1 ea. 1 1/4 inch x 12 inch NPT SCH 80 316-55 nipple
  - + 1 ea. 1 1/4 inch x 1 1/2 inch NPT forged bushing
  - + 1 ea. 1 1/2 inch NPT 300 P.S.I. coupling
- o Baski Water Instruments Band-It Tool
- o Baski Water Instruments Banding. 4 boxes galvanized 3/4 inch banding 100 feet/box P/NC 306
- o Baski Water Instruments Buckles. 3 boxes, 100 buckles per box P/N 6356

TABLE 2-5. PURCHASED EQUIPMENT INVENTORY (Continued)

- o Halliburton Services Turbine Flow Meter 1-7 GPM
  - \+ Flow analyzer
  - \+ Turbine unit
- o Halliburton Services Turbine Flow Meter 5-50 GPM
  - \+ Flow analyzer
  - \+ Turbine unit

2.4.3 Drilling Contractor Requirements

The responsibilities and requirements of the drilling contractor include:

- Hole cleanout
- Install plugs and wedges
- Drill off wedge and take 200 feet of core
- Provide, install, and operate equipment for water injection
- Assist geophysical wireline subcontractor
- Provide for supply and storage of water and equipment for water supply.
- Provide drilling needs, and chemical and mechanical plugs
- Provide tubing string for water injection
- Be licensed as a certified Water Well Driller as per regulations administered by the Arizona Department of Water Resources (ADWR)
- Be a licensed contractor with the Arizona Registrar of Contracts
- Provide ADWR with completion record and driller logs for each hole drilled within 30 days of completing work.

The drill rig inventory is listed in Table 2-6, and Table 2-7 lists the crew data reporting requirements. The flow meter manifold used during water injection is shown in Figure 3-1.

Additional performance requirements to be met by the drilling contractor are listed below:

- The drilling rig will have the capability of coring to a depth of 2,000 feet for the specified hole dimensions.
- The drilling rig will have the capability of hoisting 1,500 feet of 2-3/8 inch tubing.
- The drilling rig and pumping system will have the capability of circulating materials from a depth of 2,000 feet during coring, drilling, and clean-out operations.
- The contractor will have staff experienced with wedge setting in mineral core holes.

TABLE 2-6. ITEMS TO BE INCLUDED IN
DRILLING CONTRACTOR RIG INVENTORY

Item #	Description
1.	Oxyacetylene torch set <available on call>
2.	Arc welding machine (portable) <available on call>
3.	Bit for cleaning 3.79" hole (SC-46)
4.	Bit for cleaning 2.98" hole (SC-19)
5.	NC drill rods, 1800 ft HQ rod O.D. = 3.5"
6.	NX drill rods, 1600 ft.
7.	Pulling plugs and foot clamp for handling necessary tools. Mission slips for 2/38" O.D. tubing; casing bowl/slips for 1/12" pipe
8.	Mechanical bridge plug (Van Ruth plug), 2 each for 3.79" and 2.98" holes
9.	Sand hopper that will fit on NC and NQ rods
10.	Hoses
11.	Wedge for HQ and NQ hole. HQ = "Window" or "casing" wedge NQ = NX wedge welded into NX casing
12.	Water pump (pressure 500 psi minimum, 35 gpm)
13.	Revert mud or equivalent (Baroid easy mud)
14.	Hoses from pump to swivel joint
15.	NQ core bits NQ = 1.875" I.D.; NX = 2.155" I.D., both are 2.980" O.D.
16.	Triple-Tube core barrel or equivalent: Split barrel - also chromed 1-piece barrel is available
17.	Core boxes & blocks for NQ core
18.	2 3/8" USS improved buttress thread tubing, 1600 + ft.
19.	5 x joint of 1-1/2" SCH 40 pipe

TABLE 2-6. ITEMS TO BE INCLUDED IN
DRILLING CONTRACTOR RIG INVENTORY (Continued)

Item #	Description
20.	Change-over 2-3/8" API 10-RD by 1-1/2" (1.9") API 10-RD
21.	Rag packer
22.	Cement
23.	Pull plug or elevators and slips for 2-3/8" API non-upset tubing
24.	Pull plug or elevators and slips for 2-3/8" API non-upset tubing
25.	Water tank or water truck
26.	Mud tank(s)
27.	Pressure relief valve for high pressure pump setting pressure 500 psi, adjustable
28.	Desurger (pulsation dampener) for pump if plunger type is used
29.	Compressor for operating air hammer

Fittings for Meter maniford for Water Injection Test

Note: All fittings except meters are malleable cast iron or steel, suitable for 500 psi working pressure, minimum.

Figure 3-1 Item	Quantity	Description
1	3	Reducing Tee 1-1/2" x 1", FIP 300 lb class, black, 500 psi min. working pressure
2	2	Nipples, 1-1/2" x 12", MIP, extra heavy, black
3	2	Nipples, 1" x 12" MIP, extra heavy, black
4	2	Unions, malleable iron, FIP, 300 lb class (600 psi working pressure), 1-1/2"
5	2	Hydraulic hose with 1-1/2" MIP steel and connections, 500 psi min. working pressure 30 foot lengths

TABLE 2-6. ITEMS TO BE INCLUDED IN
DRILLING CONTRACTOR RIG INVENTORY (Continued)

Figure 3-1 Item	Quantity	Description
6	2	Nipples 1-1/2" x 6" MIP, extra heavy, black
7	1	Gate valve, 300 lb class, 1-1/2" FIP 600 PSI working pressure
8	1	Ball valve, 1-1/2" FIP, 600 psi working pressure
9	4	Couplings, 1", malleable iron, 300 lb class (heavy), 600 psi working pressure
10	1	Turbine meter 1" MIP (Purchase by SAIC)
11	1	Turbine meter 1" MIP (Purchase by SAIC)
12	2	Nipple, 1" x 8", extra heavy, black, 500 psi min. working pressure
13	2	Reducer, 1" x 1/2" FIP, concentric, Glass 300 (heavy), 500 psi min. working pressure
14	1	Ball valve, 1" FIP, 600 psi working pressure
15	4	Nipples, 1/2" x 6", extra heavy, black, 500 psi working pressure
16	1	Ball valve, 1/2" FIP, 600 psi working pressure
17	3	Nipples, 1" x 6", extra heavy, black, 500 psi working pressure min.
18	1	Globe valve, 1" FIP, 600 psi working pressure, min.
19	1	Globe valve, 1/2" FIP, 600 psi working pressure
20	2	Union, 300 lb. class, 600 psi working pressure or better, 1" FIP
21	1	Hydraulic hose, 1" I.D., with 1" MIP end connections. Hose and fittings capable of 600 psi minimum. 30 foot length.
22	1	Bushing, 1" x 1/2", class 300, 600 psi working pressure min.

TABLE 2-6. ITEMS TO BE INCLUDED IN
DRILLING CONTRACTOR RIG INVENTORY (Continued)

Figure 3-1 Item	Quantity	Description
23	2	Nipple, 1-1/2" x 6", extra heavy, black, 500 psi minimum working pressure
24	1	Ball valve, 1/2" FIP, 600 psi working pressure min.
25	1	1" N.P.T. Pin x 1-1/2 N.P.T. box
26	1	1-1/4" N.P.T. Pin x 1-1/2" N.P.T. box

TABLE 2-7. CREW REPORT

WELL NO. ____________ DATE ____________ HOURS ____________ TO ____________

CONTRACTOR ____________________________ RIG ________________

DRILLER ________________________ ENGINEER ________________

I. DRILLING

CIRCULATING FLUID & ADDITIVES ________________________________

____

TYPE: TOTARY, HAMMER, OTHER ________________________________

BIT SIZE / TYPE ____________/______________________________

DRILL STRING DESCRIPTION ________________________________

____

____

____

DIAGRAM:

______________ ______ ______________ ______ ________

DRILLING STRING WEIGHT __________ Lb. ROTATION R.P.M. __________

HOLDBACK WEIGHT ________________ Lb. (GAUGE PRESSURE ________P.S.I.)

WEIGHT ON BIT ________________ Lb.

END DEPTH ________________ HOURS DRILLED ________________

START DEPTH ________________ AVG. PENETRATION RATE ____________

MUD PUMP SIZE / RATE / PRESS. __________/__________G.P.M./________P.S.I.

COMPRESSOR TYPE ____________________________C.F.M. ____________

PRESSURE, IN ________________ (P.S.I.) RETURN ____________P.S.I.

WATER / FORM INJECTION RATE: ________________________________

SURVEYS: DRILLED DEPTH ________________ SURVEY DEPTH ____________

VERTICAL ANGLE ________________ ° BEARING ________________

II. SERVICE WORK (Running Casing, Tubing, Equipment, Testing, Standby, Fishing, Etc.

START TIME

DESCRIPTION ____

____

____

III. REMARKS (Drilling & Hole Conditions, Delays, Equipment Descriptions, Service Work)

NOTES ____

____

____

- o The contractor will follow the design of the chemical system specified below for use in plugging back existing core holes.
  - \+ 1 pound of EZMUD polymer per 100 gallons water
  - \+ between 1 and 1-1/2 pounds of Benseal per gallon above. This is the EZMUD Mix. The exact amount of Benseal will be specified by the Field Manager by inspecting the polymer/water mix.
  - \+ For hole SC-46, 200 gallons of the EZMUD Mix
  - \+ For hole SC-19, 150 gallons of the EZMUD Mix
- o The contractor will specify a composition of the circulating fluid used during coring to ensure that core recovery exceeds the historical level of 90% previously obtained at the Santa Cruz site.

2.4.4 Logging Contractor Requirements

The responsibilities of the logging contractor involve providing equipment and services for conducting production and electric logs over an interval of 200 feet in core holes 2.98 inches in diameter at a maximum depth of 2,000 feet. The logs to be run and equipment to be provided by the contractor are listed in Table 2-8.

TABLE 2-8. WIRELINE LOGS TO BE RUN AND EQUIPMENT TO BE PROVIDED BY CONTRACTOR

- Wire line logging to be conducted

  1. Gamma Density
  2. Thermal Neutron
  3. Induction
  4. Sonic Velocity
  5. Caliper
  6. Temperature
  7. Differential Temperature
  8. Spinner

- Equipment to be provided by contractor

  1. All equipment to conduct each specified wireline log
  2. Hewlett-Packard pressure gauge, w/surface indicator and recorder
  3. Logging capability for NQ Hole (2.98 inches in diameter at depths up to 2,000 feet

     Gamma Density
     Thermal Neutron
     Induction
     Sonic Velocity
     Caliper
     Temperature and Differential Temperature
     Spinner

  4. Downhole shut-in tool. For 2-3/8 API non-upset tubing
  5. Tubing head lubricator to fit 2-3/8" tubing
  6. Sinker bars

CHAPTER 3

FIELD TEST OPERATIONS

3.1 SUMMARY OF TEST OPERATIONS SCHEDULE

The field test began on October 8, 1987 and ended on November 9, 1987, a total of 33 days.

3.1.1 SC-46

- o Mobilize rig to site. Set up over hole, check & assemble equipment. remove wellhead.
- o 1 day

- o Cement surface casing - well casing annulus
- o Run wash pipe to casing bottom (1080′); wash out old NC core hole to 1726′.
- o 1 day.

- o Pull out NX rods and run in NC rods. Wash to 1696 feet. Pump down & set van ruth plug at 1696 ft.
- o Fill core hole from plug top (1696′) to 1417 ft. with thick bentonite slurry. ("benseal").
- o Pump down & set a van ruth plug at 1416′.
- o 2 days.

- o Run wedge in hole, set, shear off the connecting bolts and cement the wedge. Allow cement to set 24 hours. Run in NC rods & stab into wedge. (Temporary casing).
- o 2 days.

- o Pull out wedge connection & run in NX coring equipment. Drill 5 ft. of hard cement to 1400′; core out of wedge by 1410.′ USBM selected 1425 ft. as starting depth for 200′ of contracted core.
- o 1 day

- o Core 200 ft. to 1625 ft. USBM requested an additional 60 ft. core, to T.D. of 1685 ft. Overall core recovery was about 99%. Condition and clean hole for logging.
- o Mobilize logging contractor & run open-hole logs.
- o 4 days.

- o Run in NX rods, condition & clean hole. Place chemical "breaker" in NX hole, to decompose drilling fluid. Allow 24 hrs. for mud to decompose. Pull out NX rods and NC "casing."
- o 2 days.

- o Rig up & run in packer, shut-in tool and injection tubing string.
- o 1 day

- o Run pressure transient (permeability) tests.
- o 1 day.

- o Pull injection equipment out of hole. Rig up for flow profile tests.
- o Run flow profiles.
- o 1 day.

- o Rig down, move to SC-19 hole. Install locking cap on well & abandon site.
- o 1/2 day.

- o Total 16 1/2 days hole SC-46

3.1.2 SC-19

- o Check & assemble equipment. Drill out cement plug. Wait on washover pipe delivery to site.
- o 2 days.

- o Open & cement SC-19 annulus. Run NX rods to 1530 ft. (No significant obstacles encountered). Set van ruth plug at 1530'. Set cement & mud "breaker" solution in hole above the plug. Wait for mud to breakdown. No circulation returns achieved.
- o 1 day.

- o Check location of plug & add small amount of benseal & cement to improve fluid seal. Circulation returns of approx. 90% achieved, indicating a good plug.

- o 1 day.

- o Run in packer & tubing. Perform 2-rate injection test in existing core hole. Pull equipment out of hole. Install benseal to 1252 ft. depth.

- o 2 days.

- o Install to van ruth plug at 1252 ft. depth. Set & cement wedge. W.O.C. 2 days. Mobilize loggers.

- o 3 days.

- o Run in NX coring equipment, drill hard cement from 1238′ to top of wedge at 1239′. Drill off wedge by 1244.′ USBM representative selected the starting point for 200′ of core as 1249.′ Drilled 200 ′ to 1269′ with 90% or better core recovery and about 90% circulation returns. USBM requested additional core, which was drilled from 1449 to 1461′. Run wireline geophysical logs. Condition hole with mud viscosity reducing solution (hypochlorite & water solution).

- o 2 days.

- o Wait 24 hours for mud viscosity reduction.

- o 1 day.

- o Circulate fresh water into hole (no trouble re-entering); clear water returned after about 360 gallons circulated. Run resistivity log in water-filled hole - no difference seen between this log and similar log run in mud-filled hole. Install packer at 1259′ and downhole shut-off tool & pressure gauge at 1144.′ In this case the packer was equipped with a tailpipe 126 ft. long, in order to enable circulation of fluids to a depth of 1444 ft (near the proposed T.D. of 1449 ft.), in order to facilitate placing additional mud viscosity reduction solution in the test interval. Perform injection & falloff test, injecting at 2 gpm for about 4 hours.

- o 1 day.

- o Run another injection/falloff test in the same hole interval (1259' to 1461'), injecting at 4 gpm, for about 3.75 hours. Unseat packer lower bottom of tailpipe to 1444' (as deep as equipment allowed), and circulate in 260 gallons of mud viscosity reducing solution (hypochlorite and water). Set packer at 1288' (30 ft. lower than before, in an interval which appears more competent and less fractured, as seen in drill core), and shutoff nipple/pressure gauge at 1174.' Perform the final injection/falloff test, injecting in the 1288' to 1461' interval at 3 gpm, for approximately 3.5 hours. The first 260 gallons injected was the 0.025% hypochlorite solution, followed by water, in order to assess the effect of mud viscosity reduction of drilling mud which may have penetrated deeply into the rock fracture system.

- o 1 day.

- o After termination of the test, the wireline seating mandrel and pressure gauge were removed, the packer was released, and 3 tubing joints removed. The Packer was reset at a depth of 1198', in the well casing. This was done in order to determine if water injection rates over the entire open-hole interval would be sufficient to obtain useful spinner tool (flow profile) data. The manufacturer of this spinner tool indicated minimum flowrate of 7 to 10 gpm in an NX sized hole would be necessary for reliable tool operation. A flowrate this high had not been observed in previous injection tests in the new core hole. After injection of approximately 200 gallons of water, annulus fluid returns were noted, with no injection pressure rise. The Packer was released, pulled to surface, and reset just below the well casing collar. Injection into the well over a period of approximately 30 minutes reached a rate of 6 gpm, at a pressure of about 180 psi (surface).

  It was evident from this pressure buildup that fluid previously injected (with the packer set near the well casing bottom) had not been lost to the formation, but had somehow bypassed the packer. A possible mechanism for this would have been holes in the casing (possibly resulting from drill rod wear) and poor bottomhole cement integrity. 180 psi was about the pressure at which previous injection tests were conducted. It was apparent that increasing the flowrate to the 7 to 10 gpm minimum tool operating range would have increased injection pressures near or past the pressure necessary to dialate existing fractures in the rock. If fractures were induced or dialated, the flow profile obtained by the spinner tool would not accurately reflect the distribution of injected fluid during previous injection tests. Therefore, the spinner tool was not run. Since this was the last proposed item in the test program, the loggers were released, and site demobilization initiated.

- o 1 day.

- o The drill rig & equipment were demobilized, the site was cleaned up, including filling mud pits, the purchased equipment was stored at the ASARCO-SACATON mine site. A wellhead cap was installed and locked.

The key to the locks for both wells (SC-19 and SC-46) were left with the ASARCO-SACATON caretaker.

- 1 1/2 days.

- Total time 16 1/2 days SC-19.

3.2 HOLE INSPECTION AND REPAIR

3.2.1 Hole SC-46

Hole inspected by ASARCO personnel during 4/87. Top of casing was rod worn & damaged. Roy V. Huff and Associates (RHA) installed new top casing section & screw cap 5/13/87.

3.2.2 Hole SC-19

SC-19:

Hole inspected by RHA personnel 5/13/87. Cut off section of capped casing protruding above ground level. Discovered cement and PVC pipe plugging hole. Replaced existing cap.

3.3 HOLE RE-ENTRY

3.3.1 Hole SC-46

- Move rig on-site & rig up 10/9/87. Cement the existing annulus between the conductor and the center casing to 20 + ft. depth with "benseal" followed by 15 gallons of cement slurry.

- Run in rods to 1204′ before encountering fill. (casing bottom at 1080′). Circulation returns using EZ mud (polymer mud) varied around 70%. Washed to 1726′ by 10/12/87.

3.3.2 Hole SC-19

- Move rig on-site & rig up 10/23/87. Drill out a cement plug in casing (about 1 ft. long or less). No surface casing existed. Enlarge casing-hole annulus with 6" O.D. washover pipe, to about 15′ depth before bit chatter & hard drilling stopped progress. Cemented annulus with about 14 gallons of cement, after plugging up downward fluid flow with about 1/2 bag of "benseal" & water slurry.

- Ran rods to 1530 ft. depth unobstructed, by 10/26/87 p.m. No fluid was circulated during this operation.

3.4 PLUGGING AND WEDGING

3.4.1 Hole SC-46

Washed rods to 1730'. Pull rods, remove wash rod & run in hole to 1696'. (A mistake in counting rods resulted in 30' upward displacement from planned depths during plug installation). Set lower van ruth plug at 1696.' Mix & pump 170 gallons of benseal slurry above the plug. Circulated out excess benseal above 1416' depth. Installed a van ruth plug at 1416'. Pulled out of hole, attached wedge and ran in hole. Set wedge on top of van ruth plug at 1416'. Sheared off connecting pins and cemented wedge with 2 sacks (18 gallons) of portland type II cement. Washed out excess cement above wedge & pulled rods out of the hole, by 10/14/87. Cement was allowed to cure for about 28 hours. NC "casing" was pulled out of the hole, following logging operations.

3.4.2 Hole SC-19

Set rods at 1530', pumped & set van ruth packer at 1530'. In order to provide a suitable fluid seal for an injection test in the existing open hole above the plug, 1 sack (10 gallons) of cement was placed above the plug. The open hole was filled to about 1230' with weak clorox solution, to breakdown any remaining polymeric mud in the test interval. No circulation returns had been achieved up to this point (10/26/87). Water circulation to remove "broken" mud resulted in about 30% circulation returns. Found hard cement about 2 ft above the van ruth plug, at 1528'. Placed 10 gallons of benseal slurry and 10 gallons (1 sack) cement slurry above this plug, to improve fluid sealing. Circulation returns improved to about 90% by 10/28/87. Performed injection test (described in Section 3.7). Mix & pump in 100 gallons benseal on 10/29/87, & allow to expand overnight. Circulate out excess benseal above 1252' depth & set van ruth packer at 1252'. This depth was selected to allow sufficient room below the well casing, in the event a second wedge was required to be set above the first one. (This could arise from faulty alignment of the wedge in the hole.) Twenty gallons of cement slurry was placed above the first wedge, and excess cement circulated out above 1207', using drilling mud. Wait on cement 48 hours to assure a good set.

3.5 CORING

3.5.1. Hole SC 46

Locate solid cement at 1395′ (inside wedge) on 10-14-87. Run NC rods to top of wedge at 1390′, as temporary casing. Run in NX core barrel and bit and drill out of cement-filled hole into rock at about 1413.′ USBM representative decided to start the contracted 200′ core interval at 1425.′ Core drilled to 1625′ with 90 + % recovery and 100% circulation returns, showed low grade mineralization. USBM authorized coring an additional 60 ft. to a total depth of 1685,′ to obtain higher grade mineralization. T.D. was reached 10/17/85. Overall core recovery aproached 100%. USBM personnel took possession of core at the drill site.

3.5.2 Hole SC-19

Solid cement was drilled from 1214′ to 1218′ (below the well casing bottom) and from 1238′ (above the top of the wedge by 2 ft), until drilling off the wedge & out of the old hole at 1244′, on 11/2/87. The USBM representative decided to start collecting the contracted 200 ft. of core at 1249.′ Circulation returns dropped from about 95% to about 85% in the interval from 1435′ to 1440′ and below. Rock type changed from granitic to diabase at about 1446.′ USBM representative received approval to obtain additional core. Stopped coring in diabase rock 11/4/87, at 1461′ depth. Core reocvery was above 90%. USBM personnel took possession of core at the drill site.

3.6 LOGGING

3.6.1 Hole SC-46

Loggers arrived in town 10/18/87 pm. Circulated hole clean with drilling mud and ran logs on 10/19/87. No problems were encountered in running logging tools past the wedge into the new core hole, or with the logging equipment, generally. The hole remained open to the total depth of 1685′ during logging operation, which required about 6 hours. The following logs were run:

- o Temperature/differential temperature
- o Gamma ray/gamma density/caliper
- o Neutron
- o Focused electric
- o Multi-channel sonic
- o Spinner (flow meter, without fluid injection)

3.6.2 Hole SC-19

Loggers arrived in Casa Grande at 5:30 pm, 11/4/87. Hole had been circulated clean and drill rods removed, by about 5:00 pm that day. Logs were run from 8:00 pm to 12:45 am, 11/5/87. The hole remained open to the total depth of 1461 ft. during logging operations. The same suite of logs was run as in SC-46 hole, excepting the spinner (flowmeter) log.

3.7 PRESSURE TRANSIENT TESTING

3.7.1 General Discussion

Pressure transient testing operations consisted of injecting water into the test interval at a constant flowrate, recording the pressure increase with time during injection, and the pressure decrease with time after injection had been terminated. Equipment used for these tests is described briefly:

Water Source:

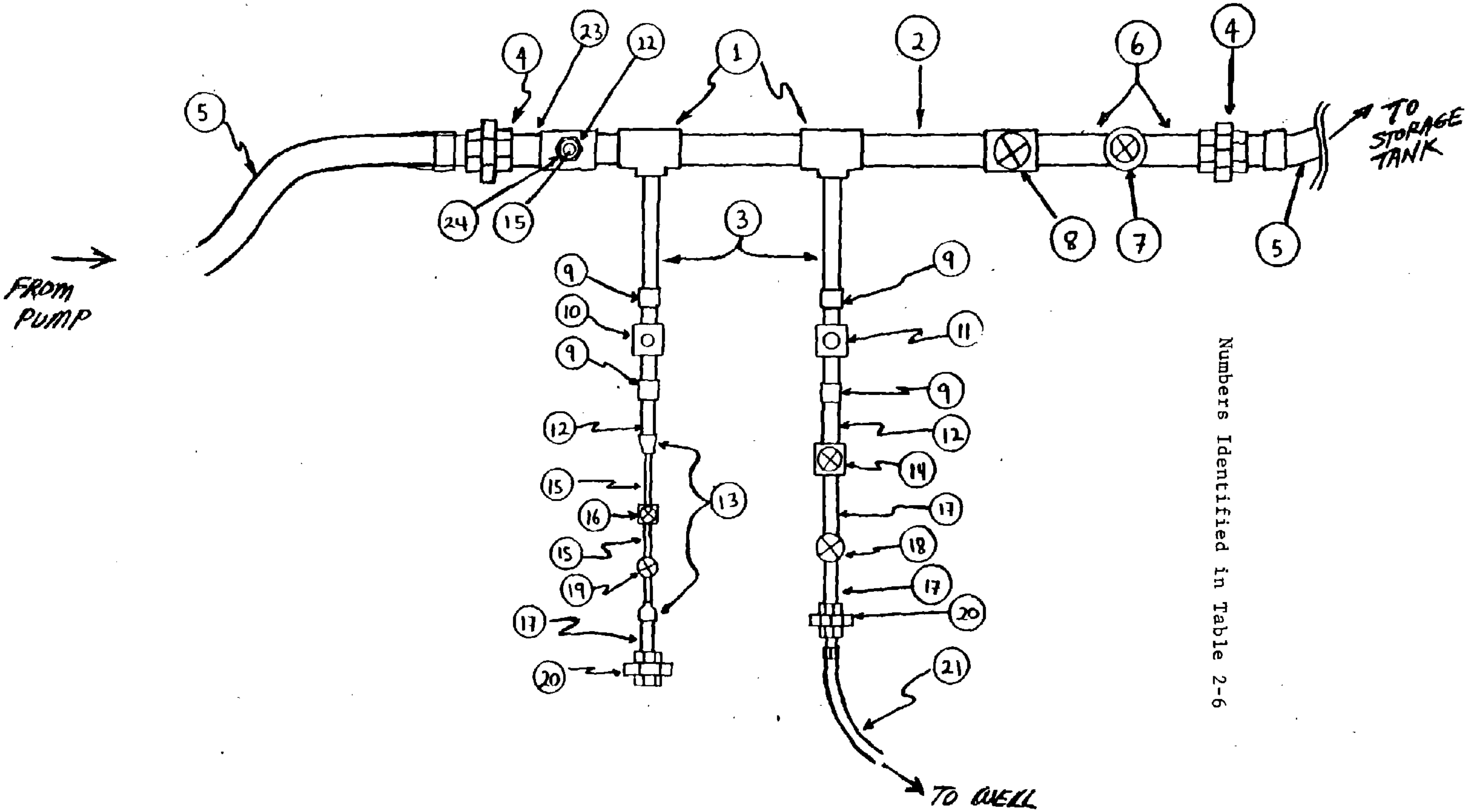
Stock tanks of 500 and 180 gallon capacities were supplied with potable water from nearby commercial wells by the drilling contractor water truck.

Pump:

A Bean Co. model 35 piston pump, capable of flowrates up to 20+ GPM, at pressures up to about 650 psi. Owned & operated by drilling contractor.

Injection Manifold:

Consists of a combination of high pressure pipe fittings, valves, hose, a pressure gauge and flowmeters. These were connected so as to enable accurate control and measurement of pressures from 0 to about 500 + psi, and flowrates in two ranges (from 0.75 to 7.5 gpm and from 5.0 to 50 gpm). All manifold equipment except the flowmeter was provided by the drilling contractor; the flowmeters were purchased by SAIC. The manifold was operated by a representative of RHA. See Figure 3-1.



Numbers Identified in Table 2-6

FIGURE 3-1 DIAGRAM FOR PIPING AND METER MANIFOLD FOR WATER INJECTION TEST

Downhole Tubing:

Two tubing strings were required, as a result of small core hole diameters utilized, tubing tensile strength operating limits, tubing I.D. requirements and thread connection sealing requirement.

The tubing string utilized within the larger-diameter portion of the holes was non-upset, thread and coupled improved U.S.S. buttress threaded, 2 3/8" O.D., 2.041" I.D., in random 30 ft (range 2) lengths.

This tubing string was selected due to price and availability considerations (which prevented use of the originally specified non-upset 2 3/8" API tubing string), and possessed necessary tensile strength, thread sealing properties, and internal/external sizes. This tubing string was connected to the shut-in tool seating nipple. The tubing string utilized within the small (3 inch) diameter NX core holes consisted of 105 ft. of 2" schedule 40 black iron pipe, utilizing N.P.T. threads & coupling. Tensile strength limitations which prevented its use throughout the entire hole were not significant in the short 105 ft. length used. This tubing string was connected to the packer on the bottom, and the shut-in tool seating nipple, on the top.

A third string of tubing, consisting of 126 ft. of schedule 40 black iron pipe was extended below the packer in hole SC-19 tests. This tubing allowed circulation of fluids to the test interval bottom without removal of the entire tubing string.

All tubing and thread changeovers (except those associated with the packers) were provided by the drilling contractor. See Figure 3-2.

Downhole Shutin Tool:

The purpose of this tool was to isolate hydrostatic pressure (resulting from the fluid-filled tubing string) from the downhole pressure gauge and well test interval, following termination of injection operations.

Exclusion of this tubing pressure from the test interval allows formation pressure alone to be monitored during the "pressure falloff" portion of the

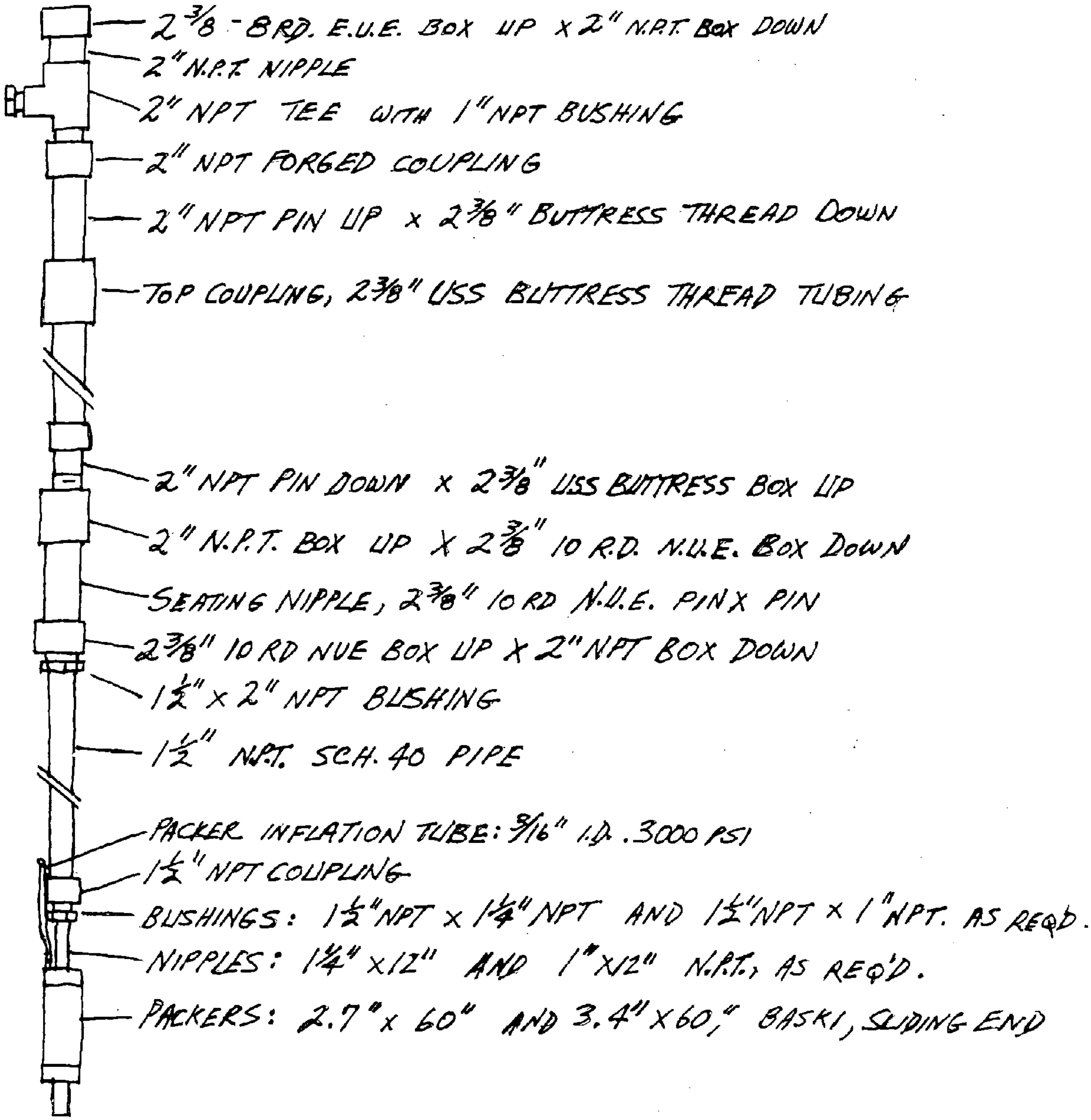


Figure 3-2. Downhole Tubing String & Equipment

test, without the confusing effects of "wellbore storage" appearing in the data. This tool consists of 2 parts, one being a "seating nipple," which is attached to the tubing string above the packer and the other part being a "seating mandrel," which is suspended on the logging company wireline. This part is attached to the real-time downhole pressure gauge. See Figure 3-3.

During fluid injection, this seating mandrel is suspended a few feet above the seating nipple. Upon termination of injection, this downhole valve is closed by lowering the seating mandrel into the seating nipple.

The seating mandrel and nipple were owned and operated by the logging contractor.

Packer:

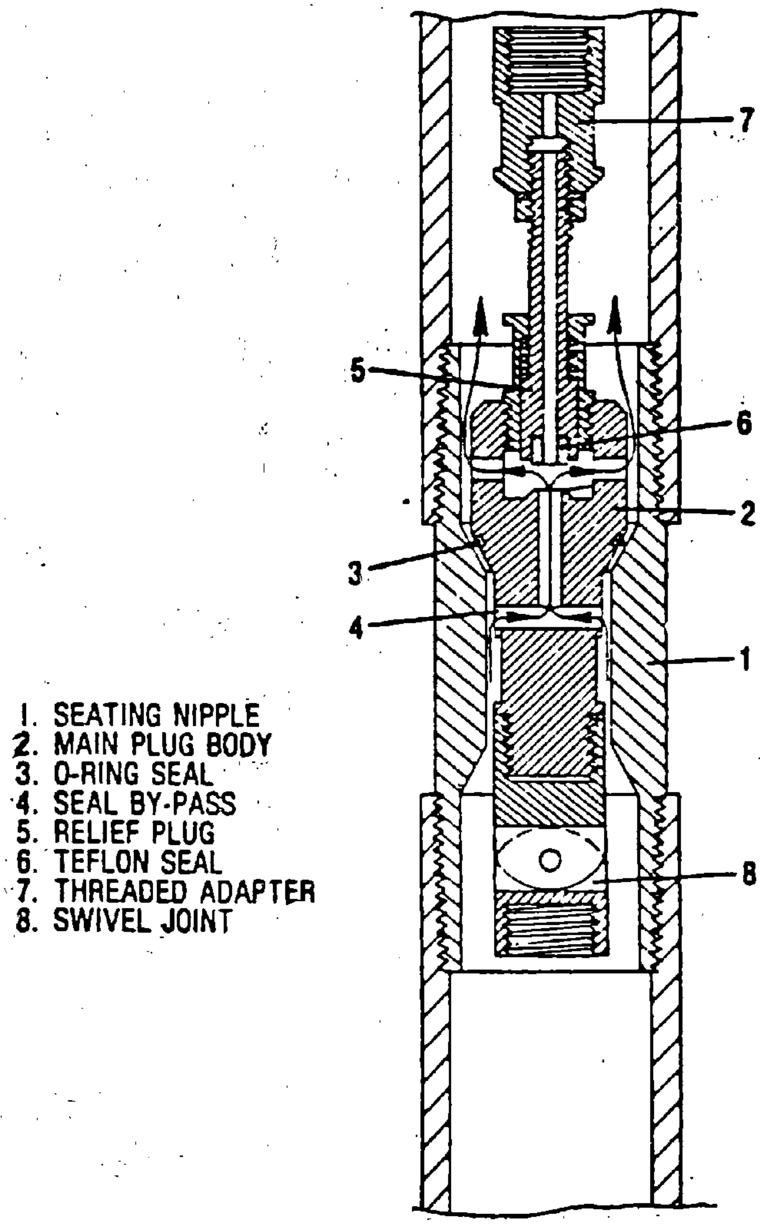
Packers were used for pressure transient testing to provide a fluid seal in the hole in order to confine fluid pressures to the test interval. The packers selected were tube-inflatable sliding-end types. These were attached to the bottom of the 1 1/2" pipe described above, and were inflated by means of a high pressure tube, a pressure regulator and a high pressure nitrogen gas bottle.

Wireline Seal:

This unit was attached above the injection tee (on the surface) and provided a fluid seal to prevent fluid loss while suspending and lowering the seating mandrel during and following pressurized injection operations. This equipment was provided by and operated by the logging company.

Injection Tee & Adapters:

This was a 2" high-pressure tee with thread adapters to allow connection of the wireline seal above it, the tubing string below it, and the injection hose into the side port. This equipment was provided by the drilling contractor.



Bottom hole shut-in plug developed by Conoco is lowered and retrieved by wireline. With the relief plug (5) held in tension against spring loading, as shown, Teflon seal (6) is held open allowing fluid communication across O-ring seal (3). Slacking off allows spring to close the Teflon seal, communicating pressure only to hollow adapter (7) that contains the BHP gage or senser element for surface recording instrument. Swivel joint (8) accepts sinker bars or a backup conventional BHP gage. A tubing-casing packer is used in conjunction with the plug.

FIGURE 3-3 BOTTOM HOLE SHUT-IN PLUG.

Brief descriptions of pressure transiet test operations in each hole follow.

Generally, procedures consisted of 1) circulating drilling mud out of the hole (a polymeric drilling fluid was utilized); 2) filling the test interval with a weak hypochlorite-water solution to lower the viscosity of mud remaining in the hole; 3) waiting 24 hours for the mud viscosity to be "broken" and circulating out the "broken" mud with water (this was only required during the first test in a specific interval); 4) install the test tubing string and equipment; 5) connect the injection manifold to the tubing string, inflate the packer, set the seating mandrel and downhole pressure gauge in the "open" position above the seating nipple, and 6) commence injection operations.

Based on estimates of fracturing gradient and experience in the first test, attempts were made to establish injection at rates that would not result in downhole pressures rising above gradients of about 0.7 to 0.8 psi/ft of depth. A sufficient duration of injection was indicated by establishment of relatively constant pressure over time periods of about 20 minutes or more. Following termination of injection, the downhole shut-in tool was closed, and formation pressure decline was automatically recorded. Recording of both injection and falloff pressures was done automatically, at short time intervals (15 seconds or more, as specified), by logging contractor equipment.

3.7.2 Hole SC-46

The packer was set at 1431′ on 10/21/87. Pressure gauge and seating nipple were at 1379′ depth. Hole bottom was at 1685′. Initial injection at 2.0 gpm resulted in surface pressure rise of only 20 psi over about 8 minutes, followed by a presure drop to 0 psi. Flowrate was increased to 6.5 gpm over about 20 minutes, before well-tubing annulus fluid returns occurred. Assumed fluid was bypassing packer, and stopped injection. Re-set packer 10 ft. higher, at 1421 ft. Initiated injection at about 0.2 to 0.3 gpm (below the accurate range of the small flowmeter), to prevent rapid pressure rise. Continued injection at this rate for 3 hours during which time surface pressure increased to 60 psi (downhole pressure increased to 662 psi at 1369′

depth), which represented a gradient of 0.47 psi/ft. at the 1421 ft. packer depth. Clo sed the shut in tool & allowed pressure to fall for about 3 hours.
Left packer set at same depth overnight.

Resumed injection at 08:20 am 11/22/87, at 1.0 gpm. Pressure rose steadily for about 71 minutes, to 365 psi surface (950 psi downhole), representing a gradient of 0.69 psi/ft at the packer depth of 1421 ft. After 71 minutes of injection, the surface pressure quickly dropped to about 200 psi, and the flowrate increased to 2 or 3 gpm. Injection was terminated, the shut-in valve closed, and pressure falloff recorded for about 3 hours.

Packer, tubing and equipment were removed from the hole without damage or difficulty on 11/23/87.

3.7.3 Hole SC-19

Set the packer in the existing NX core hole, at 1255', on 10/28/87. Downhole pressure guage was not used since the logging contractor was not present during this unscheduled test. A van ruth packer had been set at 1530' and covered with 37 ft. of benseal slurry, to a depth of 1493', which was the effective bottom of the test interval. After about an hour of trial and error, an injection rate of 14 gpm was established, and maintained for about 2 1/2 hours, during which time the surface pressure rose to about 41 psi. (Equivalent to 584 psi at the packer depth of 1255 ft. resulting in a gradient of about 0.47 psi/ft.). The injection rate was then increased to 18 gpm, and maintained for 3 hours, during which time the surface pressure increased to about 70 psi (equivalent to 613 psi at 1255' downhole, resulting in a gradient of 0.49 psi/ft). The 18 gpm rate was selected because it ws the highest rate at which the injection water supply could be maintained, using available equipment. No pressure falloff was recorded after injection was terminated, since the surface pressure dropped to 0 psi within 15 seconds, and no downhole monitoring equipment was available.

After completion of coring and mud "breaking" operations, the packer was set at 1259' on 11/6/87. The downhole pressure gauge was set at 1144 ft.; the new NX core hole test interval bottom was at 1461 ft. After about 1 hour, (including a minor pump repair), injection was established at 2 gpm, and maintained for 3 hours, during which time surface pressure incresed to 110 psi, (corresponding to 610 psi at downhole gauge depth-of 1144 ft., resulting in a gradient of 0.53 psi/ft.). Injection was terminated and falloff pressure recorded for about 6 hours. Equipment was left in place.

Injection at a higher rate of 4 gpm was initiated on 11/7/87 (8:00 am) with equipment in the same configuration as for the previous test. After 3 hours of injection, surface pressure had reached about 175 psi (658 psi downhole at 1144 ft., for a gradient of 0.57 psi/ft.). Injection ceased, the downhole valve was closed, and falloff pressures monitored for about 2.5 hours. The packer was released, and tubing added until the bottom of the packer tailpipe was at 1444'. (This was as close as possible to the original intended hole bottom of 1449'; subsequent addition of 12 ft. to the hole T.D. caused the tailpipe to remain 17 ft. above the final T.D. of 1461'.) A weak hypochlorite and water solution (recommended for polymer drilling mud viscosity reduction) was circulated into the test interval. The packer was re-set at a depth of 1288,' to place it in a less fractured interval of rock, in preparation for the next test.

Injection was established at 3 gpm on 11/7/87 (7:18 pm), injecting weak hypochlorite solution (260 gallons) followed by water, for about 3 hours. During this time, downhole pressure (gauge was at 1170 ft) increased to 606 psi after about 1 hour, then decreased to about 598 psi after 2 hours (total), then increased to about 600 psi after 3 hours, when injection was terminated. The highest gradient (606 psi at 1170 ft.) was about 0.52 psi/ft, which was lower than that of the previous test. The downhole valve was closed and falloff pressure was recorded for 2 hours.

The purpose of this final test was assessment of the effect of reducing the viscosity of remaining drilling mud which may have deeply invaded the rock fracture system, and which was therefore not previously exposed to hypochlorite solution within the wellbore.

3.8 FLOW PROFILING

3.8.1 General Discussion

A flow profile is a representation of the variation of the amounts of injected fluid exiting a borehole over a particular depth interval. This profile may be related to rock permeability variations in the same depth interval.

Direct indications of injected fluid flow profiles may be obtained by use of a downhole flowmeter (spinner) tool. This tool measures variations in fluid velocity as it is raised on an electric wireline through the depth interval of interest in a well.

Fluid velocity measurements are translated into flowrates by correcting for hole diameter variations by means of a caliper log. These flowrates may then be used to define permeabilities of various intervals of interest in the vertical column.

Another method of flow profiling is to run sequential temperature logs at several time intervals following injection of fluids. If there is sufficient difference in temperatures of the injected fluid and the rock, and if insufficient quantities of fluid are injected, a measurable change in the existing rock temperature gradient will result. This difference is more pronounced in intervals which receive the most fluid. Therefore a sequence of time-spaced temperature logs, run immediately following injection, can define intervals which take more or less time to return to the normal temperature gradient, thus giving a qualitative measure of rock permeability variation.

Both of the above methods are restricted to tool sensitivity limits. The spinner log lower threshold sensitivity requires a fluid velocity of approximately 20 to 30 ft/minute, which corresponds to about 7 to 10 gpm flow in an NX (2.98") diameter core hole. The temperature log is quite sensitive, but detection of small induced temperature variations requires that the log be run before these variations disappear. This method was not utilized during the field test at the Santa Cruz site due to the small volumes of fluid injected during each test, combined with the long time required to observe pressure falloff (which usually required about 3 hours), followed by removal of downhole tubing and equipment (which usually required 5 to 6 hours).

3.8.2 Hole SC-46

A flow profile was run during initial open-hole logging operations in order to detect naturally ocurring fluid movement in the well.

No evidence of naturally ocurring fluid movement was observed in the initial logging run. Following pressure transient testing, the tubing and packer were removed from the hole, the spinner tool and seal rigged up and the packer was set just below the well casing collar. (Equipment size limitations prevented running the spinner tool through the transient test tubing string.) Several spinner tool runs were made during water injection, as summarized below:

Run No.	Wireline Speed	Injection Flowrate	Surface Pressure
5	80 ft/min	1 gpm	100-150 psi
6	80 ft/min	7.2	380 psi
7	80 ft/min	7.5	285 psi

No information differing from the static tool run was observed; injected flowrates were insufficient for proper tool operation. Rates were not increased for fear of inducing hydraulic fractures, which would cause a different flow profile than that which existed during pressure transient tests. (This may have happened in Run No. 7, when the injected flowrate had increased, and the pressure had decreased in comparison to run No. 6.)

3.8.3 Hole SC-19

In order to evaluate likelihood of obtaining useable spinner tool information, the packer was set at 1198′ depth (inside the well casing bottom), to determine if injection rates in excess of 7 to 10 gpm could be achieved without fracturing the rock. Injection in this equipment configuration resulted in a small surface pressure increase (to 20 psi), followed by a fall in pressure to 0 psi, followed by tubing-casing annulus flow at the surface equal to the injection flowrate. The packer and tubing were pulled out of the hole and reset just below the well collar, to repeat the test. In this equipment configuration, injection at 6.0 gpm had raised surface pressures to the 180 psi range, within 30 minutes. It was decided that injection at higher rates was likely to cause fracturing (or dilation of existing fractures) so the flow profile test was not run.

Anulus returns observed during the first injection were thought to result from water bypassing the packer (probably outside the casing), and returning into the casing through one or more holes in the casing. Rod wear on the casing, resulting from previous coring operations, could explain the existence of such holes.

3.9 WELL ABANDONMENT

3.9.1 Hole SC-46

The drill rig was moved off SC-46 hole on 10/23/87. A locking cap was installed on the well casing at the surface on 10/26/87, and a lock was installed on the well. The key for this lock (which also fits the lock on well SC-19) was left with the ASARCO SACATON mine caretaker, Mr. Bud Bebee, on 11/9/87. The site was cleaned and the mud pits backfilled for abandonment. See section 3.3.1 for well annulus cementing procedures.

3.9.2 Hole SC 19

The drill rig was demobilized on 11/9/87. A locking cap was installed on the well and locked on 11/9/87. The site was cleaned and mud pits backfilled upon abandonment. The key to the installed lock was left in possession of ASARCO SACATON Mine Caretaker, Mr. Bebee, on 11/9/87. Well annulus cementing procedures are described in section 3.3.2.

CHAPTER 4

RESULTS AND CONCLUSIONS

4.1 FLOW TESTS

4.1.1 Pressure Transient Testing

A total of 8 separate flow tests were conducted in SC-46 and SC-19 and analyzed to determine whether the design criteria of 2 md for the commercial operation and 10 to 50 gpm flow rate for the field experiment can be achieved. Table 4-1 describes these tests. Each test consists of two parts: the pressure build-up in which an attempt is made to maintain a constant rate of injection while monitoring the increase of pressure with time; and the pressure fall-off, which occurs after the fluid injection is terminated and the pressure decrease is measured as a function of time. The flow analysis is divided into two parts: comparison of specific injectivities; and calculation of permeabilities derived from pressure build-up analysis.

- Specific Injectivity Results

  The specific injectivity is used to compare the relative flow conductivities associated with different tests. It is equal to the gpm per foot of interval divided by the injection pressure drop. The injection rates and pressures at the end of the build-up tests are used to calculate the specific injectivities, which are summarized in Table 4-2, with average test values denoted by the Column I_A.

  + The injectivity of the old SC-19 core hole is 5 times larger than that in the new SC-19 core hole. Since both intervals are at approximately the same locations, and geological inspection of core from both intervals did not show significant variation, it is likely this difference in injectivity can be attributed to mud damage in the new core hole. The drilling fluid (mud) invades fractures, partially or totally plugging the flow paths. Any mud that was used in the old core hole had years to break down. Assuming that a 5-to-1 mud damage also existed in the new core hole section of SC-46, the rock permeability is sufficient to provide a 5 gpm flow rate when wells are drilled in the field experiment, 15 gpm after short radius hydrofracing. The 5 gpm rate is the minimum required for operation of the field experiment at the minimum 10 gpm capacity using two 5-spots.

  + The injectivity of SC-19 is 7 times more than SC-46 (comparison of data in new core hole sections).

TABLE 4-1. FLOW TEST SUMMARY

Test	Packer Setting Feet	Injection Interval Feet	Avg. gpm	Avg. Surface Pressure psi	Comments
<u>SC-46 new core hole</u>					
1	1,431	254	7.4	0	Test stopped when fluid rose to surface in SC-46. Possible leak in rock around packer.
2	1,421	264	0.4	52	---
3	1,421	264	0.95	260	After reaching 360 psi surface pressure (950 psi downhole pressure at 1,370 feet) pressure dropped and test stopped.
<u>SC-19 old core hole</u>					
1A	1,255	238	14	40	No downhole pressure measurement
1B	1,255	238	18	70	No downhole pressure measurement
<u>SC-19 new core hole</u>					
2	1,259	202	2	105	Pressure build-up data indicate permeability increases with increasing downhole pressure in each test.
3	1,259	202	4	170	
4	1,288	173	3	160	

Fracture pressure of 0.7 psi/foot equivalent to surface pressure of 380 psi in SC-46 tests and 336 psi in SC-19 tests.

TABLE 4-2. SUMMARY OF SPECIFIC INJECTIVITY DATA SC-46 AND SC-19

$$I = \frac{q}{H \times \Delta p} = \text{gpm per foot per psi}$$

Hole	Test	q gpm	p_i psi Bottom Hole Pressure	H Injection Interval Feet	p_o psi Static Bottom Hole Pressure	$\Delta p = p_i - p_o$ psi	I	I_A Avg
SC-46 New core hole	1	7.4	617	254	413	204	1.4×10^{-4}	Expect leak by packer
	2	0.4	665	264	413	252	6.0×10^{-6}	6.4×10^{-6}
	3	0.95	953	264	413	540	6.7×10^{-6}	
SC-19 Old core hole	1A	14	583 from 40 psi surface pressure 1,255 feet of head in tubing	238	336 Assume 480 foot static water level	261	2.2×10^{-4}	
	1B	18	613 same as above for 70 psi surface pressure	238	336 same as above	277	2.7×10^{-4}	2.6×10^{-4}
SC-19 New core hole	2	2	605	202	286	319	3.1×10^{-5}	
	3	4	660	202	286	374	5.3×10^{-5}	4.7×10^{-5}
	4	3	600	173	299	301	5.8×10^{-5}	

p_o values: 1,370 feet tests 1, 2, 3 in SC-46; 1,142 feet tests 2, 3, 4 in SC-19; 1,255 feet tests 1A, 1B in SC-19

+ In the original test design, it was envisioned that the holes would be sidetracked, cored, and permeability tested. Further, it was believed that the mud used for coring could easily be broken. This does not appear to be the case. Because of this, a test was conducted in the old core hole of SC-19 prior to side tracking as well as after side tracking and coring. Tests in SC-46 suggested the possibility of mechanical problems would be associated with the execution of the test in the old core hole.

o Pressure Build-Up and Fall-Off Analysis

Analysis of the pressure transient data obtained during the pressure build-up and fall-off periods of the water injection testing in SC-46 and SC-19 was conducted to calculate rock permeability values. A summary of this work is provided below for a total of 2 build-up and 2 fall-off tests in SC-46,and a total of 5 build-up and 3 fall-off tests in SC-19.

+ The transient analysis indicates that portions of each build-up and fall-off test exhibit radial flow. Linear flow was indicated in Test 3 in SC-46 and Test 1A in SC-19. Spherical flow as indicated in test 3 in SC-46 and test 3 in SC-19. Permeability values associated with linear flow cannot be calculated because the length of the fracture is not known.

+ Tables 4-3 and 4-4 summarize the transient data analysis for radial flow and spherical flow geometries. Data plots and the discussion of the transient analysis are found in Appendix A.

+ In SC-46 the permeability range (in md) is between 0.03 and 0.93 during build-up and 0.07 and 0.85 during fall-off. In SC-19 the range in the new core hole interval is 0.27 to 4.0 during build-up and during fall-off is 0.19 to 1.9. The permreability range for the old core hole during build-up is 21 to 37.

+ The range in permeability reflects both variations between tests and changes in permeability that occur during a given test. The latter may be related to the mud damage or reflect permeability sensitivity to pressure (dilatancy). The highest value of permeability obtained during a given test is associated with the highest pressure in that test. All pressures are below the fracing pressure of 0.7 psi per foot of depth. Essentially no dilatancy was noted during the pressure build-up in the old core hole section of SC-19, where mud damage is thought to be at a minimum level.

+ The skin factors shown in Table 4-3 are all negative indicating that at the wall of the wellbore the permeability is greater than that away from the wellbore. Injection of water during the test would have moved the invaded mud further into the deposit. This in turn would leave relatively unimpaired rock adjacent to the wellbore and be reflected as a negative skin.

TABLE 4-3. SUMMARY OF PRESSURE TRANSIENT ANALYSIS FOR RADIAL FLOW GEOMETRY

Test Number	Interval H-Feet	Injection Rate q-Barrels/day	Slope m-psi/cycle	Build-Up Time T-Hours	Permeability k-md	Skin S	Reference Figure Number
SC-46 new core hole							
2	264	13.7	27	2.56	0.03 BU	----	A-1
			114		0.07 FO	-2.62	A-5
3	264	33.3	22	1.15	0.93 BU	----	A-8
			200		0.10 FO	-3.24	A-12
SC-19 old core hole							
1A	238	483.4	15	----	22 BU	----	A-15
1B	238	483.4	9, 16	----	21, 37 BU	----	A-18
SC-19 new core hole							
2	202	70.8	215	3.55	0.27 BU	----	A-19
			294		0.19 FO	-3.93	A-23
3	202	138	120	3.95	0.93 FO	-2.0	A-30
4	173	102.9	24	3.66	4.0 BU	----	A-33
			200		0.48 FO	-3.36	A-37

BU = Build-up portion of test
FO = Fall-off portion of test

TABLE 4-4. SUMMARY OF PRESSURE TRANSIENT ANALYSIS FOR SPHERICAL FLOW GEOMETRY

Test Number	Interval H-Feet	Injection Rate q-Barrels/day	Slope m-psi $(hr)^{1/2}$	Build-Up Time T-Hours	Perm md	Reference Figure Number
SC-46 new core hole						
3	264	33.3	74	1.15	0.85 FO	A-14
SC-19 new core hole						
3	202	138	90	3.95	1.9 FO	A-32

FO = Fall-off portion of test.

+ The highest permeability measured in the new SC-46 core hole (with mud damage) is 0.93 md. Assuming a 5-to-1 reduction in permeability due to the mud (ratio of I values old and new core holes SC-19), the permeability of SC-46 is estimated to be 4.6 md (without mud damage). This is comparable to the value of 2 md used for the commercial design and the field experiment design.

4.1.2 Flow Profile

See Section 3.8 for a description of field operations.

o SC-46

No indication of fluid flow was obtained in runs on 1, 2, and 3, which were run in the drilling-mud-filled open hole following wireline logging. The line speed of 80 ft/min used in the NX core hole resulted in an average reading of about 30 counts per second, from the depth of about 1,600 feet to the wedge depth of about 1,400 feet in run No. 1. The line speed was unchanged at about 12 counts per second above 1,400 feet. The effect of exiting the small NX hole and entering the larger NC hole was to reduce the spinner rotation to about 12 counts/second. Since there is no net deviation from these values over either interval, no fluid entry into or exit from the well is indicated. Tool run No. 2 apparently was constrained by an obstructed tool from bottom to about 1,450 feet and from 1,410 feet to 1,417 feet; otherwise it was similar to run No. 1. The tool was operating properly from bottom to about 1,605 feet during run No. 3, where it became obstructed and remained inoperable for the remainder of the run. Debris from the well was removed from the tool following this run.

Tool run 4 was a "false start" run and was not recorded. Tool runs 5, 6, and 7 were made during fluid injection at flow rates of 1, 7.2 and 7.5 gpm respectively. Tool runs 5 and 6 show essentially the same response seen in the static run No. 1, above. Tool run No. 6 indicates a decrease from about 36 counts per second at 1,626 feet (bottom of the hole) to about 30 cps at 1,570 feet. (To interpret this as fluid flow, the flow would have to be greater at the hole bottom than at 1,570 feet and higher. This condition is not impossible under pressurized injection conditions).

o SC-19

No spinner logs were run in SC-19. See Section 3.8.2 for the rationale leading to this decision.

4.2 CORING

For a description of field operations, see Section 3.5

4.2.1 SC-46

Two hundred feet of NX core were drilled, starting on 10/14/87 at 1,425 feet (the starting depth selected by a USBM representative) and proceeding to 1,625 feet by 10/16/87. USBM requested and authorized an additional 60 feet of core, which was drilled to a depth of 1,685 feet on 11/17/87. All core drilled had recovery rates higher than 90% with most runs approaching 100%. An NL Bariod Co. polymeric drilling fluid (EZ-mud) was circulated at between 10 and 15 gpm during drilling operations. No problems or significant circulation loss occurred with this mud system. A "set" diamond step type bit was run on NX core rods, which were rotated at about 80-90 rpm during most drilling operations, with a calculated weight of about 3,000-4,000 lbs. on the bit. A chromed inner tube core barrel was utilized for most runs at USBM request. A Kelly rod twisted off just below surface on 10/15/87; it was unscrewed and replaced within about 2 hours. No other problems were encountered. The entire 260+ foot interval was drilled with one bit. Drilling rates averaged about 4.1 ft/hour; mud returns averaged about 90%.

4.2.2 SC-19

Two hundred feet of NX core were drilled, starting on 11/2/87 at 1,249 feet (the starting depth selected by the USBM representative), proceeding to 1,449 feet on 11/4/87. USBM requested and authorized an additional core, which was drilled 12 feet to 1,460 feet the same day. All core drilled had recovery of over 90% with most runs approaching 100%. A polymeric drilling fluid (N.L. Baroid "EZ-Mud") was circulated at 15-20 gpm rates during coring operations. Circulation returns remained at about 95% above a drilled depth of 1,435 feet, and fell to about 85% between 1,435 feet and 1,440 feet, where it remained until T.D. of 1,460 feet. A "set" diamond step-type bit was used to a depth of 1,339 feet, rotating about about 80-100 rpm, with about 1,000 to 2,000 lbs. weight on the bit. A diamond impregnated, flat face type bit was used from 1,339 feet to T.D. of 1,460 feet, rotating at about 200 rpm, with about 2,000 to 3,000 lbs. weight on the bit. Drilling rates averaged about 4.4 ft/hour. No significant problems were encountered during coring operations.

4.3 WIRELINE GEOPHYSICAL LOGGING

Geophysical logging was conducted to obtain information concerning porosity, water saturation, hole diameter, and flow profile.

4.3.1 Porosity

Analysis of the geophysical logs with regard to determination of formation porosity is provided below.

- o The density log provides the most direct measure of porosity. Based on an assumed grain density of 2.65 grams per cc the average porosity in SC-46 is calculated as 8% with a range of 4% to 15%. In SC-19 the average value is 9% with a range of 5% to 15%. These values and ranges can be refined when the mineral content (type and level) are determined.

- o The neutron and resistivity logs reflect variations in rock properties associated with porosity and mineral content, and until the variation in mineral content is quantified porosity levels or correlations cannot be determined.

  - + In SC-46 respective variations of the velocity and electric logs are 40 to 100 microseconds per foot and 6 to 100 ohm-meters.

  - + In SC-19 the respective variations are 30 to 140 microseconds per foot and 10 to 200 ohm-meters.

- o The neutron porosity log measures hydrogen ion content, either as pore water or minerals containing hydrogen ion. The absolute value is based on a limestone calibration, and must be corrected for minerals containing hydrogen ion. The range in SC-46 is 16% to 46% and in SC-19 12% to 44%.

- o The only strong correlcation between logs in both holes was electric versus neutron. Relative correlations are listed below.

  - + SC-46

    - Electric versus density - none
    - Electric versus neutron - good
    - Electric versus velocity - weak
    - Density versus neutron - weak
    - Density versus velocity - weak
    - Density verus velocity - weak to good

  - + SC-19

    - Electric versus density - none
    - Electric versus neutron - good
    - Electric versus velocity - weak

- Density versus neutron - weak
- Density versus velocity - weak to good
- Density verus velocity - weak

4.3.2 Initial Water Saturation

Water saturation cannot be determined from the logs until the hydrogen ion content of the minerals in the interval is determined. However, the assumption of a 100% water saturation in the mineralized zone is confirmed by the following observations and measurements.

- o Piping placed in the holes during field testing shows wetting of the pipe surface at water levels corresponding to 400 to 500 feet below the surface.
- o Downhole pressure measurements at the end of the fall-off tests in SC-46 and SC-19 indicate static water levels of 416 feet below the surface in SC-46 and 480 feet in SC-19.

4.3.3 Hole Diameter

Caliper logs in SC-19 and SC-46 indicated that holes had a rather uniform diameter. No washouts were detected. Although a spinner log was run in SC-46 the injection rate was too low to provide detection of flow rate changes. In the old core hole of SC-19 it might have proven useful to run a spinner log; however, there would have been a significant mobilization charge to get the logging equipment on location. The spinner log was not run in the new core hole of SC-19 because like in SC-46 the injection rate was too low.

4.3.4 Flow Profile

This is discussed in Section 4.1.2.

4.4 ASSESSMENT OF EQUIPMENT PERFORMANCE

A wide variety of equipment was utilized in the field test, including drilling equipment, logging equipment, and injection test equipment. Materials including drilling mud, granular bentonite sealing material, and cement were also utilized.

All equipment and materials performed adequately during test operations. Comments below are directed at improvements which could be made in similar tests conducted in the future.

- The bentonite sealing material ("Benseal"), used to plug the existing core hole interval adjacent to the injection test intervals in the newly drilled core hole, was difficult to pump, using the small core rig triplex pump. This was due to the lumpy, granular nature of the benseal slurry. The relatively small quantities of slurry pumped during the field test resulted in several instances of the pressure relief valve on the pump operating. A pump with larger valves than the Bean Co. Model 35 used in the test is recommended.

- Cement was utilized for holding wedges in position and to establish in one instance a fluid seal downhole. A neat Portland Type II slurry, hand-mixed to yield about 10 gallons per sack was used without additives. Long W.O.C. (wait on cement) times evidenced when cement was utilized downhole could have been reduced by addition of fluid loss and accelerator additives, to lessen the risk of "flash setting" (which may result from dehydration under pressure during emplacement), and to assist in early strength development, thus reducing waiting time. Discussion with a commercial cementing service company is recommended in this regard.

- Making a practice of using some type of "plug" to isolate cement from preceding and following fluids during emplacement through tubing is recommended. This serves to prevent mixing of cement and adjacent fluids, which can retard or prevent proper setting.

- The downhole flowmeter (spinner) logging tool used in flow profile tests, was not sufficiently sensitive to produce useable information at the low injection flowrates encountered. Provisions for a test involving cold water injection and sequential temperature logging runs, in addition to determining if spinner tools of adequate sensitivity exist, is recommended for future test efforts.

CHAPTER 5

LABORATORY CORE LEACHING TESTS

5.1 TEST PLAN

The objective of the laboratory core leaching test program is to provide supporting data for the commercial scale operation and field experiment designs with regard to the following:

- Demonstrate 10 gpl copper loading
- Determine Al, Fe, Mg composition of effluent and impact on net gangue acid consumption
- Identify Cu/pH effluent start-up curve
- Measure permeability change as a function of the extent of leaching.
- Determine Cl build-up in effluent when atacamite is present in the core.

The U.S. Bureau of Mines (USBM) Twin Cities Research Laboratory (TCRC) in Minneapolis, Minnesota conducts these tests. The experimental facilities can accommodate 10 simultaneous core tests. The initial test plan was based on the following:

- Injected acid concentration of 50 gpl H_2SO_4. This is sufficient to attain 10 gpl effluent copper loading at a gangue acid consumption of 3-1/2 lb acid per lb of recovered copper.
- Four tests on SC-46 core: two at a high percent atacamite, high and low grade ore; and two at a low percent atacamite, high and low grade ore.
- Four tests on SC-19 core: two at a high pecent atacamite, high and low grade ore; and two at a low percent atacamite, high and low grade ore.
- Two additional tests, one on a SC-46 core at lower acid concentartion, one on a SC-19 core at the same reduced acid concentration.

Descriptions of the test facility and procedures used by USBM to conduct the core leaching tests are provided in a paper by Paulson, Dahl, and Kuhlman presented at the SME-AIME Annual Meeting, Denver, Colorado, February 24-27, 1987 titled "In Situ Mining Geochemical Characterization Studies: Experimental Design, Apparatus, and Preliminary Results."

5.2 CORE LEACH TESTING

Core leaching tests on SC-46 and SC-19 cores are being conducted at TCRC to obtain supporting hydrometallurgical data for the Santa Cruz field experiment design. SAIC provides technical support to this work.

Low pressure leaching of two cores from the new SC-46 core hole (1,638 foot and 1,670 foot) was initiated 10/30/87. No flow through the cores was observed in 26 days with application of 25 to 40 psi injection pressure. The possibility exists that with small diameter core a single fracture may not penetrate the length of the core in the axial flow configuration. In an attempt to obtain a higher exposure of the leach solution to fractures, a radial flow configuration was recommended in which solution is injected over the outer circumference of the core and withdrawn from a small hole drilled in the center of the core through half the length. Water injection tests using this new configuration were initiated on 11/30/87 with two SC-46 cores (1,617 and 1,669 feet). Flow was established on the core from 1,617 feet and no flow was obtained on the core from 1,669 feet. Acid injection on the core from 1,617 feet will be initiated to determine whether the resulting flow is a short circuit.

The recommendation was made that multiple cores be prepared and water permeability tested prior to leaching, and only those cores that provide adequate flow within one day be leached. Sufficient core exists to utilize this screening procedure.

Tests are in progress to implement the test plan described in Section 5.1.

5.3 RESULTS AND CONCLUSIONS

The core leach data available at the time that this report was prepared were obtained from cores from the old SC-19 core hole. This work is summarized below. Core and test descriptions are summarized in Table 5-1.

- Copper loadings in excess of 10 gpl were achieved at injected sulfuric acid strengths of 40 to 50 gpl.

TABLE 5-1. DESCRIPTION OF TCRC CORE SAMPLES AND TESTS

CORE DESCRIPTION	TEST DESCRIPTION
o New core hole o SC-46A - 1,638 feet o Cu 1 1/2% o Biotite Quartz Diorite Porphyry o Disseminated Chrysocolla with minor stockwork atacamite	o Initated 10/30/87, terminated 11/24/87 o Low pressure test axial flow o No flow water 3 days o No flow 50gpl acid 22 days
o New core hole o SC-46-A - 1,670 feet o Cu 1% o Biotite quartz diorite porphyry o Disseminated chrysocolla	o Same as above
o New core hole o SC-46A - 1,617 feet o Cu 2% o Biotite quartz diorite prophyry o Mainly fracture hosted mineralization 60% chrysocolla/40% atacamite	o Initiated 11/30/87 water injection
o New core hole o SC-46A - 1,669 feet o Cu 0.8 to 1% o Biotite quartz diorite porphyry o Mainly fracture hosted mineralization 60% chrysocolla/40% atacamite	o Same as above
o Old core hole split core o SC-19 - 1,690/1/657 feet o Quartz monzonite host rock, no biotite o Cu 4 to 8% o Fracture hosted atacamite	o 40 gpl acid o 3,800 hours of testing o Low pressure axial flow
o Old core hole split core o SC-19 - 1,286 feet and 1,213 feet o Cu 1% o Quartz monzonite host rock, little biotite o Fracture hosted atacamite	o 50 gpl acid o Low pressure axial flow o Flow rate variations made to determine relationship between extraction rate and flow rate

- Acid consumption by gangue appears higher at low grade (1% copper range) than at high grade (4% to 8% copper range), but is significantly less than 3 1/2 lb per lb copper which is the design level used in the field experiment.

- Copper recovery rates are less than 1% per day, and were measured at flow rates less than 1 pore volume per day. This recovery rate is the lower limit observed by SAIC and RHA staff with oxide core leach tests associated with previous in situ copper projects. This prior work also indicated that the rate of copper recovery increased with higher flow rate. It was recommended that TCRC staff determine whether a similar relationship between extraction rate and flow rate can be demonstrated with the current leach experiments on SC-19 core (1,286 and 1,213 feet old core hole) by measuring the change in copper concentration obtained with a large controlled change in flow rate. The prior work indicated that the extraction rate was proportional to the square root of flow rate.

The above preliminary data obtained to date indicate that it should be possible to achieve the copper loadings and acid consumption levels projected for the commercial and field experiment designs.

Implementation of the test plan described in Section 5.1 and the data obtained from the tests will provide a correlation between chloride to copper ratios in the leach solution and the assay ratio of atacamite copper to total copper. This correlation in combination with the average atacamite content in the field experiment 5-spots, obtained from the core hole to be drilled at the start of the field experiment, will provide the data required to assess whether the SX/EW design should be modified to handle chloride levels above 5 gpl.

APPENDIX A

ANALYSIS OF PRESSURE TRANSIENT TEST DATA

A.1 TEST PROCEDURE

Although not absolutely required, the test is normally conducted by injecting water at a constant rate for a sufficient period of time to create a pressure disturbance in the formation in the vicinity of the test well. After termination of water injection the pressure decline (or fall-off) is measured. If the injection rate is not constant the data can be analyzed using a mathematical concept called the superposition principle in which the pressure contributions for each rate are added up. While effective, the application of this procedure is tedious. Maintaining a constant injection rate permits the use of simple data reduction methods.

A practical problem which arises in the measurement of pressure fall-off is wellbore storage. In this case wellbore storage affects the data when the water stored in the well after injection ceases drains into the formation. This problem is eliminated by the use of a downhole shut-in valve and by measuring the pressure fall-off below this valve. The procedure to determine if wellbore storage effects are influencing early-time data and the duration of these effects, is to plot log Δp versus log Δt. A straight line having a slope of one represents data which are influenced by wellbore storage. Additionally if the data develop a straight line having a slope of one half, this is evidence of linear flow.

A.2 METHOD OF DATA ANALYSIS

Data plots have been prepared to determine if any or all flow regimes occurred during each of the tests.

A.2.1 Possible Flow Regimes

There are several flow regimes which can occur in a formation. They are linear, radial, and spherical. A linear regime can occur if a natural or artificial high-permeability flow zone intersects the wellbore in the test interval. An artificial high-permeability flow zone would be an induced hydraulic fracture. The radial flow regime will almost always occur in a permeable formation that is bounded by low permeability or impermeable formations above and below. Spherical flow regime can occur when the test interval is small compared to the vertical extent of the formation. When analyzing test data one must determine which flow regimes exist. Often an understanding of the geology will alert the analyst to specific flow regimes.

A.2.2 Data Plotting

- Radial Flow

  For the radial flow regime the pressure drop, in this case the downhole or surface pressure (p) (proportional to the pressure drop), is proportional to the logarithm of injection time (ΔT). Radial flow is indicated where pressure versus log of time is linear. Flow is two dimensional, spreading out in a circular geometry as fluid moves away from the wellbore. Account must be made for multiple flow rates during a test.

  + For pressure build-up with a single rate, plot p vs. log (ΔT).

  + For pressure fall-off, plot p vs. log $\frac{(T+\Delta T)}{\Delta T}$ where T is the total time of the first rate. The quantity $\frac{(T+\Delta T)}{\Delta T}$ is referred to as the Horner time and is a dimensionless number.

The permeability is calculated from the slope (m) of the linear portion of the curve, the injection rate (q), and the injection inteval H using equation (A-1).

m = psi/cycle
q = Barrels per day
H = Injection interval in feet
k = permeability in md
μ = viscosity in centipoise = 1

$$k = \frac{162.6\, q\mu}{mH} \qquad \text{(A-1)}$$

In the radial flow regime, once the correct semi-log straight line has been determined and permeability has been calculated, the skin factor can be calculated:

$$\text{Skin Factor} = 1.1513 \left[\frac{(p_1 - p_w)}{m} - \log\left[\frac{k}{\phi\mu c r_w^2}\right] + 3.2275\right] \quad \text{(A-2)}$$

p_1 = pressure on straight-line portion of semi-log plot 1 hour after beginning a transient test, psi

p_w = bottom hole pressure immediately before shut-in, psi

c = compressibility of system, $psi^{-1} = 1x10^{-5}$

r_w = wellbore radius, feet

- Linear Flow

  In the linear flow regime the pressure is proportional to the square root of time, and linear flow is indicated by a linear relationship between pressure and square root of time. Flow is two dimensional with a constant area normal to flow as fluid moves from the fracture. Account must also be made for multiple rates during a test.

  + For pressure build-up with a single rate, plot p VS $\sqrt{\Delta T}$.
  + For pressure fall-off, plot p VS $\left[\sqrt{T+\Delta T} - \sqrt{\Delta T}\right]$

    The permeability cannot be calculated in this case because the length of the fracture is not known.

- Spherical Flow

  In the spherical flow regime, the pressure is inversely proportional to the square root of time, and spherical flow is indicated by a linear relationship between pressure and the reciprocal of the square root of time. Flow is three dimensional, with fluid spreading over a spherical geometry as it moves away from the wellbore. Account must also be made for multiple rates during a test.

  + For pressure build-up with a single rate, plot p VS $1/\sqrt{\Delta T}$
  + For pressure fall-off plot, p VS $\left[\frac{1}{\sqrt{\Delta T}} - \frac{1}{\sqrt{T+\Delta T}}\right]$

  The permeability is calculated from the slope of the linear portion of the curve (m), the injection rate (q), and the porosity (ϕ), viscosity (μ), and compressibility (c). For this case, m has units of psi $\sqrt{\text{hour}}$.

$$k = 182.4 \left[\frac{qu(\phi\mu c)^{1/2}}{m}\right]^{2/3} \quad \text{(A-3)}$$

A.2.3 Data Interpretation

The data for each of the pressure transient tests are plotted in Figures A-1 through A-39. Inspection of the data plots indicates that a specific flow regime is not maintained throughout the test, as no graph demonstrates linearity over the majority of the plot. This indicates that both the permeability and/or flow geometry are changing throughout the test. The former is readily illustrated by the pressure build-up data where injection pressure remains nearly constant at large time. Specific plots have been selected that are thought to come the closest to representing a specific flow regime for use in calculating values of permeability. The downhole shut-in tool was effective in eliminating wellbore storage, as none of the log-log plots are of slope unity.

Table A-1 summarizes the grouping of plots by flow regime analysis and where a specific flow regime appears to be indicated. Tables 4-3 and 4-4 list the specific values of the test parameters and data obtained from the plots that are used in the calculation of permeability.

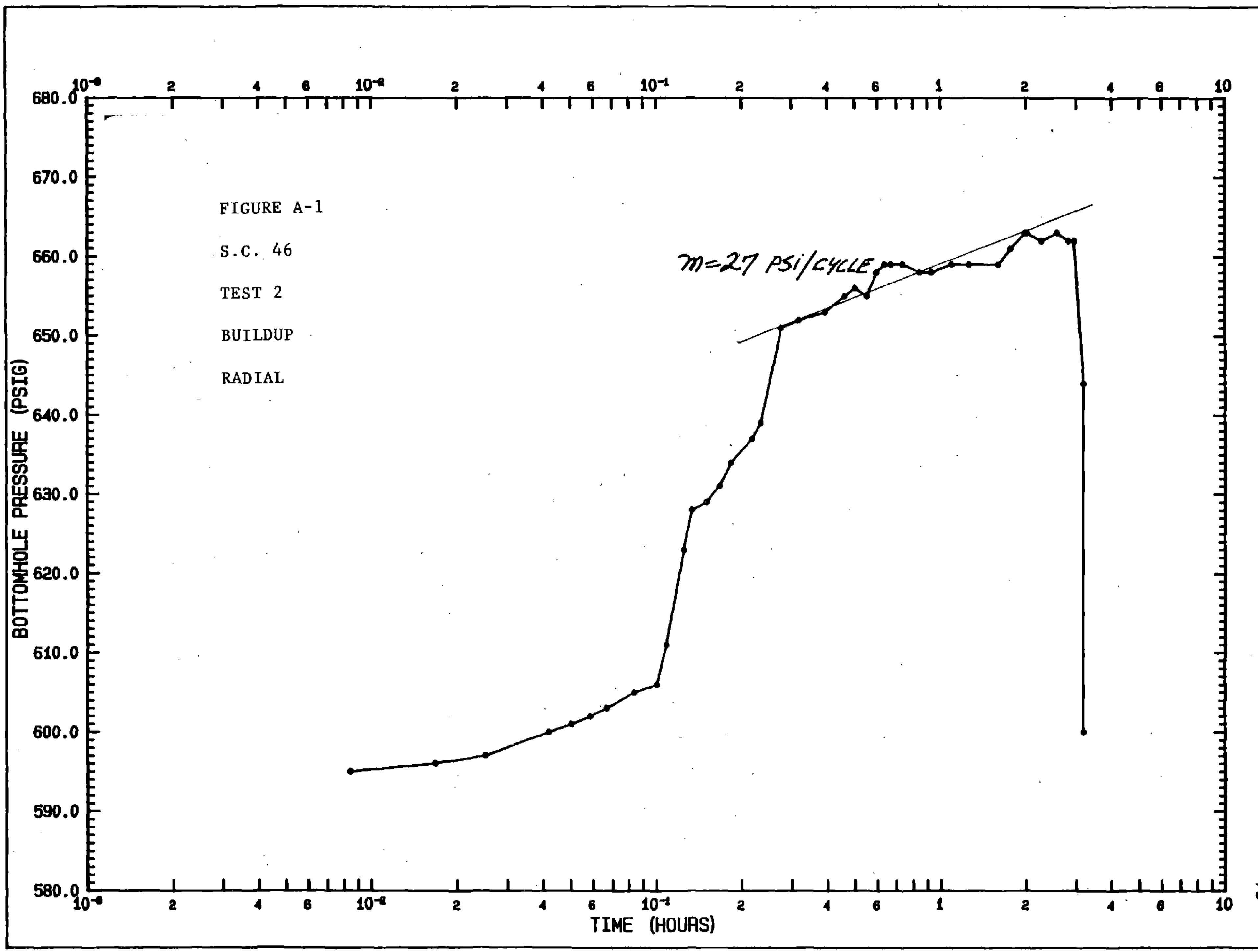


FIGURE A-1
S.C. 46
TEST 2
BUILDUP
RADIAL
m=27 PSI/CYCLE
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)
680.0
670.0
660.0
650.0
640.0
630.0
620.0
610.0
600.0
590.0
580.0

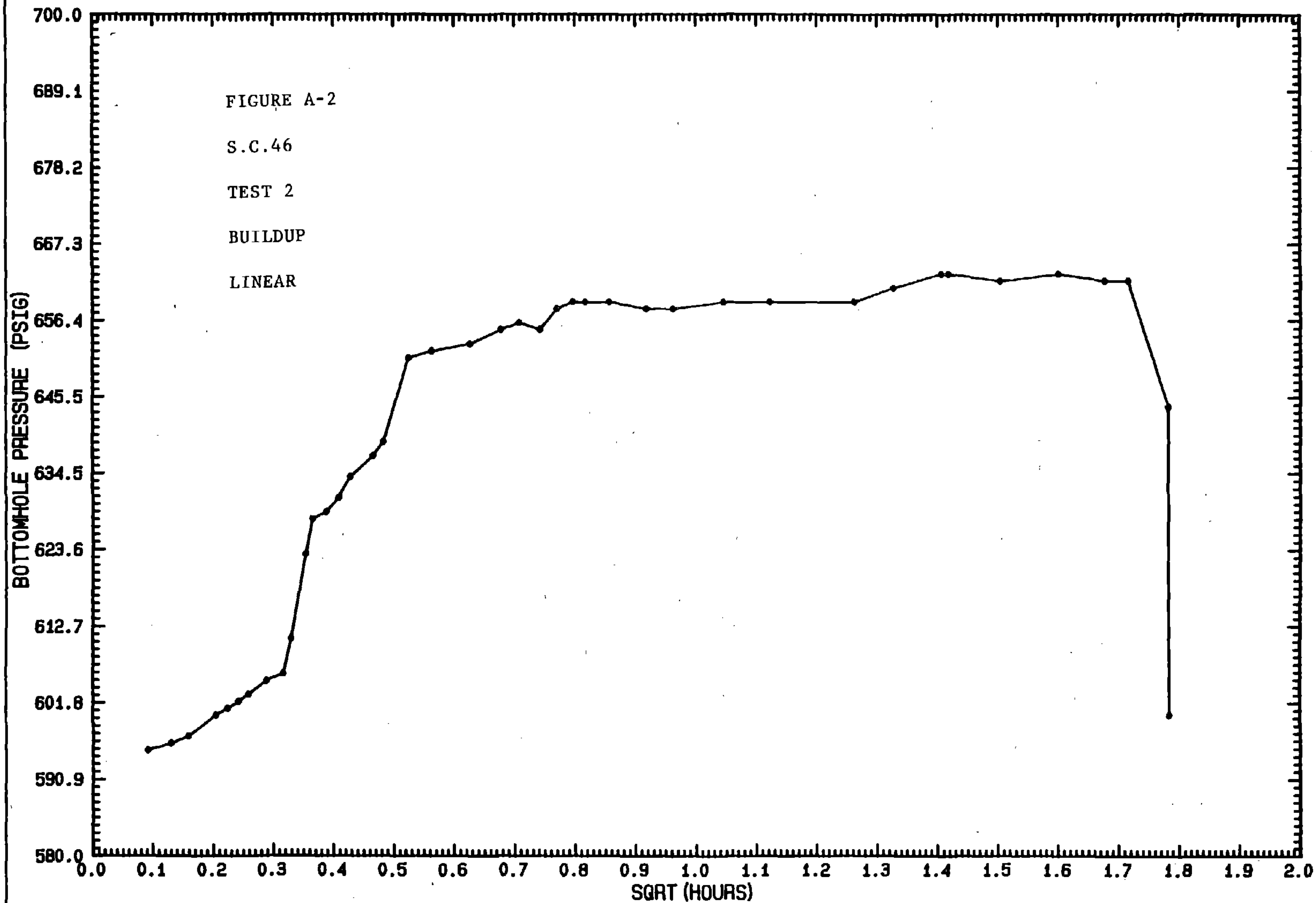


FIGURE A-2
S.C.46
TEST 2
BUILDUP
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
SQRT (HOURS)
700.0
689.1
678.2
667.3
656.4
645.5
634.5
623.6
612.7
601.8
590.9
580.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

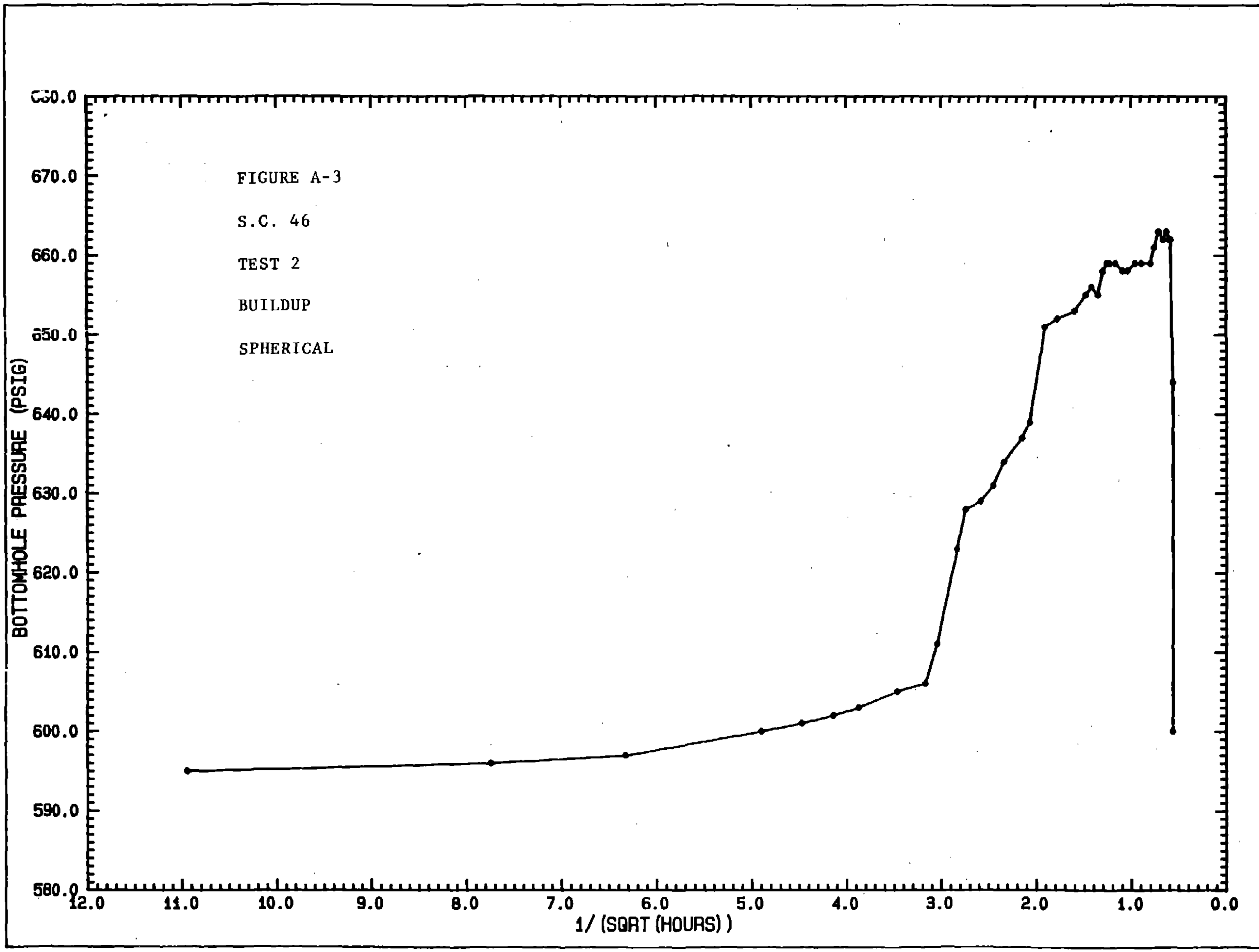


FIGURE A-3
S.C. 46
TEST 2
BUILDUP
SPHERICAL
BOTTOMHOLE PRESSURE (PSIG)
1/ (SQRT (HOURS))
680.0
670.0
660.0
650.0
640.0
630.0
620.0
610.0
600.0
590.0
580.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

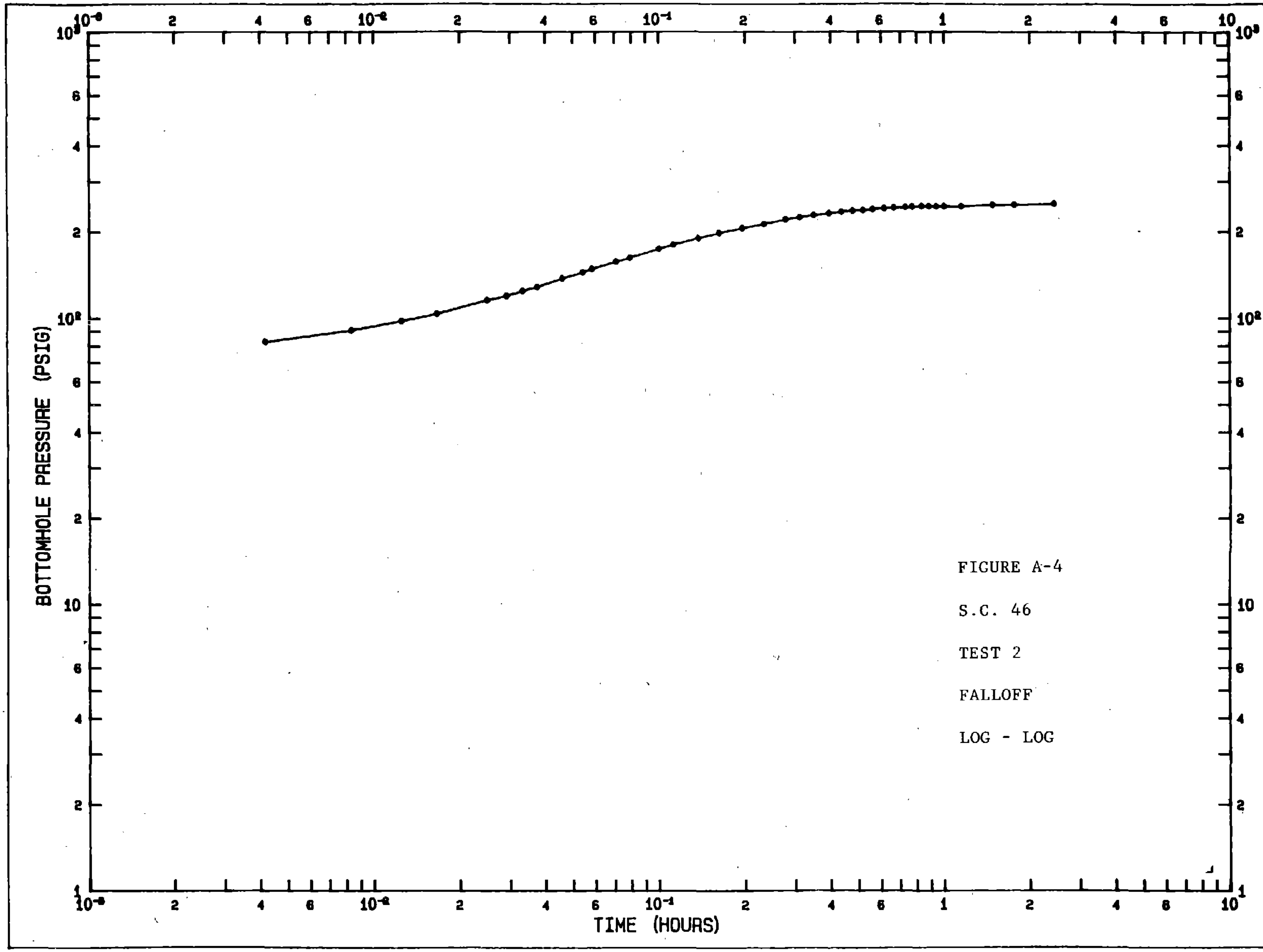


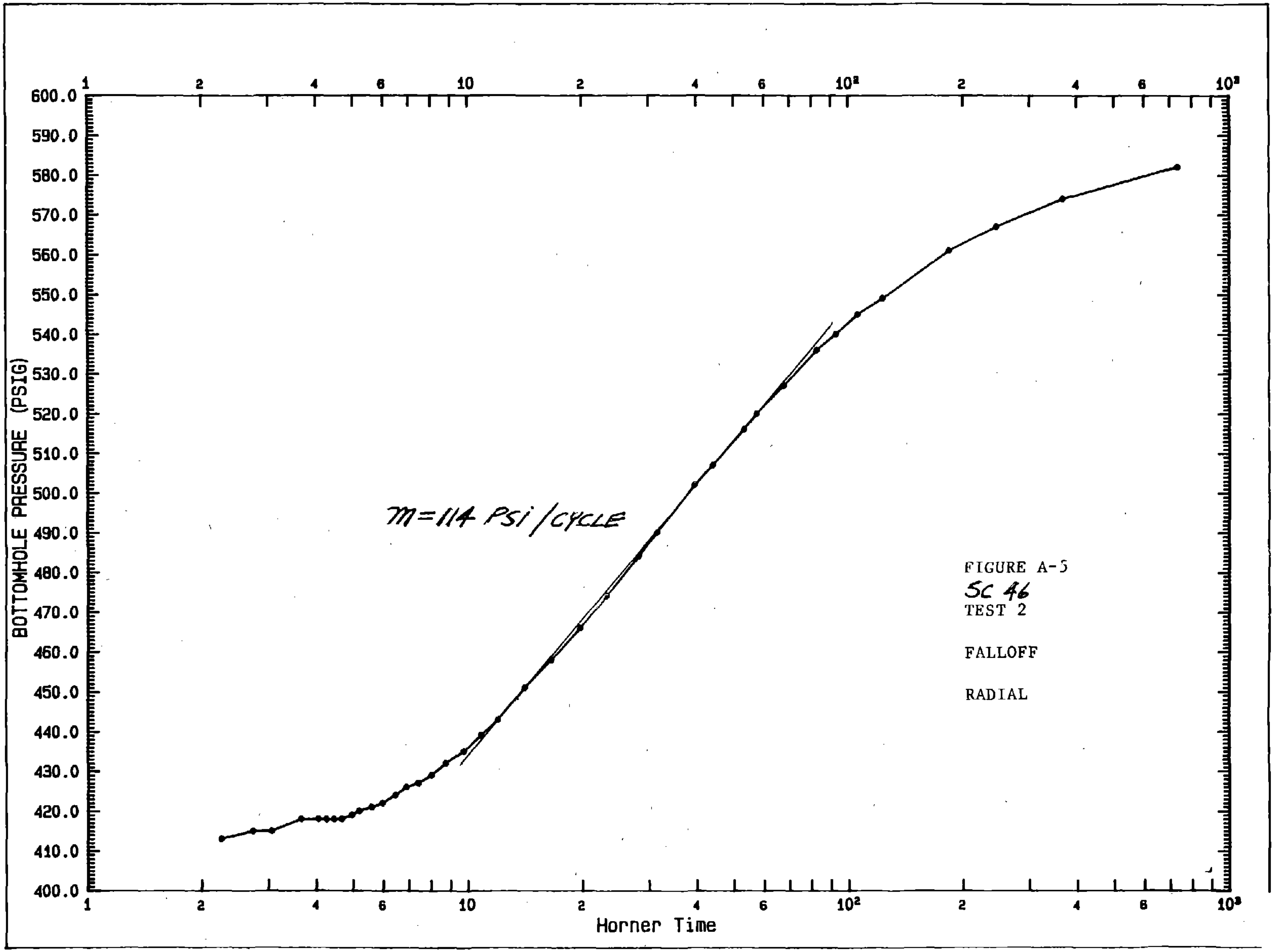
FIGURE A-4

S.C. 46

TEST 2

FALLOFF

LOG - LOG


BOTTOMHOLE PRESSURE (PSIG)
Horner Time
m=114 PSI/CYCLE
FIGURE A-5
SC 46
TEST 2
FALLOFF
RADIAL

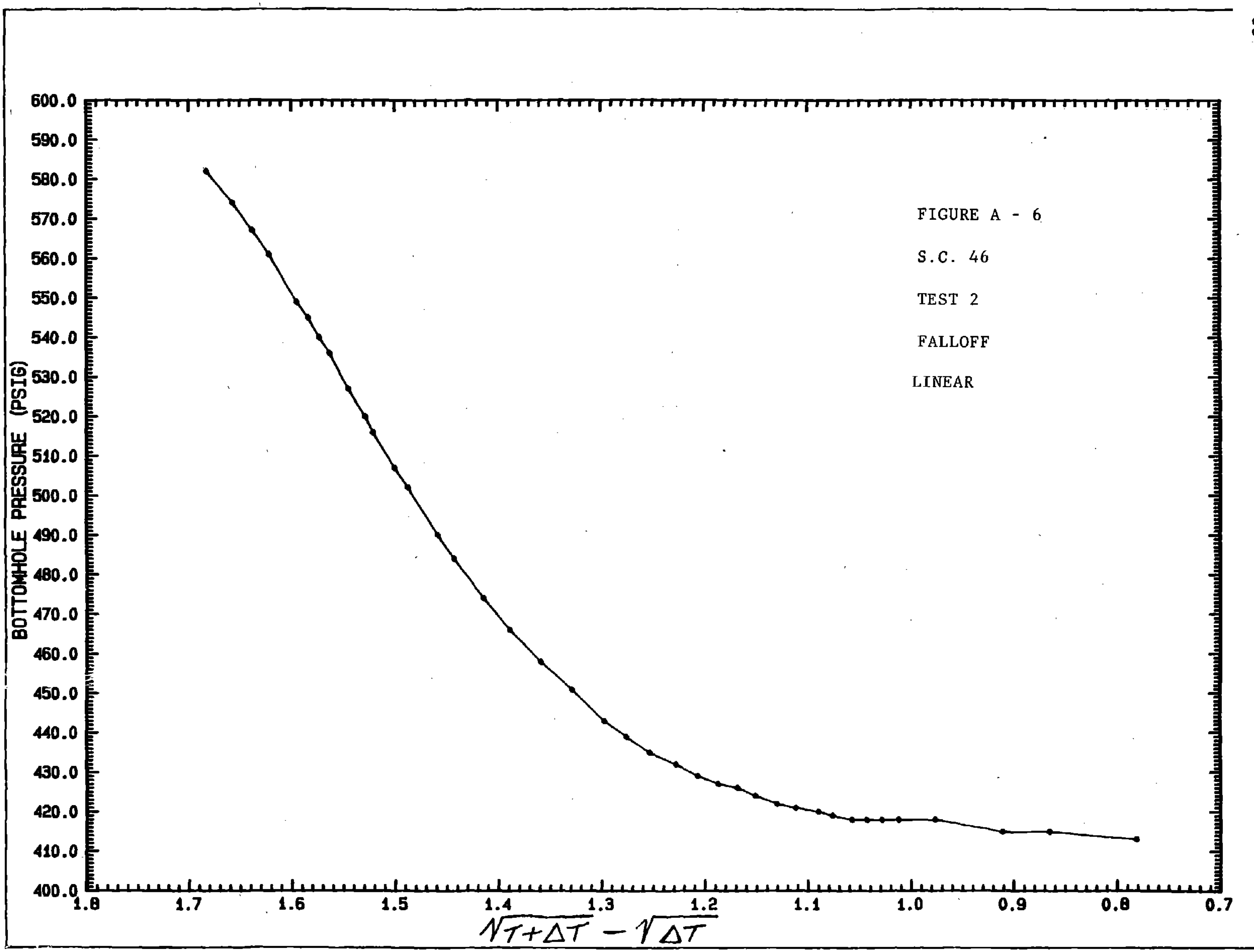
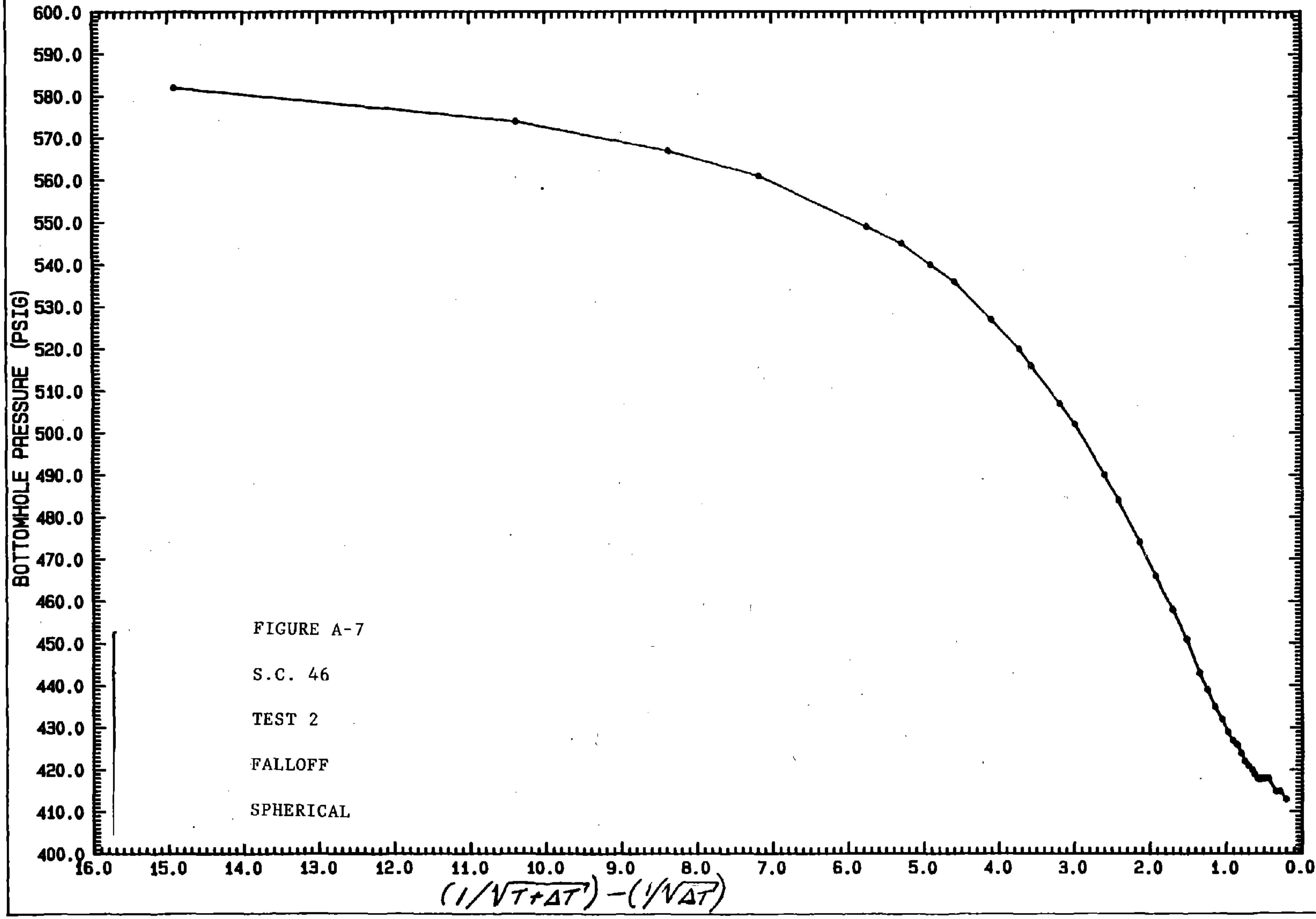


FIGURE A - 6
S.C. 46
TEST 2
FALLOFF
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
600.0
590.0
580.0
570.0
560.0
550.0
540.0
530.0
520.0
510.0
500.0
490.0
480.0
470.0
460.0
450.0
440.0
430.0
420.0
410.0
400.0
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
√T+ΔT − √ΔT


BOTTOMHOLE PRESSURE (PSIG)
600.0
590.0
580.0
570.0
560.0
550.0
540.0
530.0
520.0
510.0
500.0
490.0
480.0
470.0
460.0
450.0
440.0
430.0
420.0
410.0
400.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
$(1/\sqrt{T+\Delta T}) - (1/\sqrt{\Delta T})$
FIGURE A-7
S.C. 46
TEST 2
FALLOFF
SPHERICAL

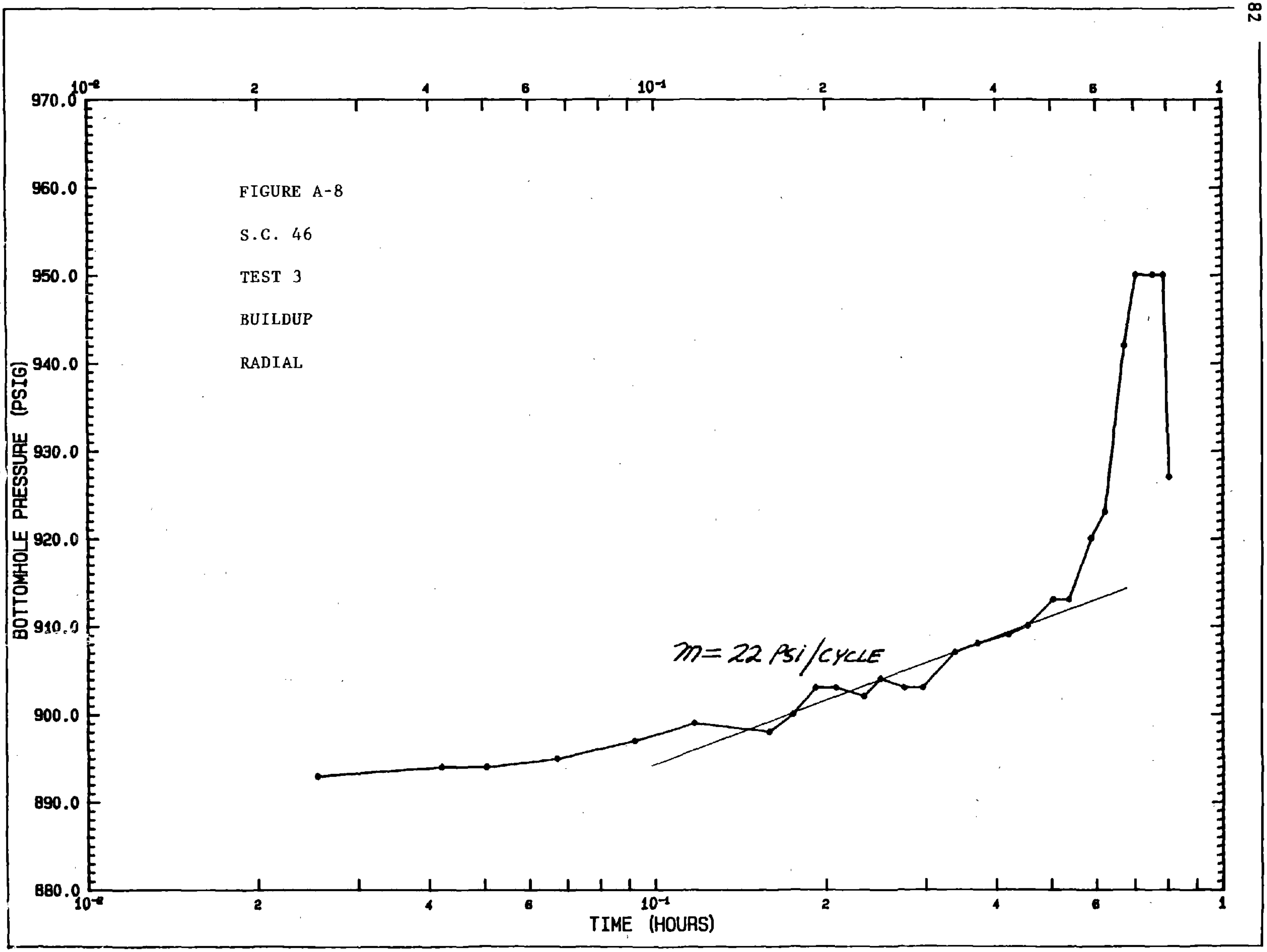


FIGURE A-8

S.C. 46

TEST 3

BUILDUP

RADIAL

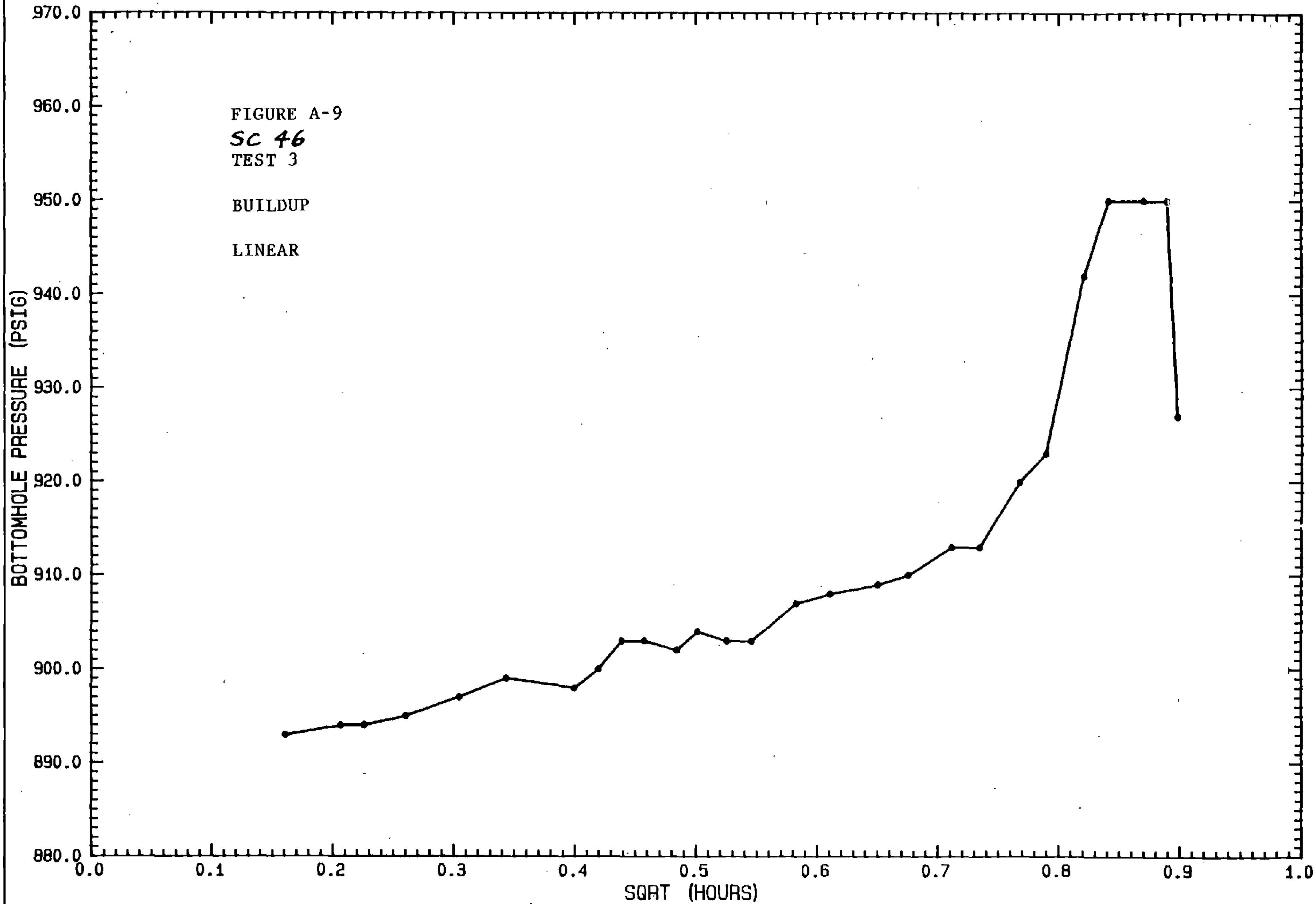


FIGURE A-9
SC 46
TEST 3
BUILDUP
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
970.0
960.0
950.0
940.0
930.0
920.0
910.0
900.0
890.0
880.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SQRT (HOURS)

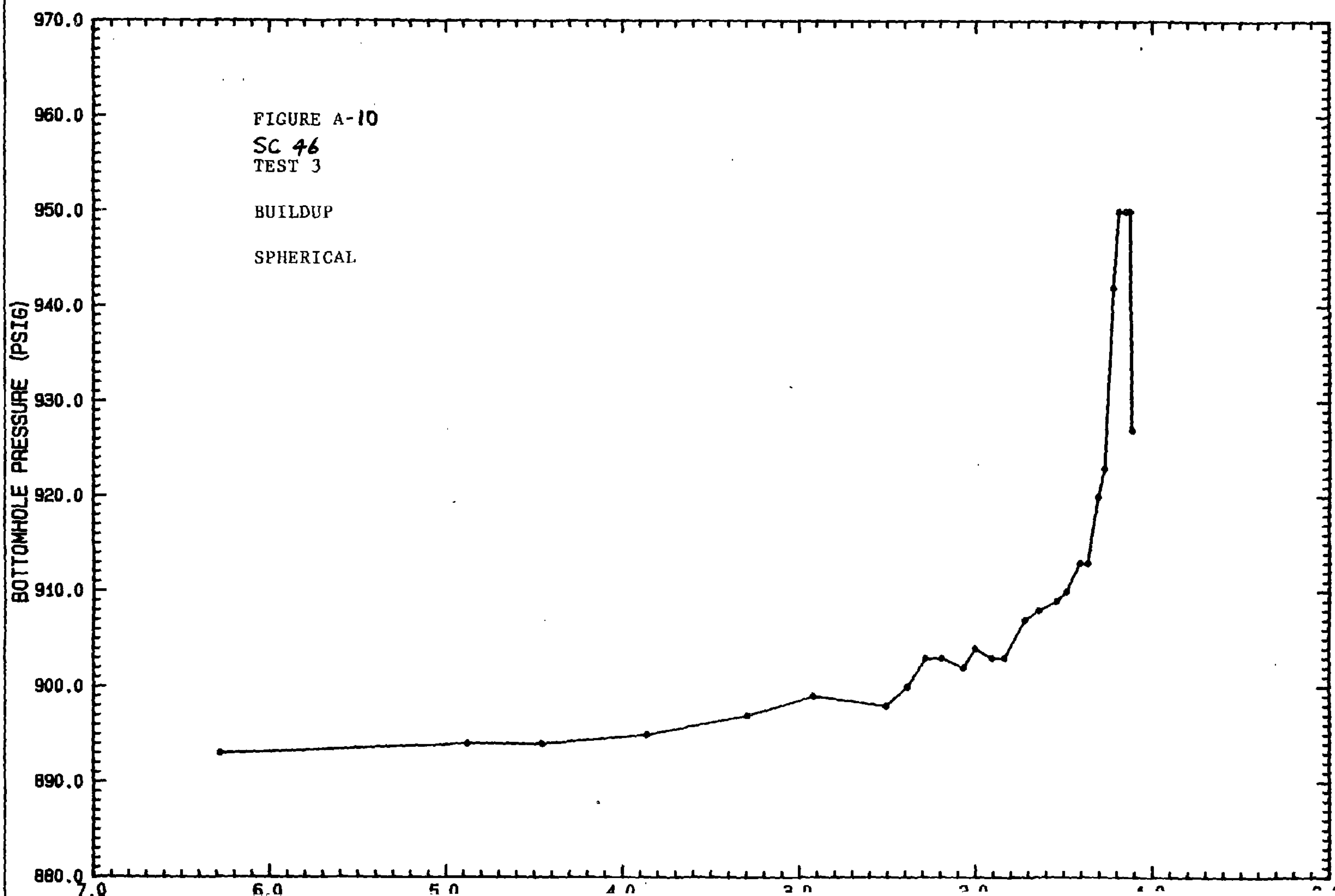
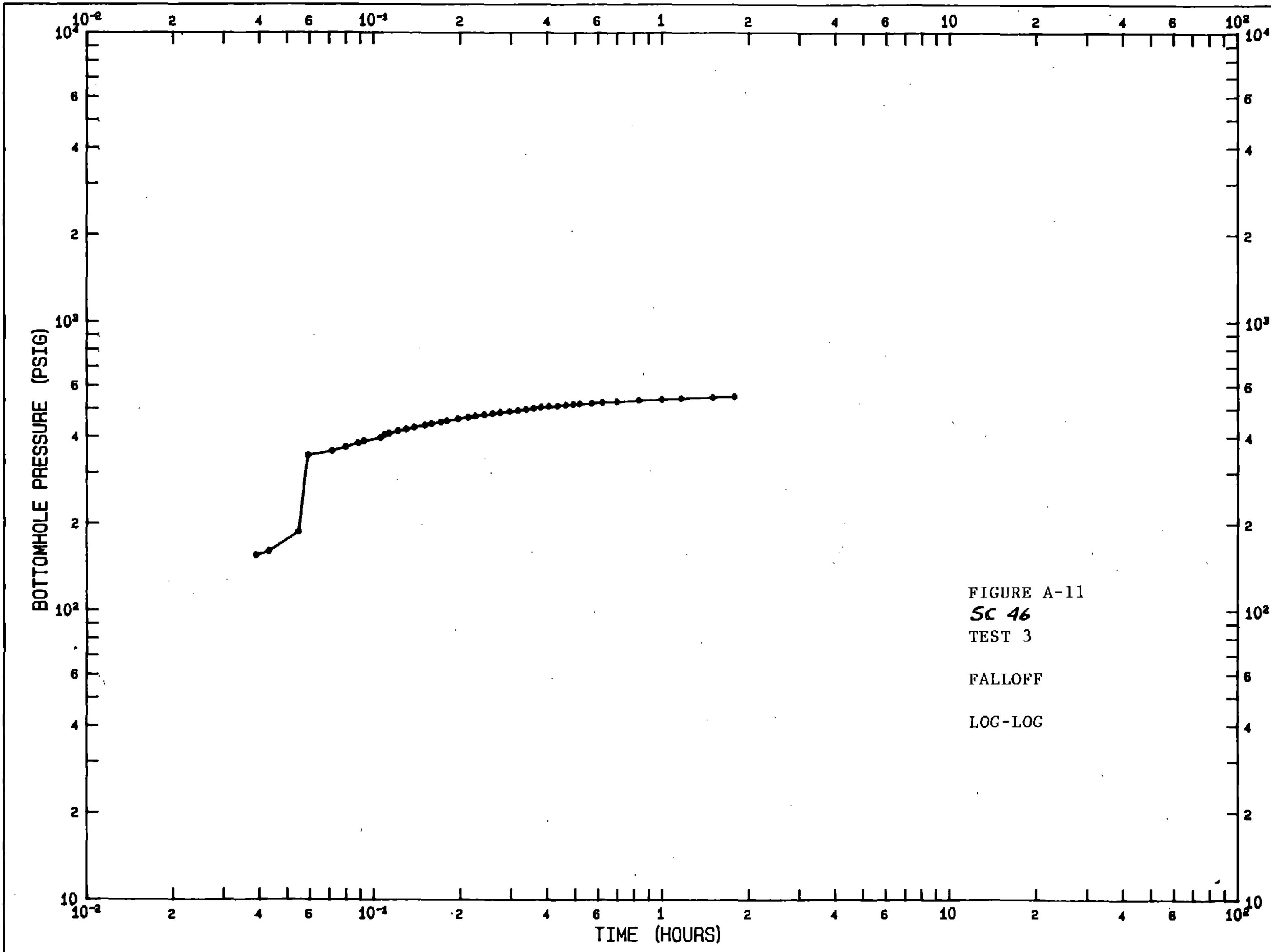


FIGURE A-10
SC 46
TEST 3
BUILDUP
SPHERICAL
BOTTOMHOLE PRESSURE (PSIG)
970.0
960.0
950.0
940.0
930.0
920.0
910.0
900.0
890.0
880.0
7.0
6.0
5.0
4.0


BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)
FIGURE A-11
SC 46
TEST 3
FALLOFF
LOG-LOG

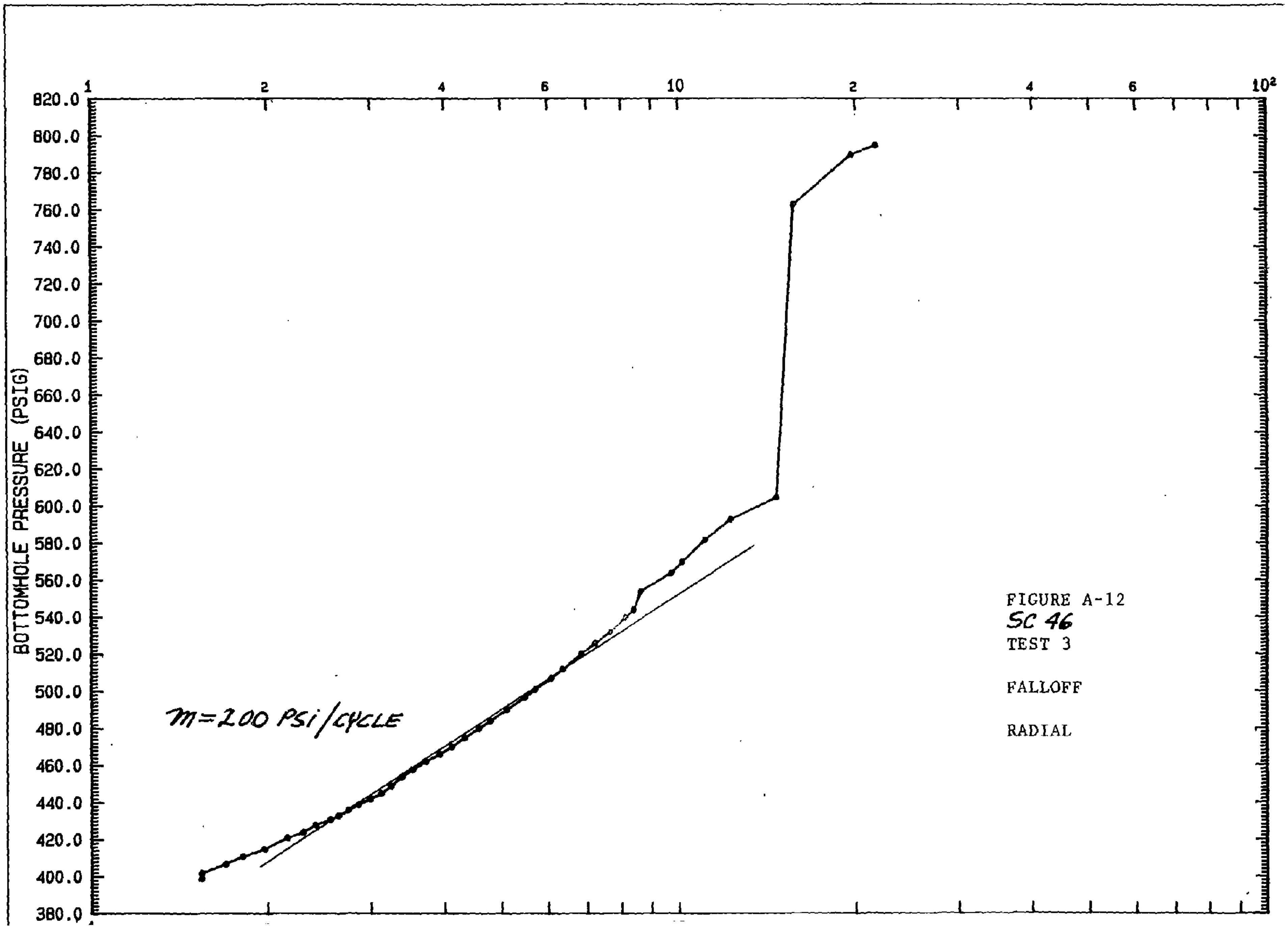


FIGURE A-12
SC 46
TEST 3

FALLOFF

RADIAL

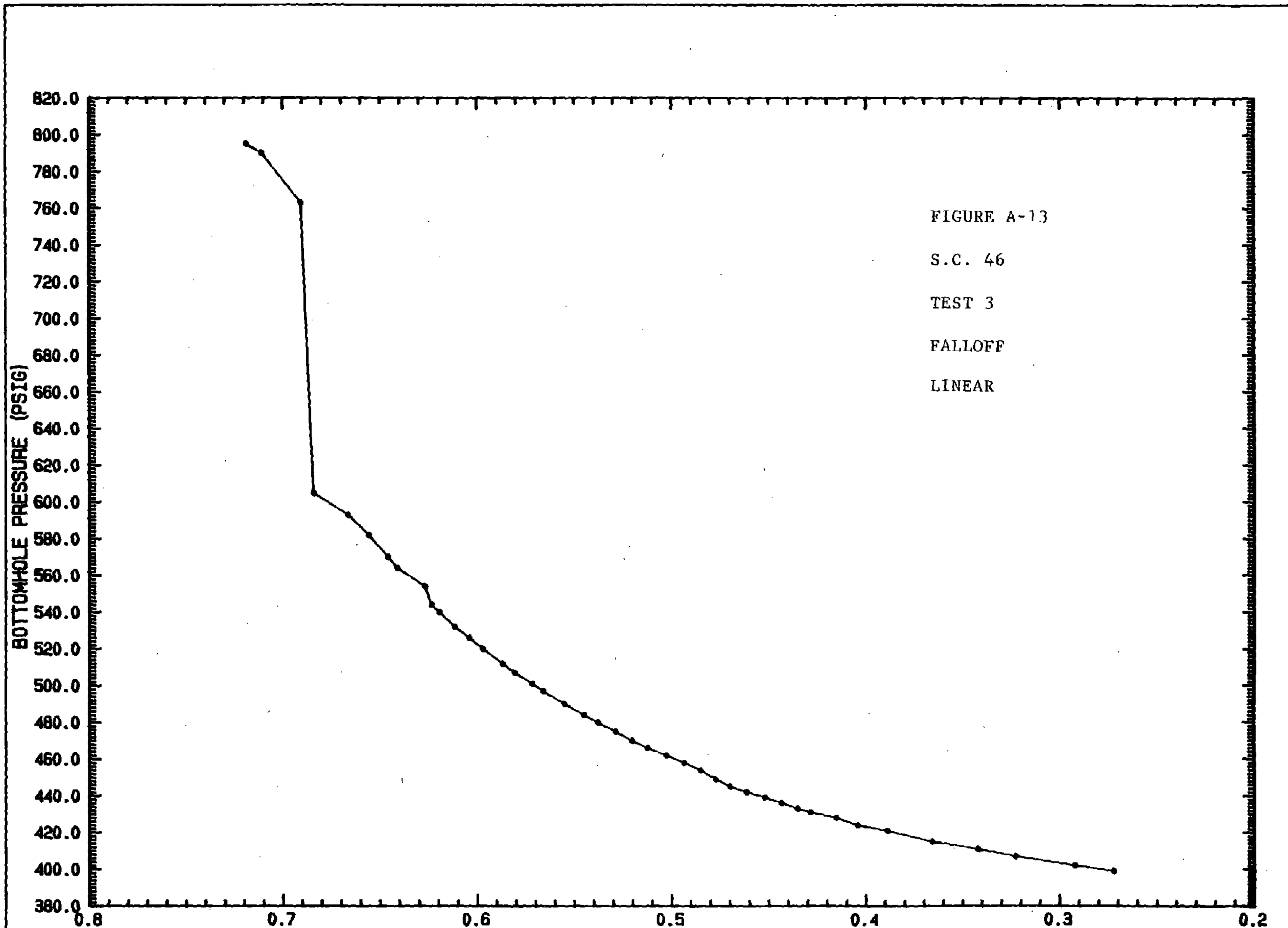
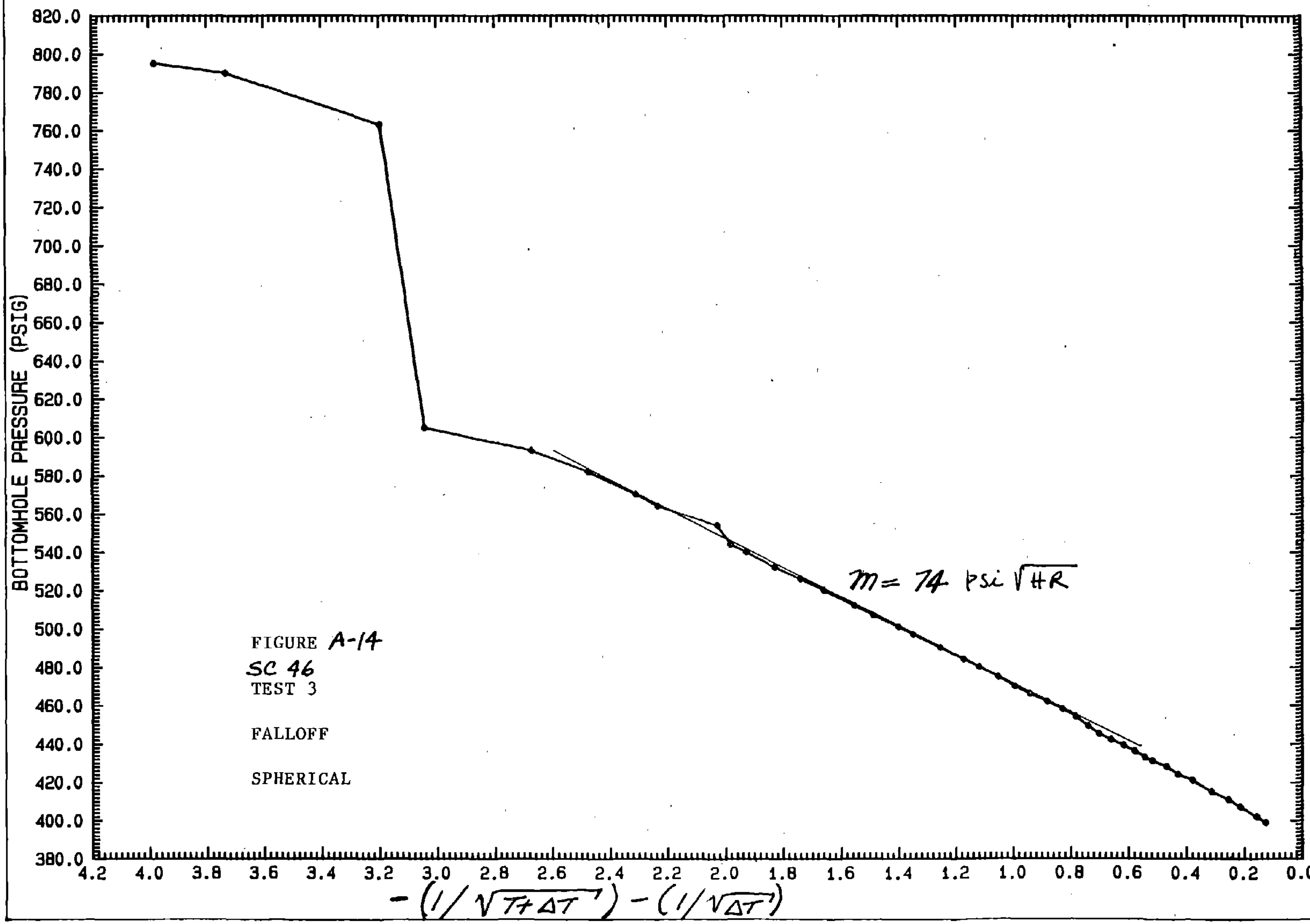


FIGURE A-13
S.C. 46
TEST 3
FALLOFF
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
820.0
800.0
780.0
760.0
740.0
720.0
700.0
680.0
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
0.8
0.7
0.6
0.5
0.4
0.3
0.2


BOTTOMHOLE PRESSURE (PSIG)
820.0
800.0
780.0
760.0
740.0
720.0
700.0
680.0
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
m= 74 psi √HR
FIGURE A-14
SC 46
TEST 3
FALLOFF
SPHERICAL
-(1/√T+ΔT) -(1/√ΔT)

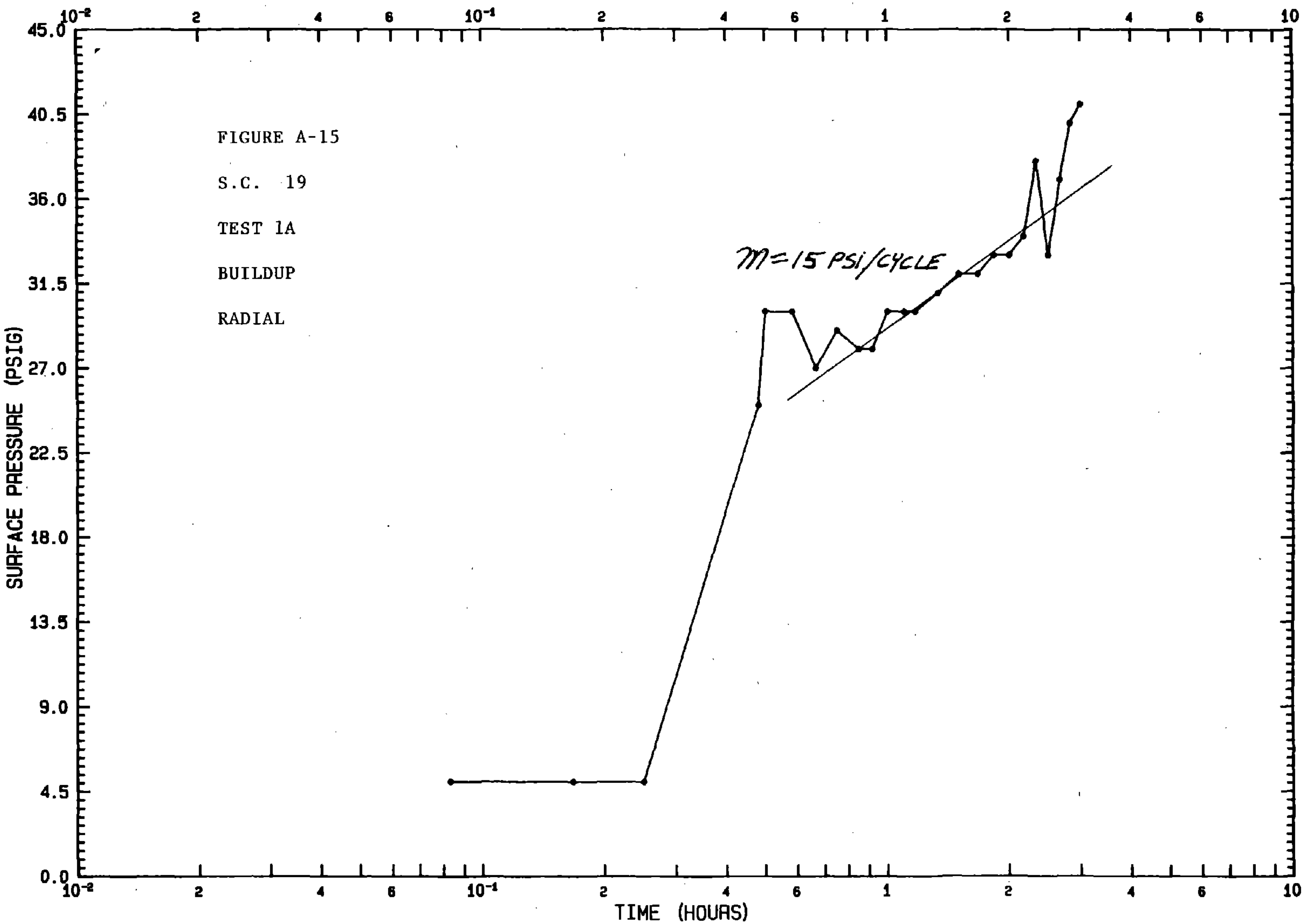


FIGURE A-15
S.C. 19
TEST 1A
BUILDUP
RADIAL
m=15 PSI/CYCLE
SURFACE PRESSURE (PSIG)
TIME (HOURS)
45.0
40.5
36.0
31.5
27.0
22.5
18.0
13.5
9.0
4.5
0.0
10⁻²
2
4
6
10⁻¹
1
10

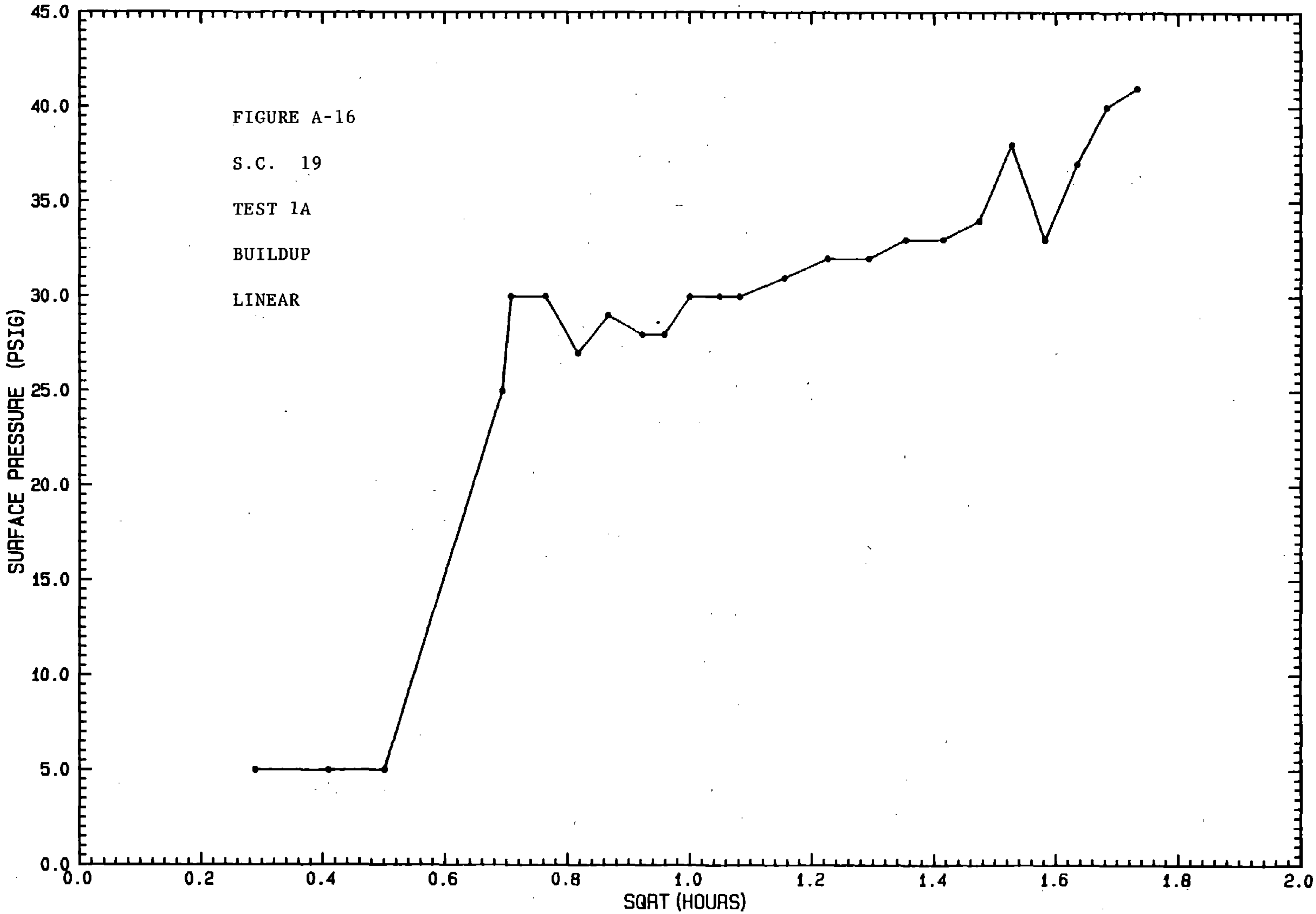


FIGURE A-16
S.C. 19
TEST 1A
BUILDUP
LINEAR
SURFACE PRESSURE (PSIG)
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
SQRT (HOURS)

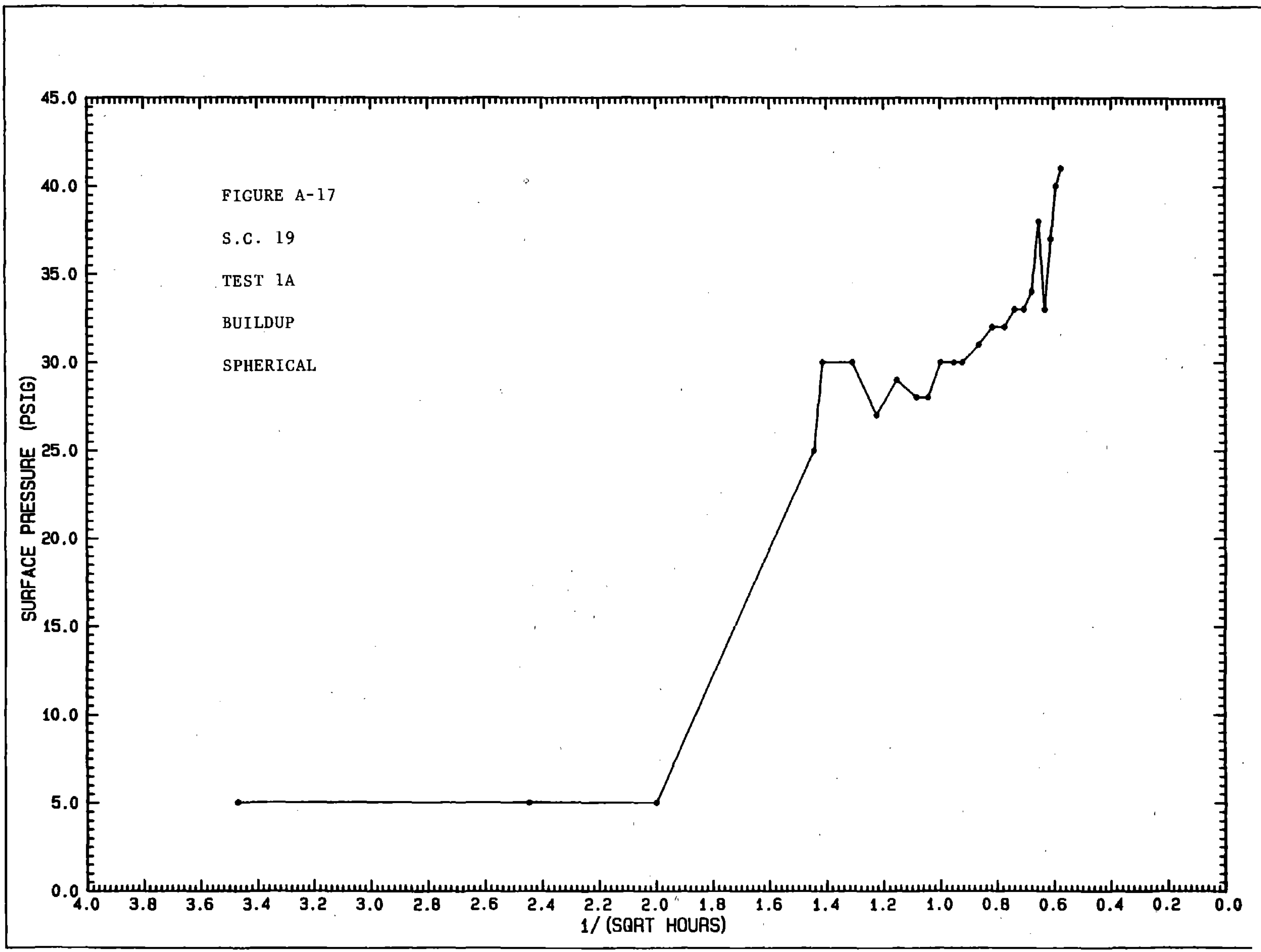


FIGURE A-17
S.C. 19
TEST 1A
BUILDUP
SPHERICAL
SURFACE PRESSURE (PSIG)
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1/(SQRT HOURS)

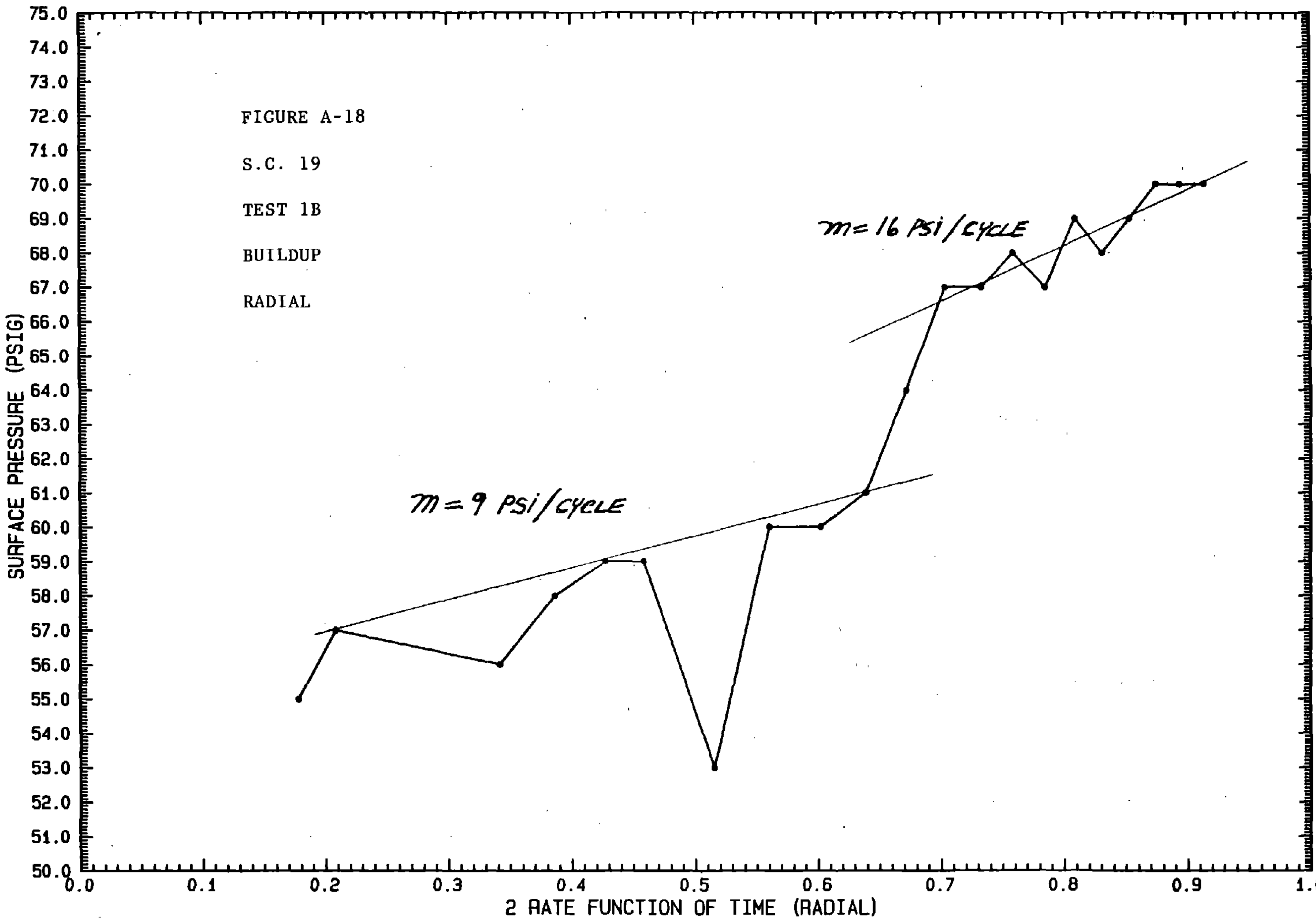


FIGURE A-18
S.C. 19
TEST 1B
BUILDUP
RADIAL
m = 16 PSI/CYCLE
m = 9 PSI/CYCLE
SURFACE PRESSURE (PSIG)
2 RATE FUNCTION OF TIME (RADIAL)
75.0
74.0
73.0
72.0
71.0
70.0
69.0
68.0
67.0
66.0
65.0
64.0
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
55.0
54.0
53.0
52.0
51.0
50.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

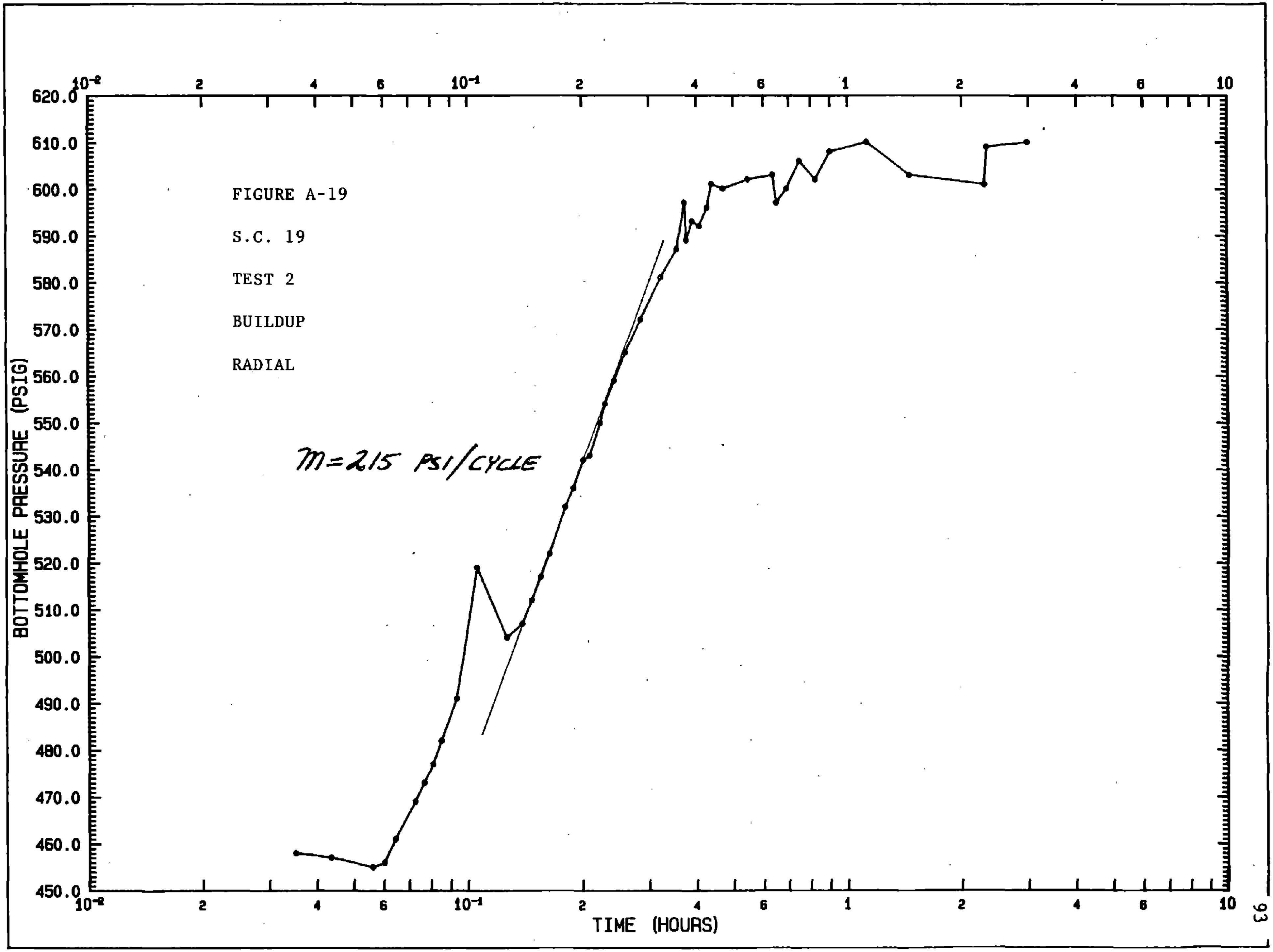


FIGURE A-19
S.C. 19
TEST 2
BUILDUP
RADIAL
m=215 PSI/CYCLE
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)

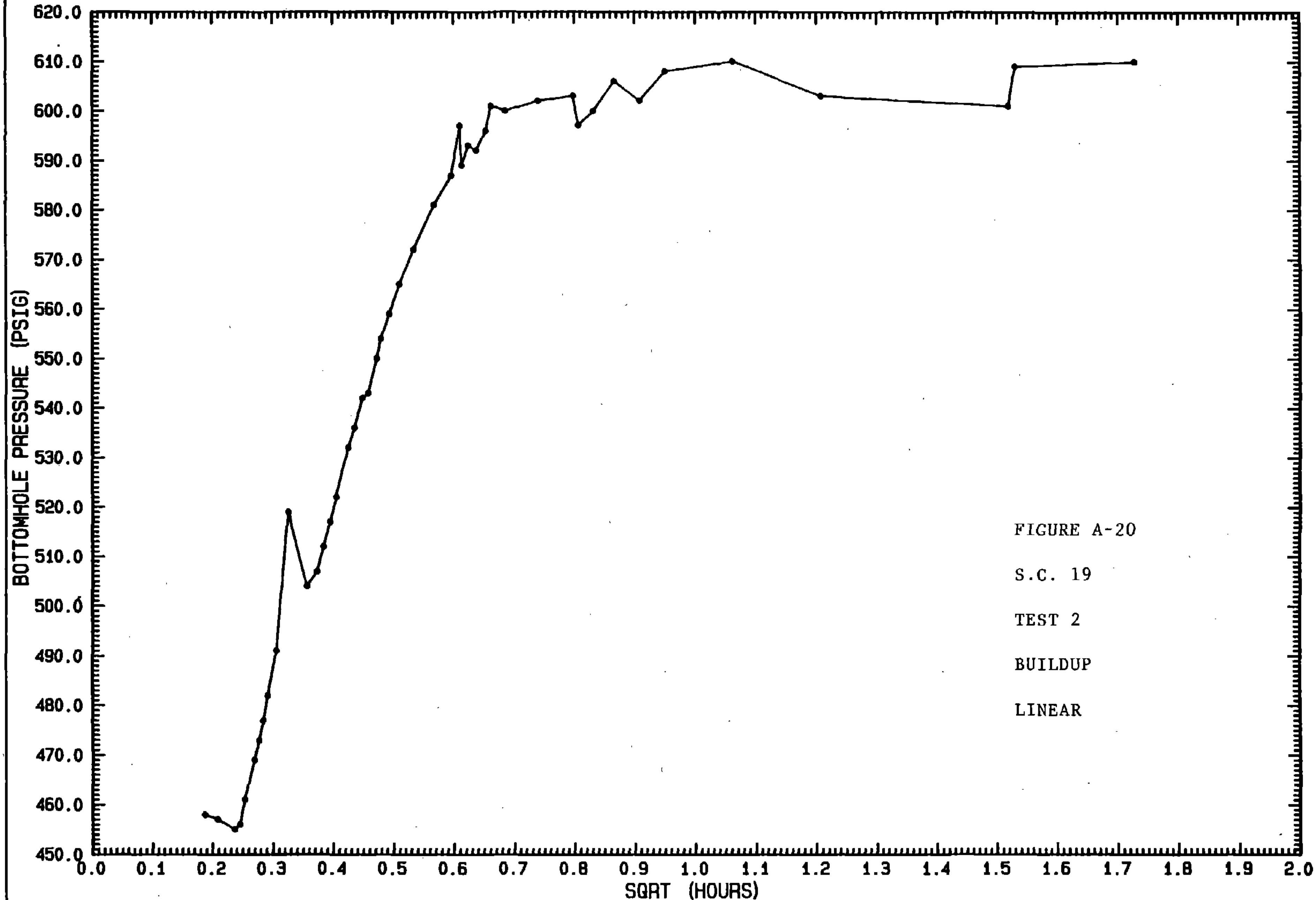


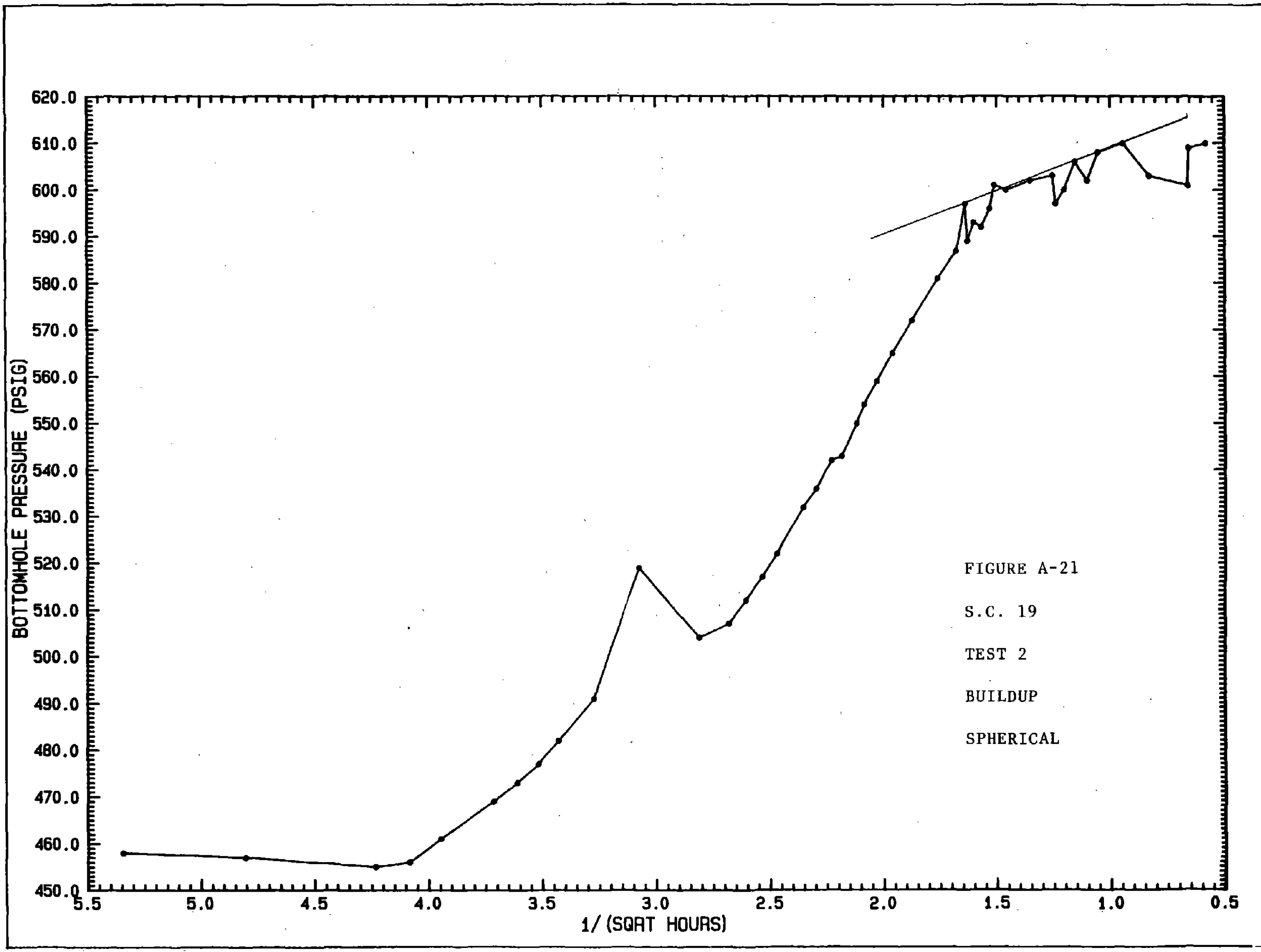
FIGURE A-20

S.C. 19

TEST 2

BUILDUP

LINEAR


620.0
610.0
600.0
590.0
580.0
570.0
560.0
550.0
540.0
530.0
520.0
510.0
500.0
490.0
480.0
470.0
460.0
450.0
BOTTOMHOLE PRESSURE (PSIG)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1/(SQRT HOURS)
FIGURE A-21
S.C. 19
TEST 2
BUILDUP
SPHERICAL

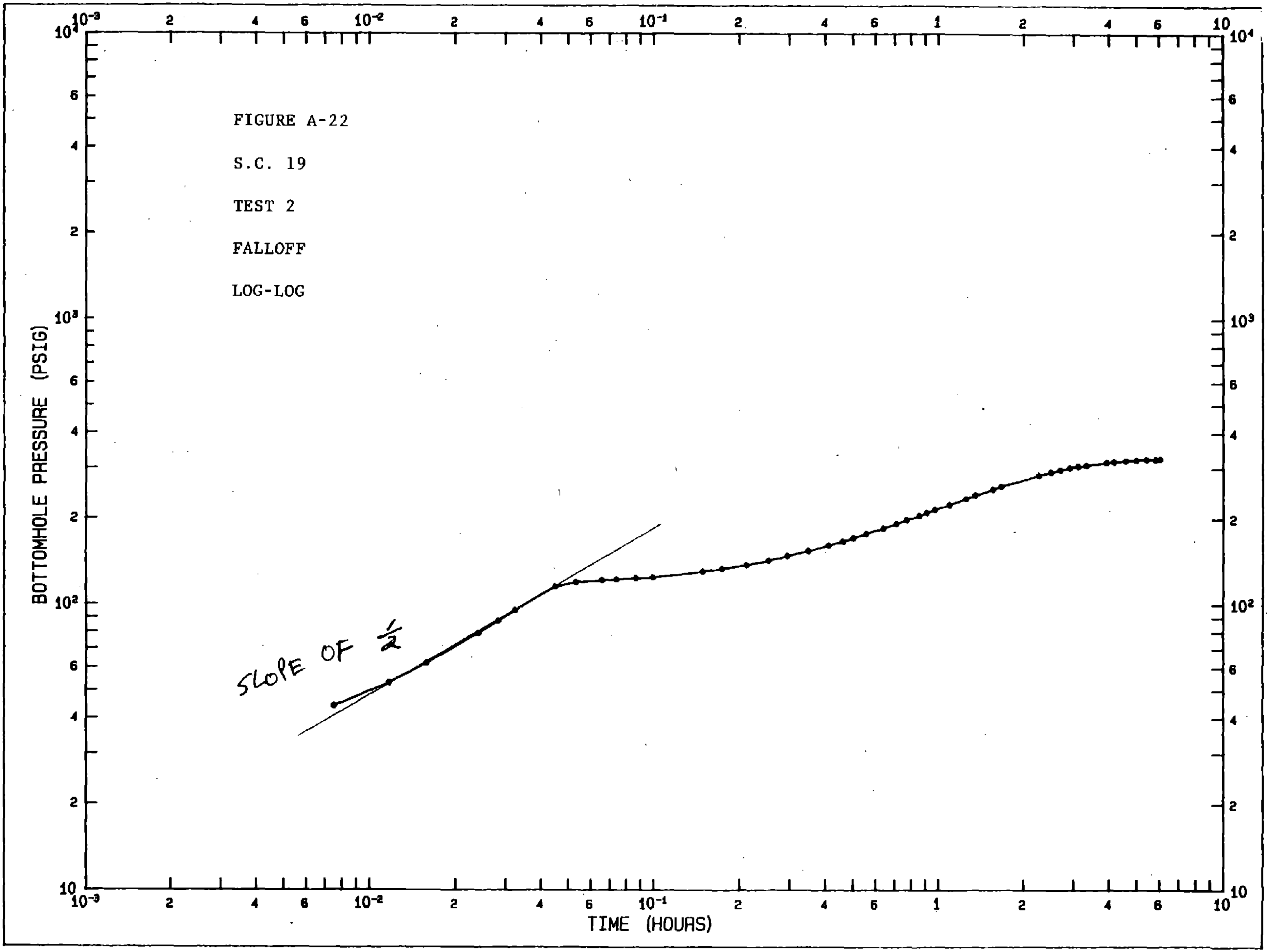
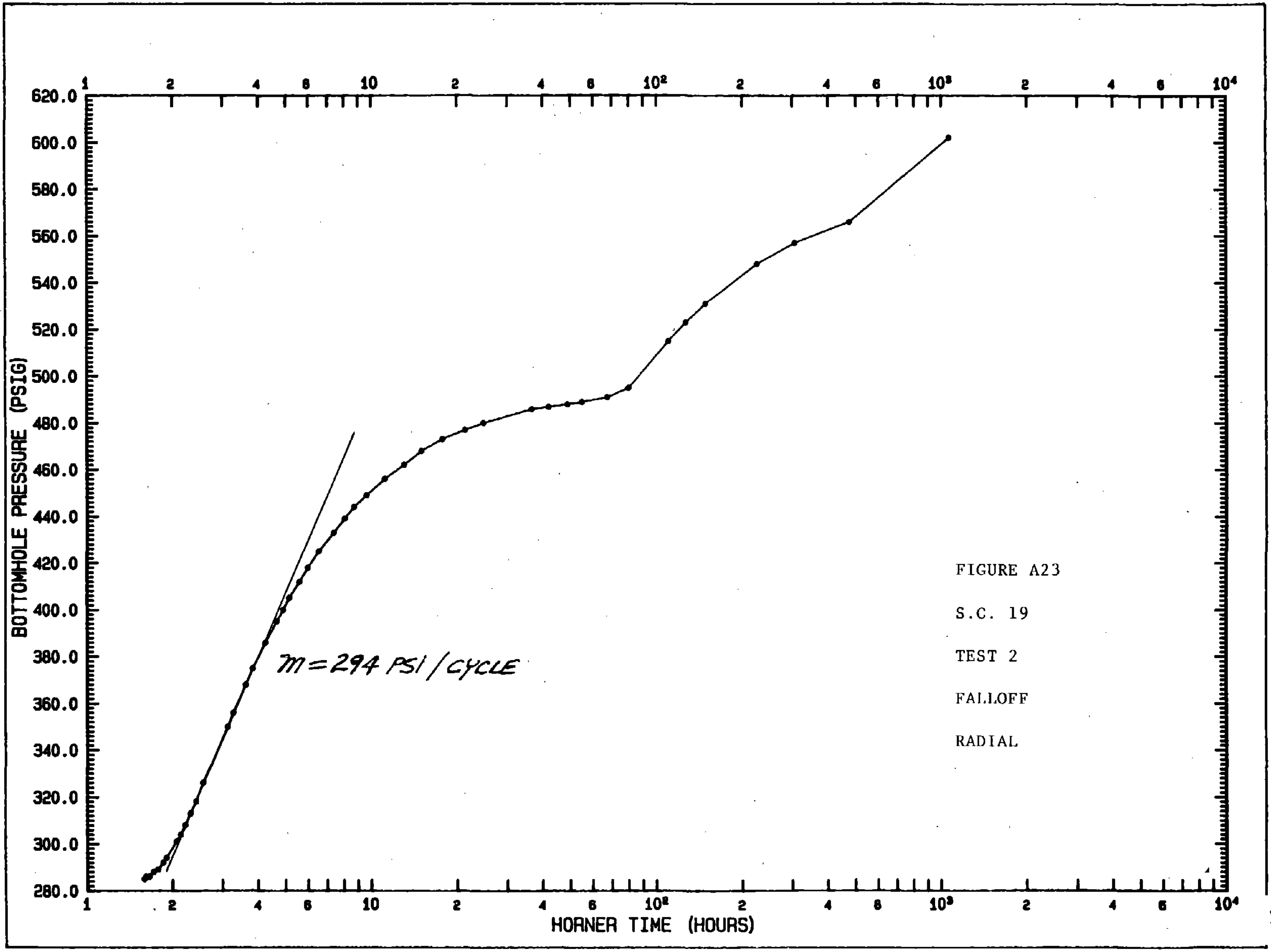


FIGURE A-22
S.C. 19
TEST 2
FALLOFF
LOG-LOG
SLOPE OF 1/2
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)
10^-3
10^-2
10^-1
1
10
10^4
10^3
10^2
10


BOTTOMHOLE PRESSURE (PSIG)
HORNER TIME (HOURS)
m=294 PSI/CYCLE
FIGURE A23
S.C. 19
TEST 2
FALLOFF
RADIAL

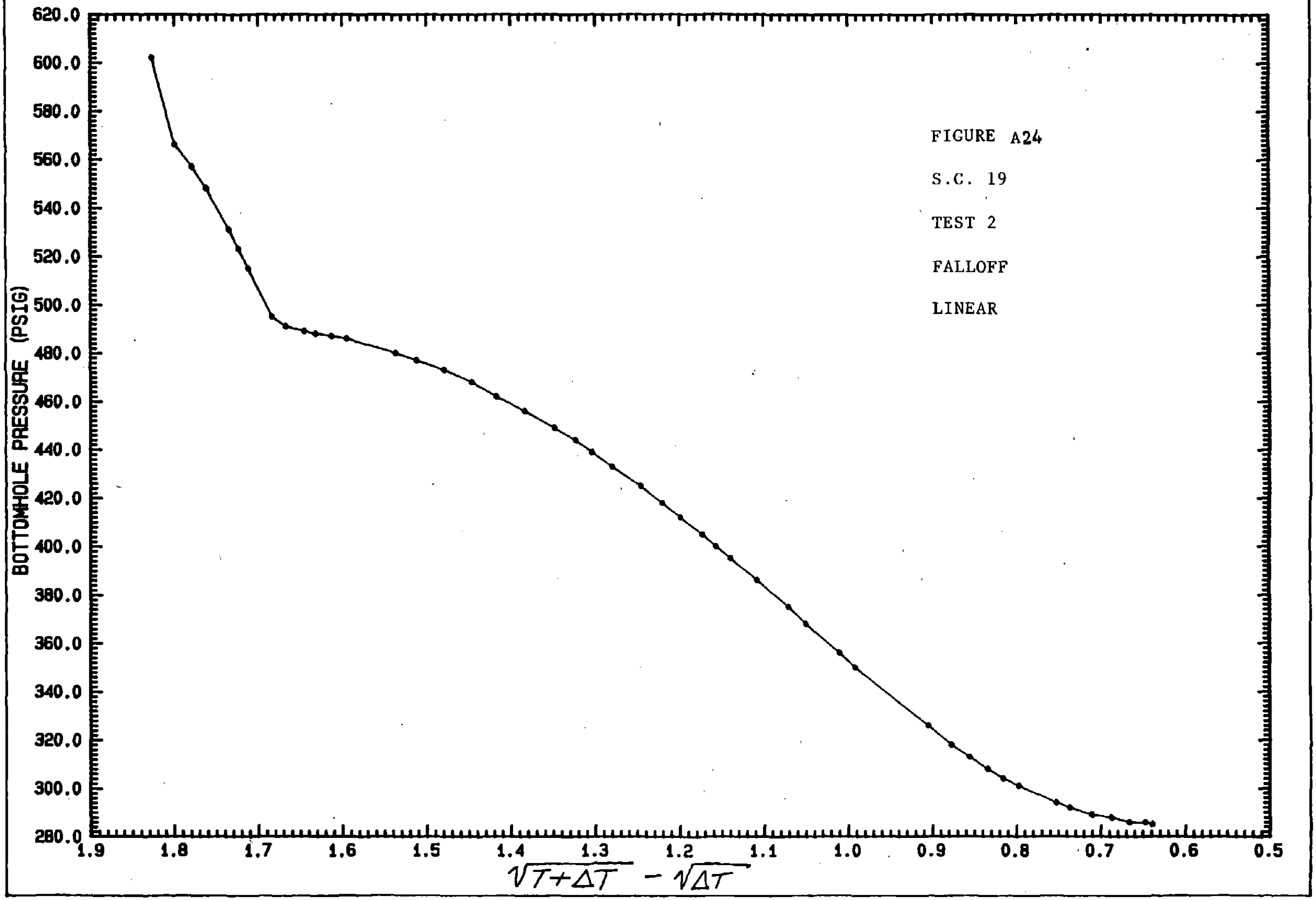
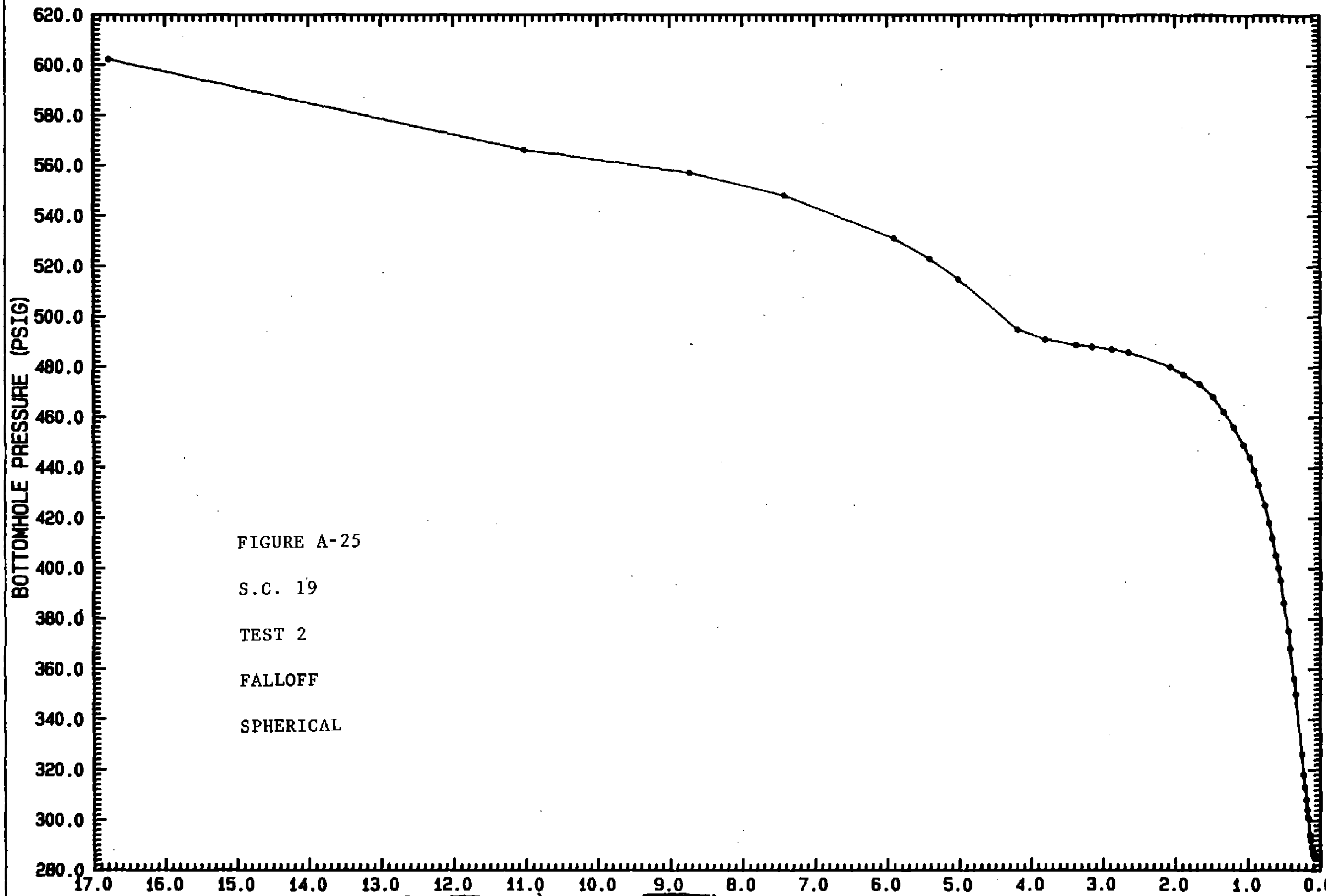


FIGURE A24
S.C. 19
TEST 2
FALLOFF
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
$\sqrt{T+\Delta T} - \sqrt{\Delta T}$



$-(1/\sqrt{T+\Delta T})-(1/\sqrt{\Delta T})$

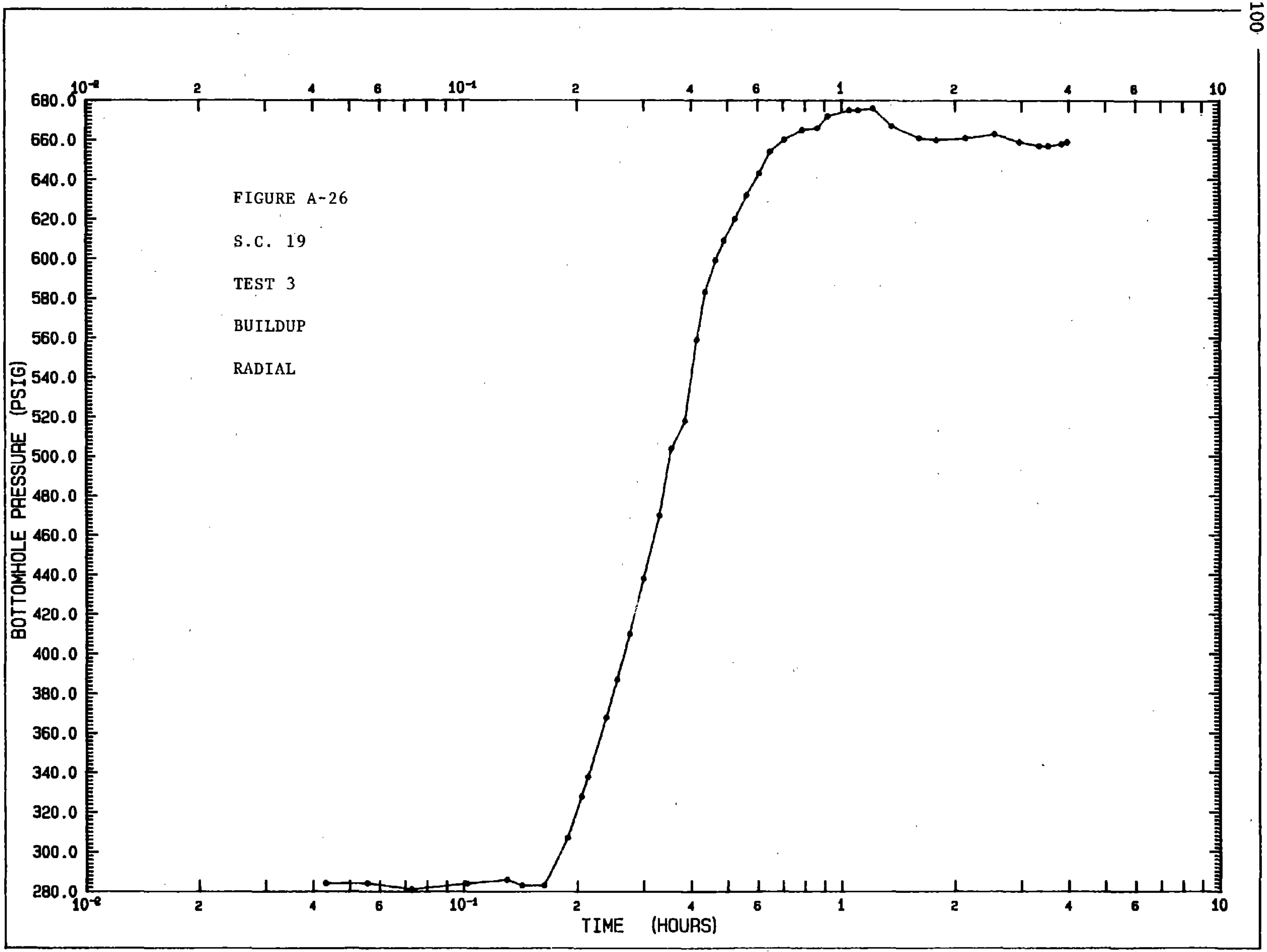
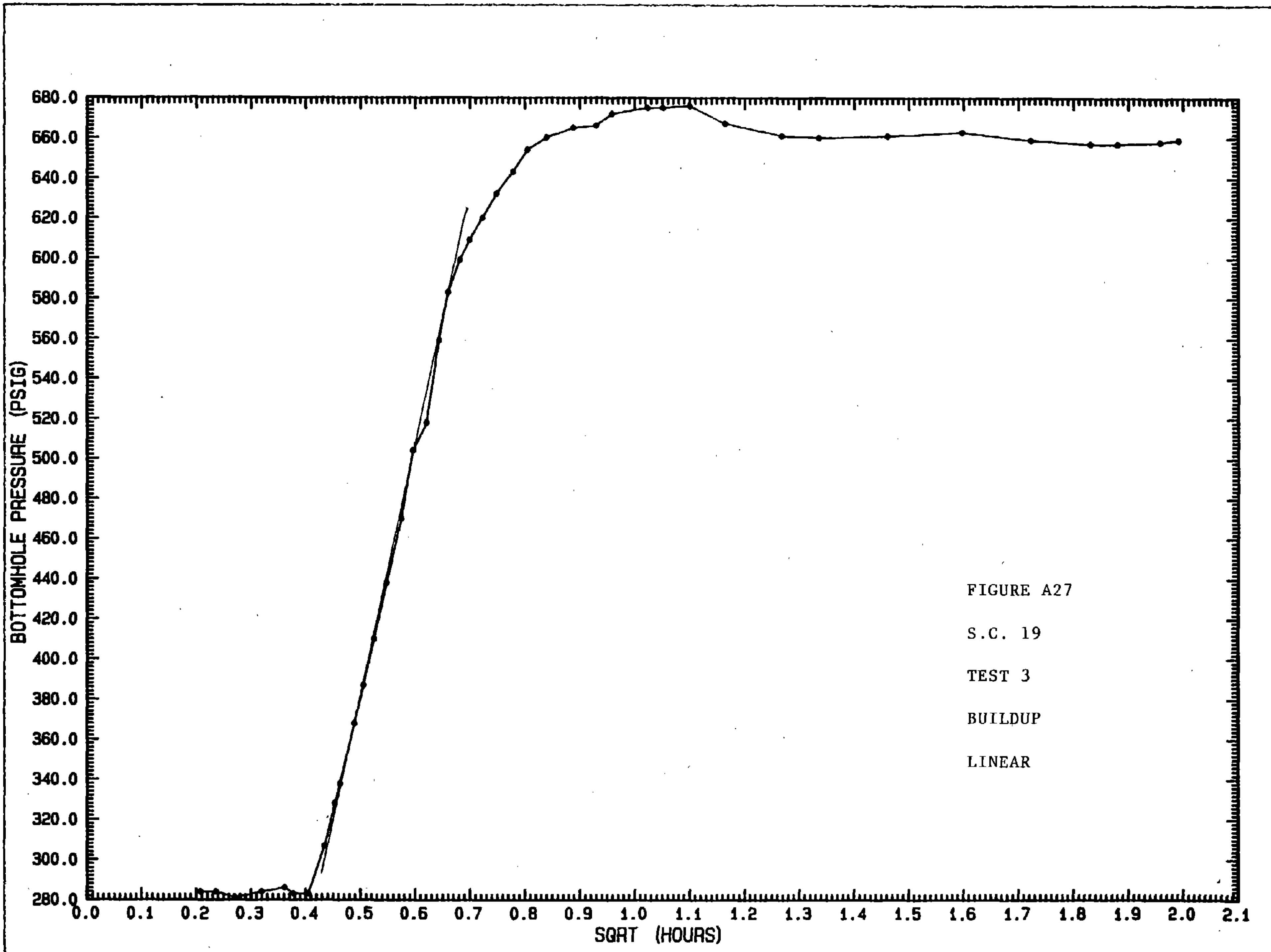


FIGURE A-26
S.C. 19
TEST 3
BUILDUP
RADIAL
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)
680.0
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
10⁻²
2
4
6
10⁻¹
2
4
6
1
2
4
6
10



BOTTOMHOLE PRESSURE (PSIG)
680.0
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
SQRT (HOURS)
FIGURE A27
S.C. 19
TEST 3
BUILDUP
LINEAR

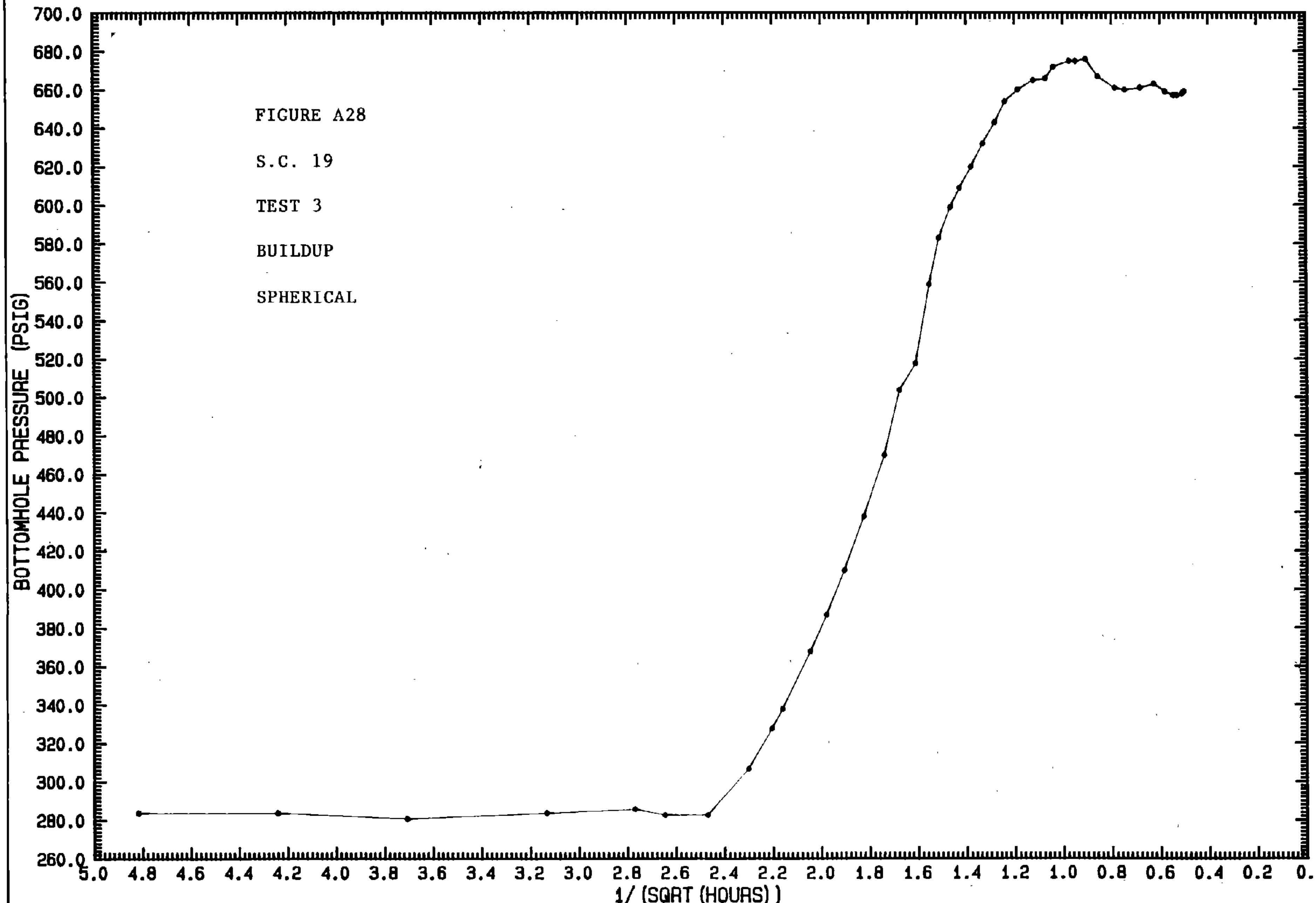


FIGURE A28
S.C. 19
TEST 3
BUILDUP
SPHERICAL
BOTTOMHOLE PRESSURE (PSIG)
700.0
680.0
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
260.0
5.0 4.8 4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
1/ (SQRT (HOURS))

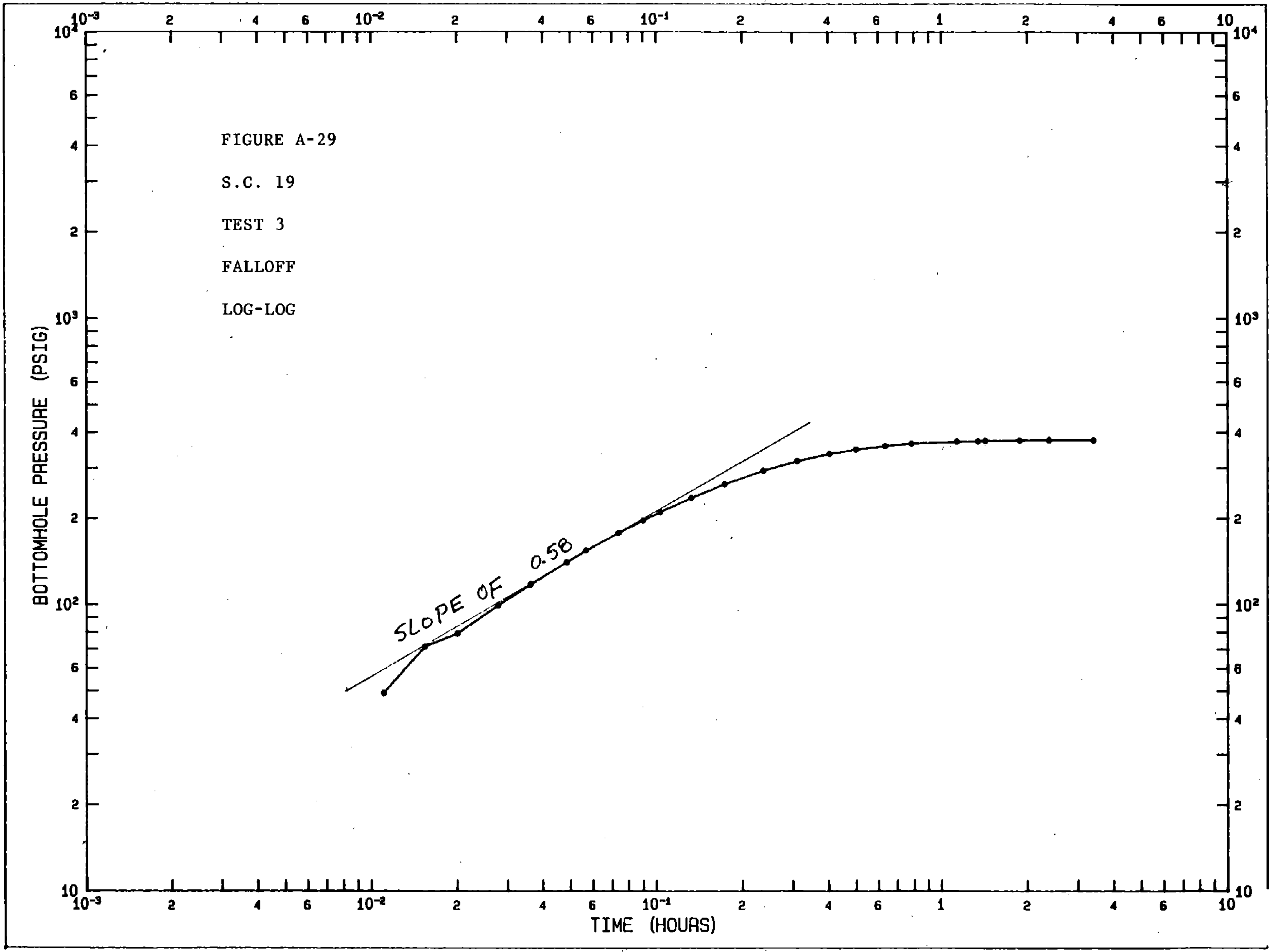


FIGURE A-29
S.C. 19
TEST 3
FALLOFF
LOG-LOG
SLOPE OF 0.58
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)

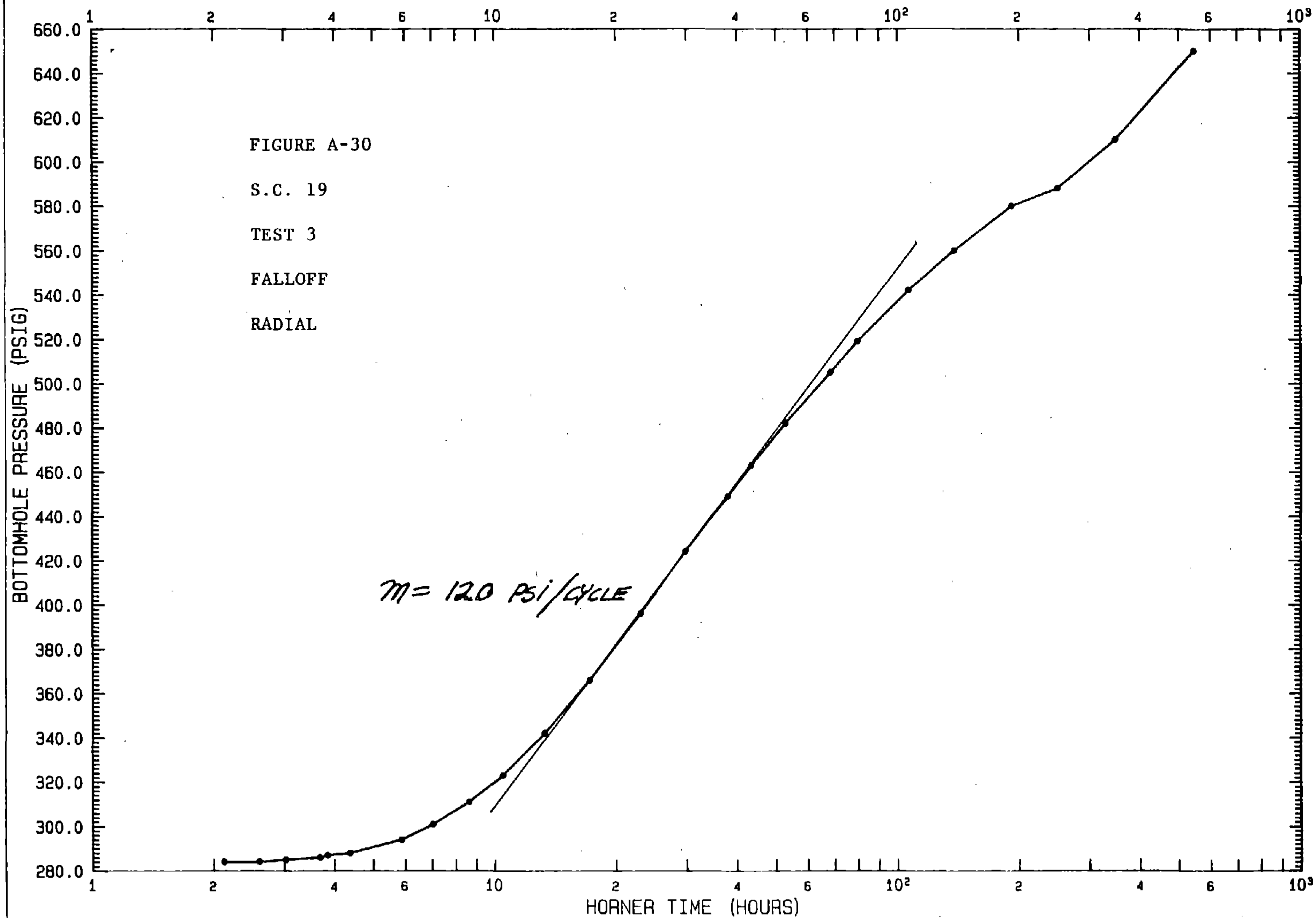


FIGURE A-30
S.C. 19
TEST 3
FALLOFF
RADIAL
m= 120 PSI/CYCLE
BOTTOMHOLE PRESSURE (PSIG)
HORNER TIME (HOURS)
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
1
10
10²
10³

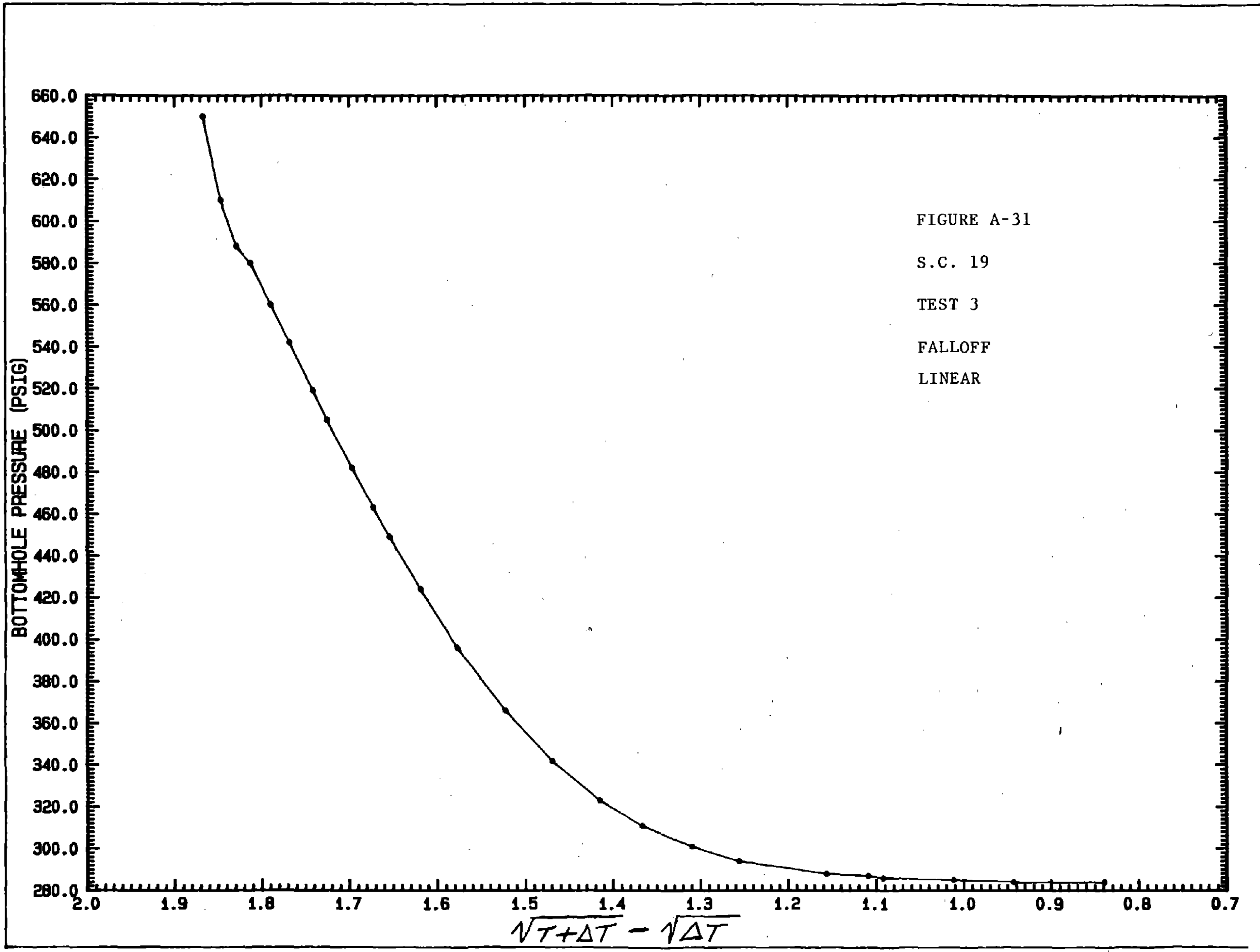


FIGURE A-31
S.C. 19
TEST 3
FALLOFF
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
$\sqrt{T+\Delta T} - \sqrt{\Delta T}$

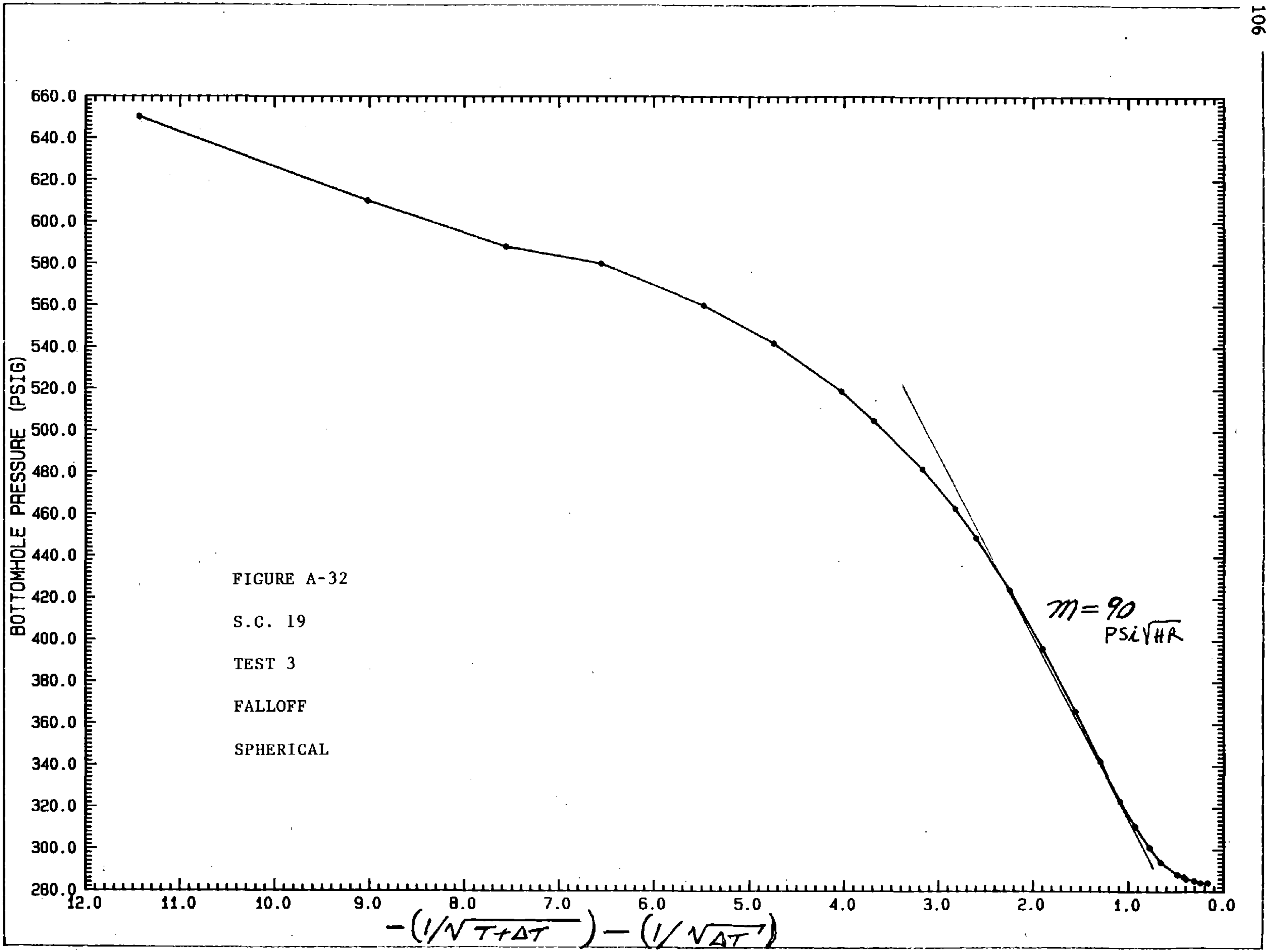


FIGURE A-32
S.C. 19
TEST 3
FALLOFF
SPHERICAL
BOTTOMHOLE PRESSURE (PSIG)
660.0
640.0
620.0
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
m = 90
PSI√HR
−(1/√(T+ΔT)) − (1/√ΔT)

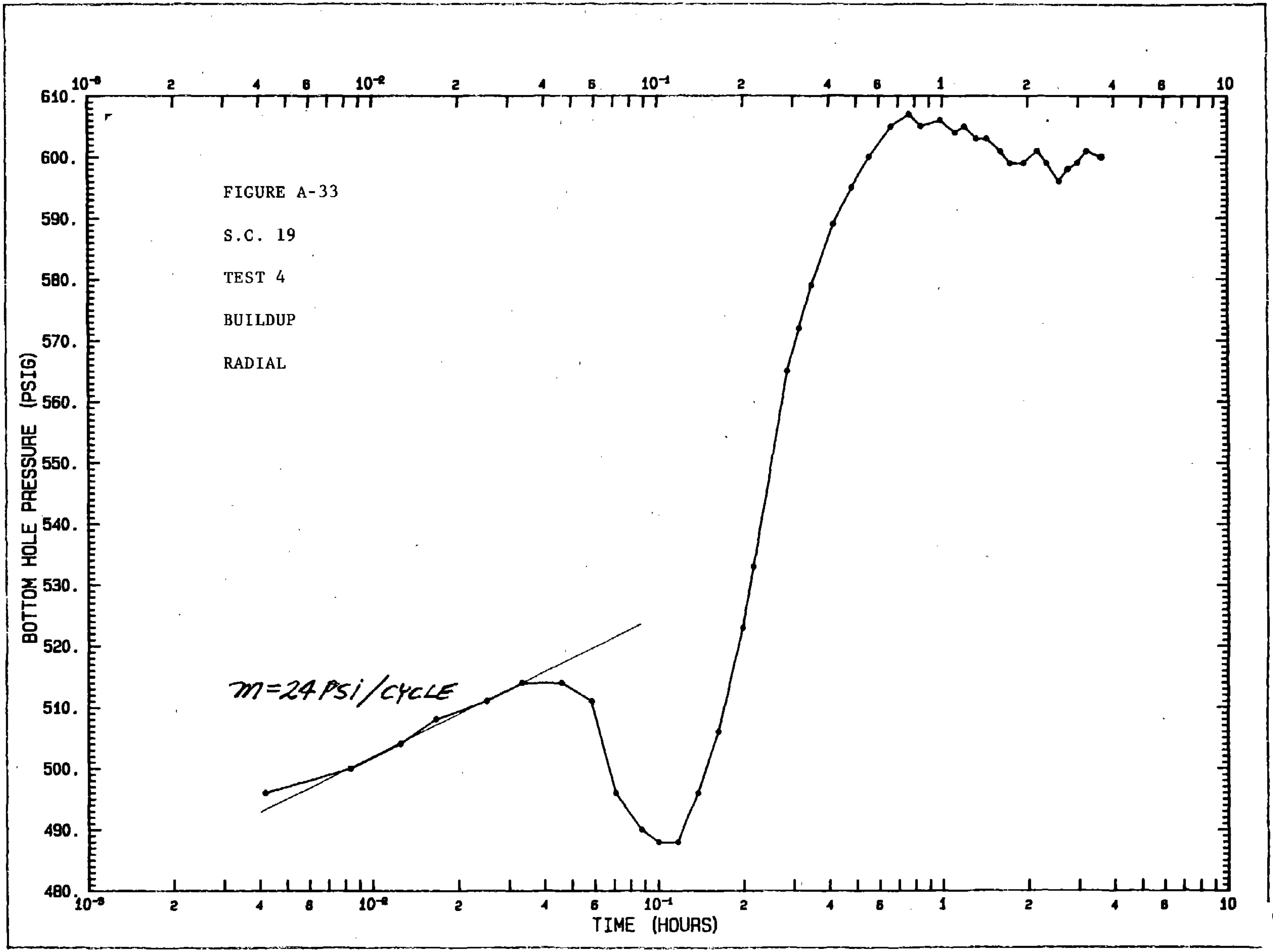


FIGURE A-33
S.C. 19
TEST 4
BUILDUP
RADIAL
m=24 PSI/CYCLE
BOTTOM HOLE PRESSURE (PSIG)
TIME (HOURS)
610.
600.
590.
580.
570.
560.
550.
540.
530.
520.
510.
500.
490.
480.
10⁻³
10⁻²
10⁻¹
1
10

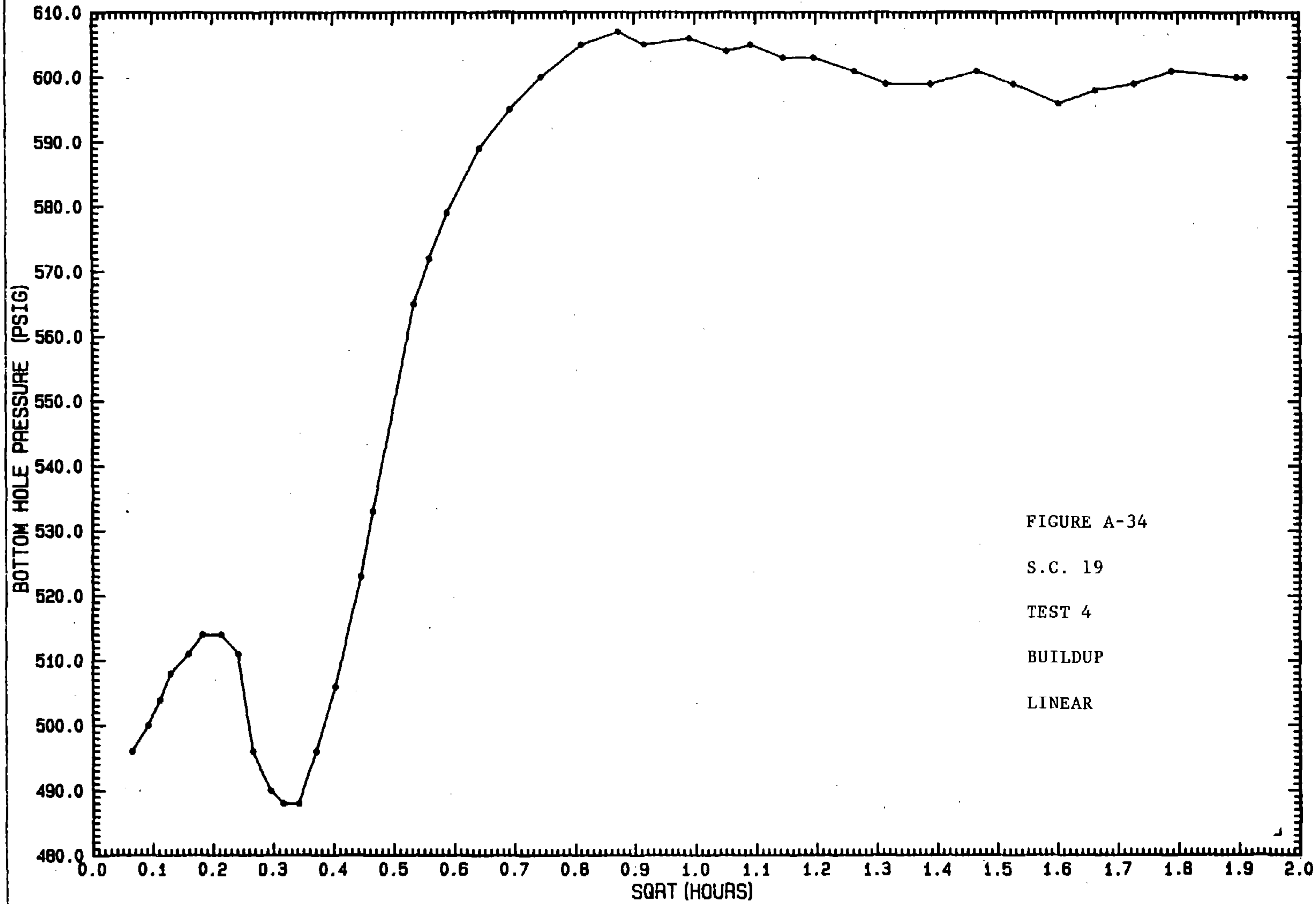


FIGURE A-34

S.C. 19

TEST 4

BUILDUP

LINEAR

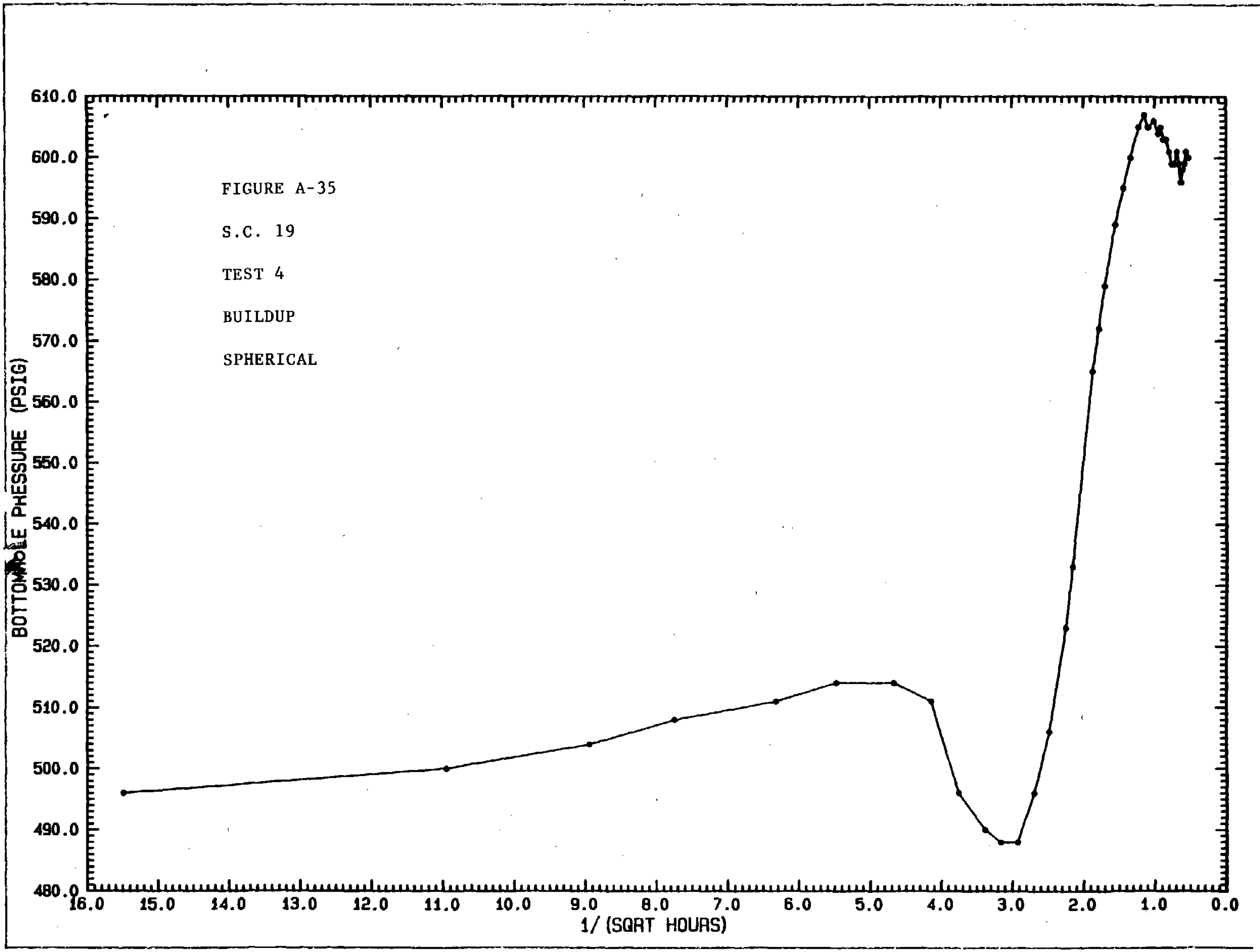


FIGURE A-35
S.C. 19
TEST 4
BUILDUP
SPHERICAL
BOTTOMHOLE PRESSURE (PSIG)
610.0
600.0
590.0
580.0
570.0
560.0
550.0
540.0
530.0
520.0
510.0
500.0
490.0
480.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1/(SQRT HOURS)

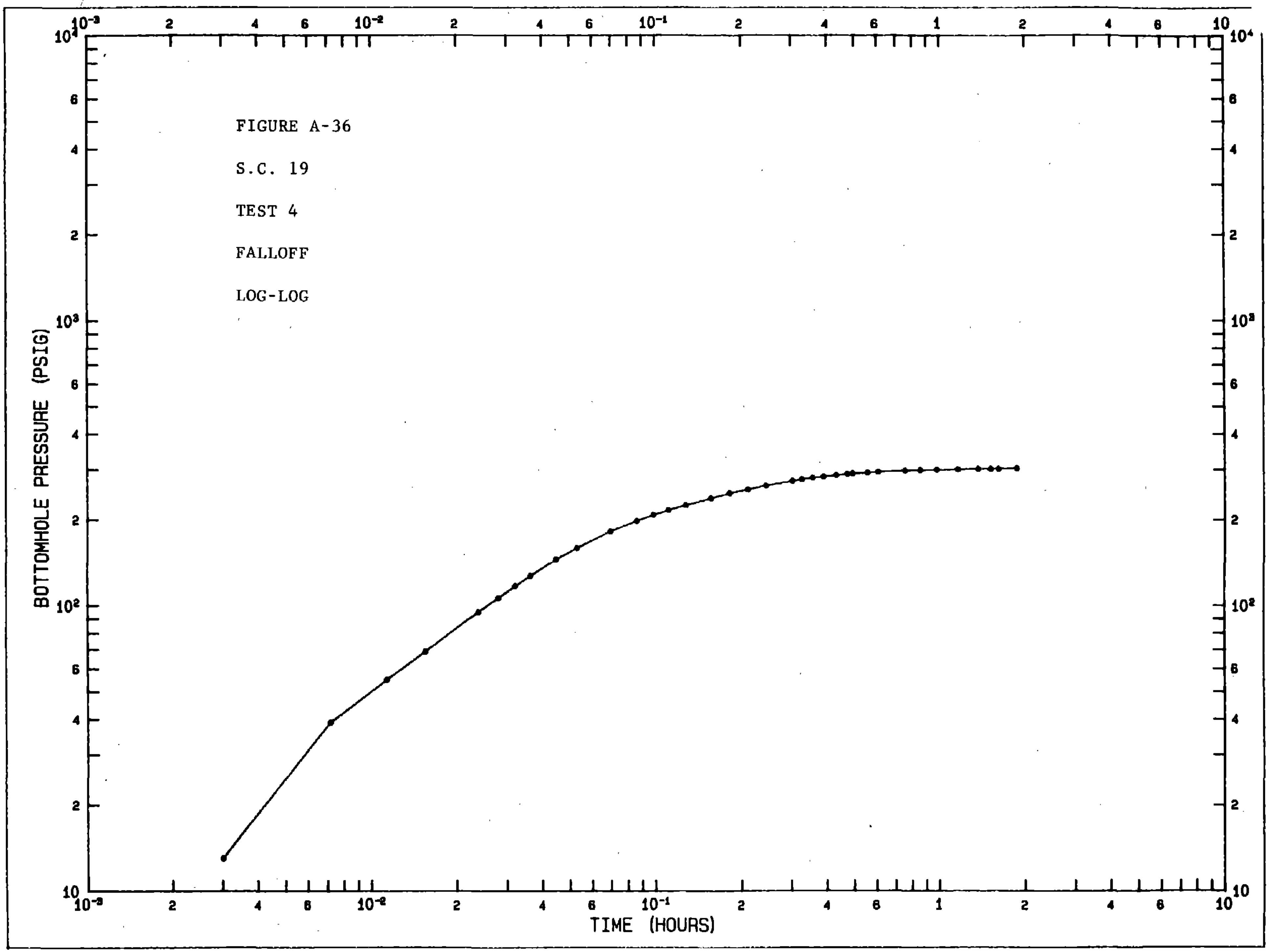
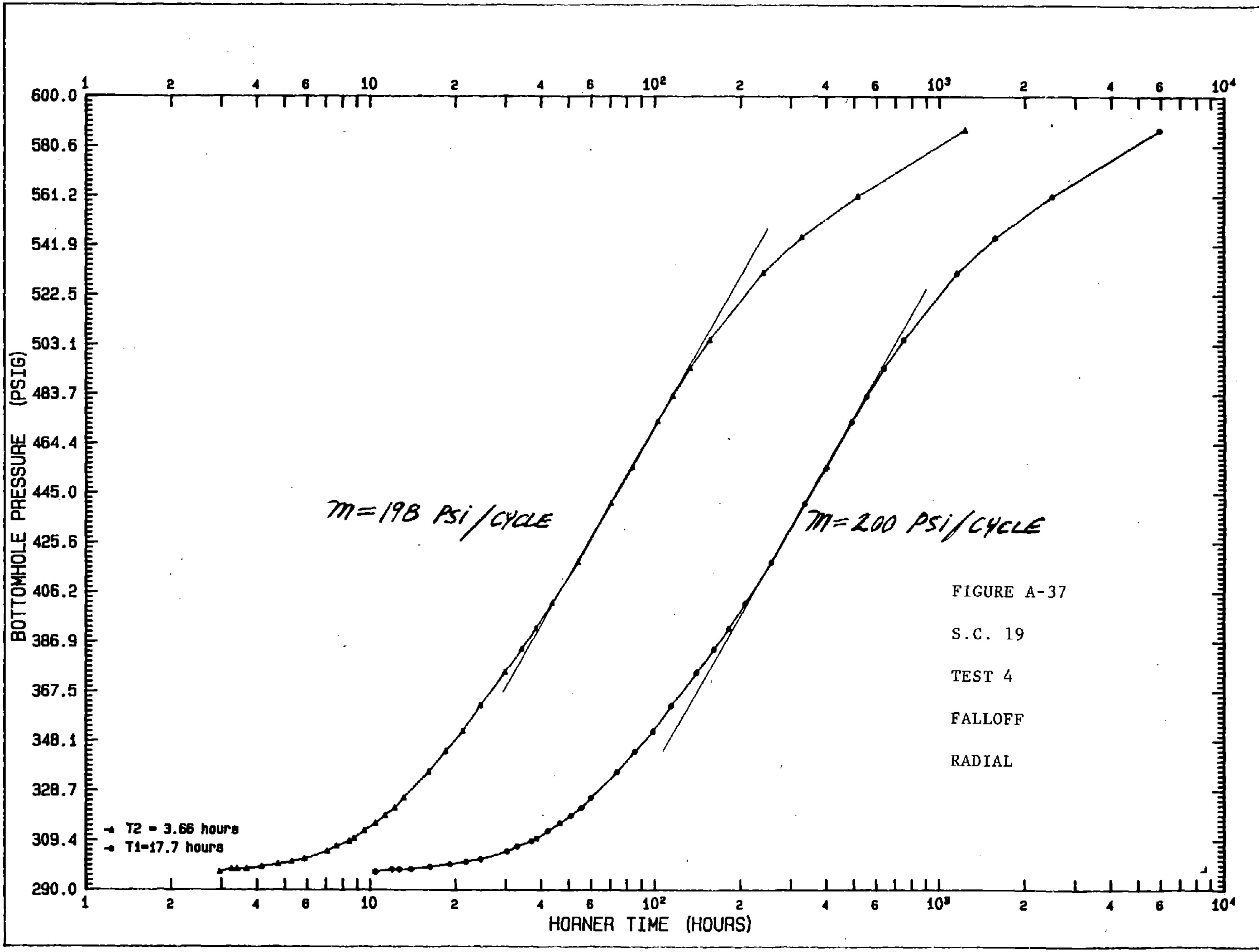


FIGURE A-36
S.C. 19
TEST 4
FALLOFF
LOG-LOG
BOTTOMHOLE PRESSURE (PSIG)
TIME (HOURS)
10⁻³
10⁻²
10⁻¹
1
10
10
10²
10³
10⁴


BOTTOMHOLE PRESSURE (PSIG)
HORNER TIME (HOURS)
m=198 PSI/CYCLE
m=200 PSI/CYCLE
T2 = 3.66 hours
T1=17.7 hours
FIGURE A-37
S.C. 19
TEST 4
FALLOFF
RADIAL

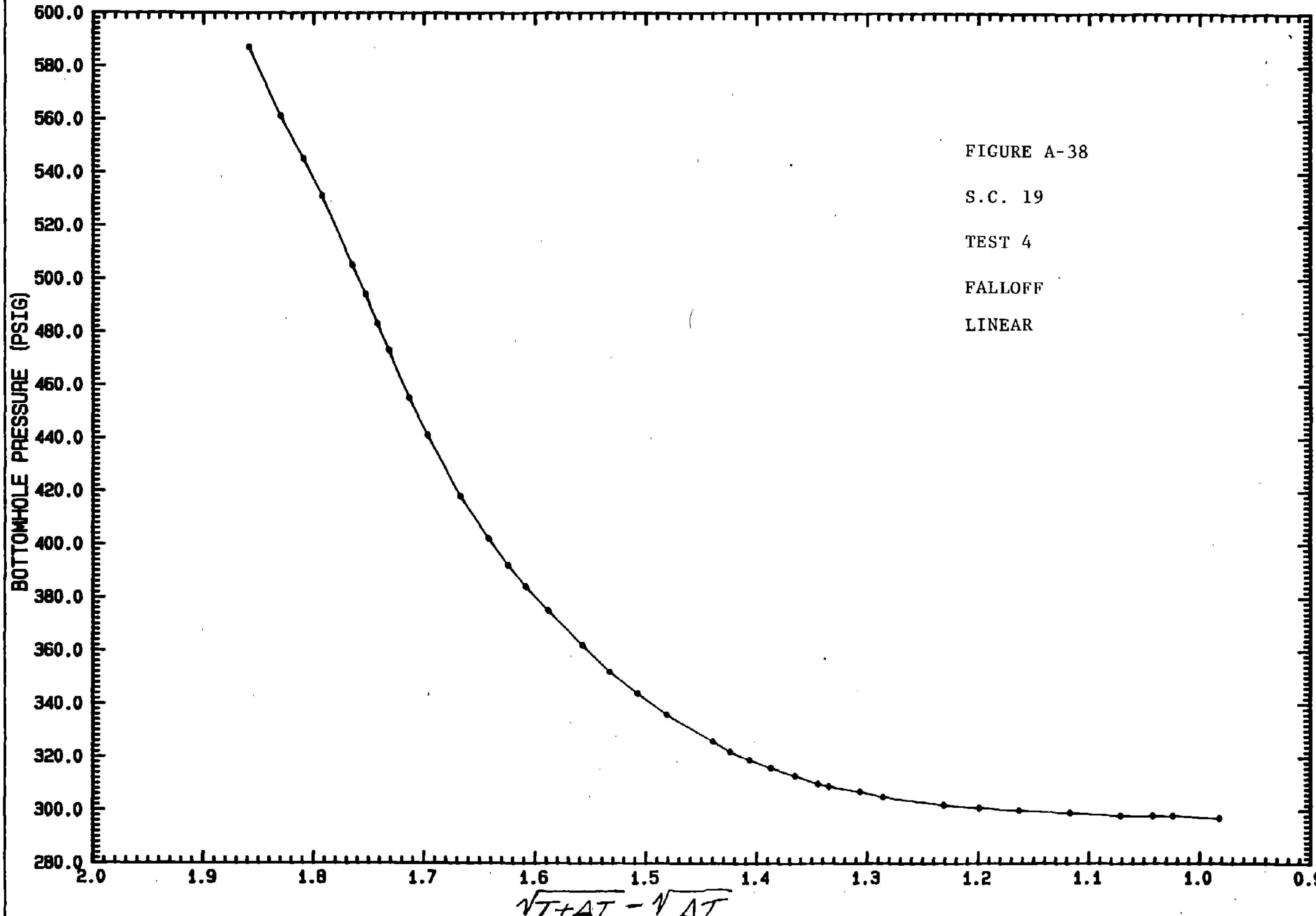
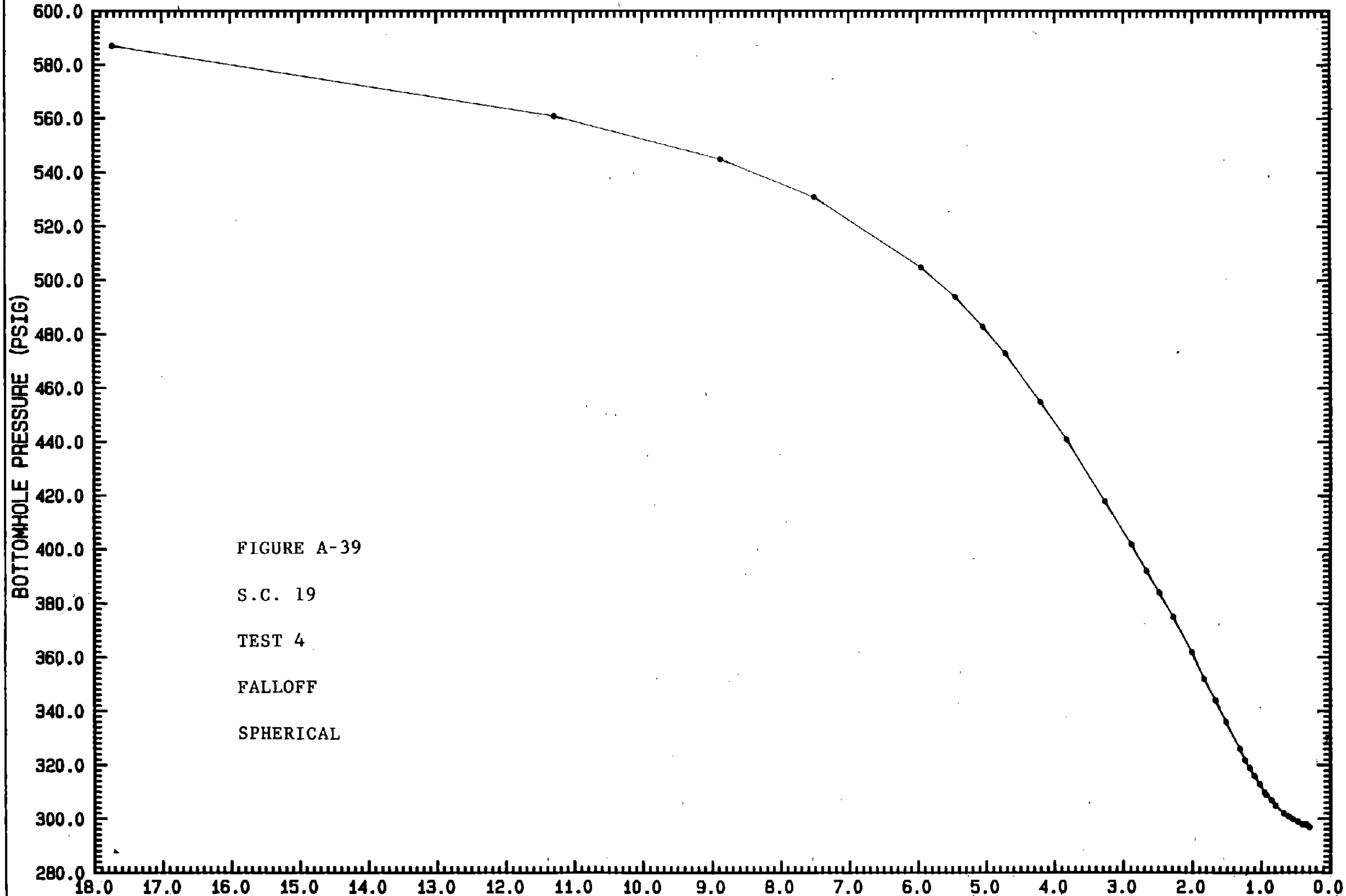


FIGURE A-38
S.C. 19
TEST 4
FALLOFF
LINEAR
BOTTOMHOLE PRESSURE (PSIG)
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
√T+ΔT − √ΔT



$-(1/\sqrt{T+\Delta T}) - (1/\sqrt{\Delta T})$

TABLE A-1. SUMMARY OF FLOW REGIME DATA PLOTS

Figures	Type of Plot	Flow Regime Indicated By Linearity of Plot
A-1, A-5, A-8, A-12, A-15, A-18, A-19, A-23, A-26, A-30, A-33, A-37	Radial	A-1, A-5, A-8, A-12, A-15, A-18, A-19, A-23 A-30, A-33, A-37
A-2, A-6, A-9. A-13, A-16, A-20, A-24, A-27, A-31, A-34, A-38	Linear	A-9, A-16
A-3, A-7, A-10, A-14, A-17, A-21, A-25, A-28, A-32, A-35, A-39	Spherical	A-14, A-32
A-4, A-11, A-22, A-29, A-36	Check for wellbore storage	No evidence of wellbore storage since slope is not one

The following values for the 1-hour fall-off pressure and the shut-in pressure where used in the skin calculations:

- o SC-46, Test 2
  - + p_1 = 418 psi
  - + p_w = 584 psi
- o SC-46, Test 3
  - + p_1 = 542 psi
  - + p_w = 762 psi
- o SC-19, Test 2
  - + p_1 = 394 psi
  - + p_w = 610 psi
- o SC-19, Test 3
  - + p_1 = 291 psi
  - + p_w = 658 psi
- o SC-19, Test 4
  - + p_1 = 279 psi
  - + p_w = 600 psi