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PROCEEDINGS OF THE GEOTHERMAL RESERVOIR WELL STIMULATION SYMPOSIUM

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RAFT RIVER STIMULATION TREATMENT RESULTS

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ABSTRACT

The Geothermal Reservoir Well Stimulation Program (GRWSP) group planned and executed two field experiments at the Raft River KGRA during 1979. Well RRGP-4 was stimulated using a dendritic or "Kiel" hydraulic fracture technique, and Well RRGP-5 was stimulated using a conventional massive hydraulic fracture technique. This presentation summarizes the analyses and results of these stimulation treatments.

Both stimulation experiments at Raft River were technically successful; however, the post-stimulation productivity of the wells was disappointing. The productivity indices (PI) of Wells RRGP-4 and RRGP-5 were found to be 0.6 gpm/psi and 2.0 gpm/psi, respectively.

Well RRGP-4 productivity was greatly increased over its pre-stimulation condition, but the artificially created fracture and/or the natural fracture system did not provide a high transmissivity connection with the source of the geothermal fluid. The artesian flow rate was 60 gpm. The artificially created fracture in Well RRGP-5 apparently connected with existing natural fractures very near the wellbore. This connection did not significantly affect the already high transmissivity of these fractured zones (artesian production rate about 200 gpm). The low temperature of the produced fluids from RRGP-5 suggests that these fractures extend upward to cooler zones of the reservoir.

Pressure transient data indicate an area of reduced transmissivity or limited entry near these wells and an area of high transmissivity (greater than 500,000 md-ft/cp) located at some distance which acts as a constant pressure boundary. The major fault lines near these wells are suspected of being the major source of the geothermal fluids. Further long-term testing is needed to confirm this fact.

DISCLAIMER

INTRODUCTION

The purpose of this presentation is to summarize the results of the Raft River stimulation experiments. Discussion of the general well selection process, mechanical preparation of the wells, and the specific fracture stimulation procedures at Raft River were presented earlier and therefore, will not be repeated here.

The operator of the Raft River geothermal field, EG&G, completed and tested the Wells RRGP-4 and RRGP-5 as part of the normal field development program. Figure 1 shows the Raft River KGRA and the well locations. The pre-stimulation well conditions are discussed herein and compared with the post-stimulation test results. It should be remembered, however, that a large portion of the original open-hole completion interval was cased off ("Planning and Execution of Raft River Stimulation Treatments," R. V. Verity) prior to the fracture treatments and the direct comparison may not necessarily be an accurate representation.

PRE-STIMULATION WELL CONDITIONS

All the Raft River production wells are completed within the naturally fractured zone from about 3,400 feet to 6,543 feet. The formation producing intervals are comprised primarily of siltstone, sandstone, metamorphosed quartz, quartz schist, elba quartzite, and quartz monzonite. Pre-stimulation borehole televiewer surveys, discussed previously ("Application of Acoustic Televiewer to the Characterization of Hydraulic Fractures in Geothermal Wells," Scott Keys), indicated that both Wells RRGP-4 and RRGP-5 have natural fractures intersecting their wellbores; however, RRGP-4 showed much less fracturing in the entire well (open-hole interval 3,526 feet to 5,115 feet) as compared to other Raft River wells. Well RRGP-5 had numerous horizontal and vertical fractures throughout the open-hole section from 3,408 feet to 4,925 feet.

After leg B of Well RRGP-4 was deepened to 5,115 feet, an attempt was made by EG&G to flow test the well. The well was found to be non-commercial and would not sustain an artesian flow rate greater than approximately 10 gpm. The maximum bottom-hole temperature was measured by borehole geophysical logs at 254 degrees F.

Well RRGP-5 (leg B) productivity was tested by EG&G several times after completion. The well was artesian flow tested for 72 hours at a rate of 140 gpm in November 1978. Short-term flow periods (approximately 1 hour) prior to this test obtained rates in excess of 280 gpm; however, the wellhead pressure was declining very rapidly and the well could not sustain this rate. No downhole transient pressure data were obtained during these tests with which to calculate a productivity index. A maximum bottom-hole temperature of 274 degrees F was measured in the well. As discussed previously (paper by R. V. Verity), leg B is believed to have penetrated a zone extensively damaged by cement during the workover of leg A. Sufficient volume of cement had been injected into leg A to fill the wellbore and the near-well natural fractures. Some confusion remains as to the actual productive potential of RRGP-5 after it was completed. Flow test results vary from over 1,000 gpm to 140 gpm. It should be stated that several very short-term production tests were attempted during the drilling operations and shortly thereafter. These tests were not fully documented and no downhole transient pressure data were obtained. It seems clear that for a number of reasons, mostly related to the drilling operations or the test procedures, the well data might indicate these rates were observed for short periods of time. However, pressure data obtained during later tests indicate that the bottom-hole pressure must have been decreasing rapidly during these early flow tests and that the well would not have continued to sustain anywhere near the high flow rates originally ascribed to this well. None of the current Raft River wells are capable of very high artesian flow rates. The most likely maximum flow rate of Well RRGP-5 prior to the stimulation treatment was about 140-200 gpm.

As described above, these wells originally had long open-hole intervals. A 7-inch casing liner was cemented in the hole such that a 200-foot open-hole interval was isolated for stimulation treatment. With the liner in place, both wells were essentially non-productive as the formation natural fractures feeding the wellbore were cased-off. Therefore, no production tests were performed under these conditions prior to the fracture experiments.

POST-STIMULATION PRODUCTION TEST INSTRUMENTATION

Both Wells RRGP-4 and RRGP-5 were production tested following the fracture stimulation treatments. EG&G assisted in this test program and provided the surface equipment required to monitor the flow conditions. The general procedure was to construct a flow line from the wellhead to the nearby holding pond. The flow line was instrumented with an orifice plate and a differential pressure gauge to monitor the single phase fluid flow rate. The flow line was also instrumented to measure wellhead pressure and temperature, and ports were provided for fluid sampling capability. In some cases the wellhead pressure was measured with a conventional Bourdon guage and, in others, with a digiquartz pressure transducer. The deep geothermal wells and the shallow water wells in the Raft River area were monitored continuously by EG&G for possible interference pressure data.

Downhole pressure (and temperature) instrumentation was utilized during the flow tests to obtain the transient pressure drawdown and buildup response. In most instances, the downhole pressure equipment was a quartz crystal pressure gauge provided by either EG&G or Lawrence Berkeley Laboratory (LBL). However, several instrument failures occurred during these tests. In the case of the September 1979 flow test of Well RRGP-4, a conventional Amerada type downhole pressure gauge was used to obtain the pressure buildup data. Downhole temperature measurements were obtained to aid in the analysis of the pressure data, which can be significantly affected by a change in the fluid temperature, and to document the flowing temperature of the well.

Fluid samples were taken periodically during all post-stimulation flow tests. These samples were analyzed for fracture fluid and tracer material returns by Vetter Research. Also, the U.S. Geological Survey ran borehole televiewer surveys in each of the wells to determine the extent of the newly created vertical fracture at the wellbore.

TEST RESULTS AND ANALYSIS

The pressure testing of the Wells RRGP-4 and RRGP-5 under the GRWSP will be discussed in chronological order. The pressure data were analyzed using conventional pressure analysis techniques, type curve (log-log) matching techniques, and numerical simulation methods.

1. RRGP-4

Well RRGP-4 was stimulated with a dendritic hydraulic fracture treatment in August 1979. A 20-hour flow test was run on August 25-26, 1979. The flow rate declined from an initial 250 gpm to about 60 gpm; however, at that point two-phase flow began to occur at the orifice meter used to measure the flow rate. The test was terminated and plans were made to re-test the well for a longer period with improved flow control equipment. A borehole televiewer survey confirmed the existence of a 200 foot vertical fracture created by the stimulation treatment. The fracture was oriented in an east-west direction which would parallel the Narrows Fault.

The September 1979 production test of Well RRGP-4 was similar to the first test in flow rates and the rapid downhole pressure response. Figure 2 gives the production data and Figures 3 through 6 show the pressure data plots. The downhole instrumentation failed about 8 hours into the drawdown phase. The test continued until September 12, 1979, at which point Amerada type downhole pressure and temperature instruments were utilized to obtain the reservoir buildup data given in Figure 3. The well was flowed at a rate of about 60 gpm for 150 hours before shut-in. The fracture flow effects are indicated to last about 6 hours by the early-time pressure versus square root of time plot in Figure 6. The bottom-hole pressure apparently reached the initial reservoir pressure after approximately 15 hours of buildup time. The data show a very flat pressure curve from 15 hours to 47 hours. The significance of this is discussed later. The conventional fracture type curve analysis (log-log plot) yields a fracture length of approximately 335 feet and a permeability-thickness (kh) of 800 md-ft. The Horner plot indicated the presence of two straight line segments, one early-time (less than 15 hours) and one late-time (greater than 15 hours) segment. These two data segments give kh values of 1070 md-ft and 85,000 md-ft, respectively, and suggest the possibility of more than one permeable zone near the wellbore. Also a negative skin factor (-6.0) indicates a stimulated zone close to the wellbore. This is further confirmed by the fact that the buildup curve approaches the Horner straight line from above. Table I summarizes the calculations of reservoir properties derived from this test. Wellbore temperature changes were small during the reservoir buildup period and did not significantly affect the pressure data.

The maximum bottom-hole temperature recorded during the September 1979 flow test was 270 degrees F. This temperature is significantly higher than past measurements have shown, i.e., about 240 degrees F before stimulation. This fact suggests that the new artificial fracture is producing fluid from a deep reservoir zone not open in the original hole.

2. RRGP-5

Well RRGP-5 was stimulated on November 12, 1979. The post-stimulation production test was performed during November 25-26, 1979 after the well had been produced several times to clean out sand. Figure 7 illustrates the production data obtained during the 6 hour flow period. The wellhead and downhole pressure and temperature conditions stabilized very rapidly (about 2 minutes). An average flow rate of about 200 gpm was maintained with a wellhead pressure of about 30 psia. The pressure drawdown of 100 psi was extremely rapid (less than 1 minute) and no early-time data were obtained. A plot of the pressure buildup data versus square root of time, shown in Figure 8, indicates the fracture flow effect near the wellbore persists for only about 38 seconds. This short linear flow period and the resulting calculated fracture length value is so small that no single fracture flow exists. The Horner plot and type curve plot of the pressure data, in Figures 9 and 10, show only a short transition phase between the fracture dominated period and the late-time constant pressure period. The results indicate a higher transmissivity than was found in RRGP-4.

Estimates of the late-time formation kh are large, i.e., greater than 100,000 md-ft.

Thus, the hydraulic fracture stimulation treatment may have reopened existing natural fractures near the wellbore and/or intersected leg A which dissipated the injected frac fluid and energy. The borehole televiewer survey did indicate a newly created vertical fracture at the wellbore of about 140 feet in length and oriented in a northeast-southwest direction which is parallel to the Bridge Fault. These reopened natural fractures did not significantly affect the already high permeability of this fractured zone. The Horner analysis indicated a very large positive skin factor; however, this skin factor is not due to any formation damage but to the limited entry nature of the completion. A limited entry, theoretical skin effect calculation yields a skin factor of the same order of magnitude.

The maximum flowing bottom-hole temperature was measured at 264 degrees F at the shoe of the 7-inch liner. Figure 11 illustrates three separate temperature surveys made in Well RRGP-5.

In March 1930, Well RRGP-5 was flow tested again using a downhole submersible pump. The maximum rate obtained during this test was 650 gpm. The productivity index obtained from the artesian flow test (2 gpm/psi) is in close agreement with the values observed during this pumped flow test. Table 2 summarizes the reservoir property calculations derived from these tests.

Pressure Interference Data

The deep exploration wells and shallow water wells in the area were monitored for wellhead pressure changes during both stimulation treatments and subsequent production tests. No interference was indicated during the RRGP-4 fracture job or its two production tests; however, the RRGP-5 fracture treatment apparently did cause a pressure spike at RRGE-1 during the injection of the frac materials. The first flow tests of RRGP-5 did not cause any pressure changes at the observation wells.

Reservoir Model

Both Wells RRGP-4 and RRGP-5 show remarkably similar pressure response following the fracture treatments. Well RRGP-4 is apparently in a less fractured, tighter area of the reservoir compared to all the other production wells. The transient pressure data indicate three distinct flow response periods:

(1)fracture flow (2)early-time low effective kh flow (near wellbore); and (3)late-time high effective kh flow (some distance from wellbore).

The late-time pressure results suggest the presence of a constant pressure boundary. It is possible to satisfy the observed pressure results of both wells with two types of reservoir models:

1. A fractured reservoir with low transmissivity near the wellbore and a constant pressure boundary (or very high transmissivity area some relatively short distance from the wellbore) or

2. A reservoir with high effective transmissivity but with a large skin at the wellbore.

The second model does not conform to the known reservoir physical characteristics and, therefore was not considered a valid model. Numerical simulations were performed using the fractured reservoir model to confirm the first hypothesis. It was possible to reproduce the pressure transient data for both RRGP-4 and RRGP-5 with essentially the same model (RRGP-4 was given a lower near-wellbore transmissivity). The single layer model consisted of a vertical fracture through the wellbore, a relatively low transmissivity near the wellbore, and a constant pressure boundary located along one short side of a two-to-one rectangular drainage area. Figure 12 illustrates the model geometry. Obviously, the numerical simulation approach does not yield a unique solution to the transient reservoir pressure response, but it does provide a confirmation of the conventional and type curve pressure analysis results. Tables 3 and 4 summarize the pre- and post-stimulation well characteristics.

It is interesting to note that the well distance from the known or suspected faults in the Raft River area are close to the distance indicated in the reservoir model calculations for the constant pressure boundary. The results discussed herein suggest that the naturally fractured rock formation, at some distance from a fault, is not sufficiently permeable to support a high productivity well. Also, hydraulic fracture stimulation does not appear to be an economic alternative to recompletion of a well since the risk of not communicating effectively with the high transmissivity zones is great.

Chemical Aspects of Field Experiments

1. RRGP-4

In addition to the conventional chemical analyses, several analytical methods were developed and applied by Vetter Research to the characterization of the produced fluids from post-stimulation flow tests at RRGP-4. These methods included total organic carbon and carbonate analysis. Wellbore and near-wellbore cooling was indicated by the lack of polymer degradation in samples collected during the clean-up flow period conducted soon after the fracture treatment had been completed. Significant polymer degradation was observed during the two production tests, but the products of degradation appear to be water soluble and were observed in the produced fluid. Of the frac polymer injected, only 45 percent can be accounted for with certainty (see Figure 13). Some of the frac material as well as water soluble degradation products were still being produced back when the flow tests were terminated.

2. RRGP-5

Similar analytical methods were utilized to characterize the fluids produced from post-stimulation flow at RRGP-5. In addition, a chemical tracer (ammonium nitrate), which was co-injected with the frac fluid, was analyzed for during the flow tests. Based upon all the chemical work, it appears that a major portion of the frac fluid entered a cold zone of limited productivity. This conclusion is based on two facts: (1) there was little thermal degradation of the polymer after a one-month period in the reservoir; and (2) less than 50 percent of either polymer or tracer was produced back even after a cumulative volume of 2.5 times the injected volume had been produced from the well. The analytical results are illustrated is Figures 14 and 15.

CONCLUSION

Well RRGP-4 was successfully stimulated using the dendritic fracture treatment method. The productivity index was increased from essentially zero to 0.6 gpm/psi and the produced fluid temperature increased approximately 20 degrees F.

Well RRGP-5 was successfully stimulated using a conventional massive hydraulic fracture treatment technique; however, the artificially created fracture probably intersected existing natural fractures near the wellbore and/or intersected leg A. No significant increase in productivity was achieved. The post-stimulation PI was 2.0 gpm/psi.

With the exception of low material return in both field experiments, there were no striking similarities between the chemical behavior of the post-stimulation fluids produced at

RRGP-4 and RRGP-5. The frac fluid injected at RRGP-4 entered a hotter zone than at RRGP-5. While the temperature at the top of the producing interval in RRGP-4 is slightly warmer than in RRGP-5 (i.e., 270 degrees F. vs. 264 degrees F. respectively), this temperature difference is not large enough to account for the extensive differences in polymer degradation that were observed.

REFERENCES

1 Kiel, Othar, Kiel Fracturing Process, U.S. Patent No. 3,933,205

2 Unpublished data reports on the Raft River Project, prepared by EG&G, 1979.

TABLE I

RAFT RIVER RRGP-4

TEST 2 - SEPTEMBER 6-14, 1979

Flow Rate = 60 gpm

Production Time = 150 hrs

Maximum Bottom-Hole Temperature = 270 degrees F.

BUILDUP DATA

A. FRACTURE TYPE CURVE ANALYSIS:

L = 335 ft

KH = 300 md-ft

B. HORNER PLOT ANALYSIS:

KH = 1,070 md-ft (Early Time)

KH = 85,000 md-ft (Late Time) (1)

S = 6.0

(1) Constant Pressure Boundary Effect

TABLE 2

RAFT RIVER RRGP -5

TEST 1 - NOVEMBER 25-26, 1979

Flow Rate = 200 gpm

Production Time = 6 hrs

Maximum Bottom-Hole Temperature - 264 degrees F.

BUILDUP DATA (1)

A. HORNER PLOT ANALYSIS:(1)

KH > 100,000 md-ft (Late Time) (2)

TEST 2 - EG&G: USING DOWNHOLE REDA PUMP (March 1980)

Flow Rate = 650 gpm

Production Time = 61.3 hrs

Productivity Index = 2.05 gpm/psi

Maximum Temperature = 257 degrees F. (Wellhead)

(1) No transition or steady-state data before constant pressure boundary effects

(2) Constant pressure boundary effect

TABLE 3

RAFT RIVER RRGP -4

PRE-STIMULATION WELL CONDITION:

Open-hole Interval 3526 ft - 5115 ft

Maximum Bottom-hole Temperature = 254 degrees F. from geophysical logs

Flow Rate = Well Would Not Sustain Flow

Natural Fractures in Wellbore

POST-STIMULATION WELL CONDITION:

Open-hole Interval 4705 ft - 4900 ft

Vertical Fracture in Wellbore (200 ft height)

Flow Rate = 60 gpm (artesian)

Maximum Bottom-hole Temperature = 270 degrees F. at 3200 ft

Fracture Effects Show L = 335 ft

Near Wellbore Effective KH = 800-1,000 md-ft

Constant Pressure Boundary
with High Effective KH > 100,000 md-ft

Communicates with natural fractures or matrix permeability in area. Did not communicate effectively with major source of reservoir fluids

TABLE 4

RAFT RIVER RRGP-5

PRE-STIMULATION WELL CONDITION:

Open-hole Interval 3403 ft - 4925 ft

Maximum Bottom-hole Temperature = 274 degrees F.

Flow Rate = 140 gpm (artesian)

Near Wellbore Cement Damage

Natural Fractures in Wellbore

POST-STIMULATION WELL CONDITION:

Open-hole Interval 4537 ft - 4803 ft

Maximum Bottom-hole Temperature = 264 degrees F. at 4,600 ft

Flow Rate = 200 gpm (artesian)

Near Wellbore Effective KH > 100,000 md-ft with Limited Entry

Constant Pressure Boundary with
High Effective KH > 100,000 md-ft

Vertical Fracture in Wellbore (100 ft height)

Communicates with natural fractures or matrix permeability in area. Did not communicate effectively with major source of reservoir fluids

Appears to have limited pressure communication with RRGE-1

FIGURE 1

RAFT RIVER FACILITY WITH GEOLOGIC STRUCTURE AND WELL LOCATION.

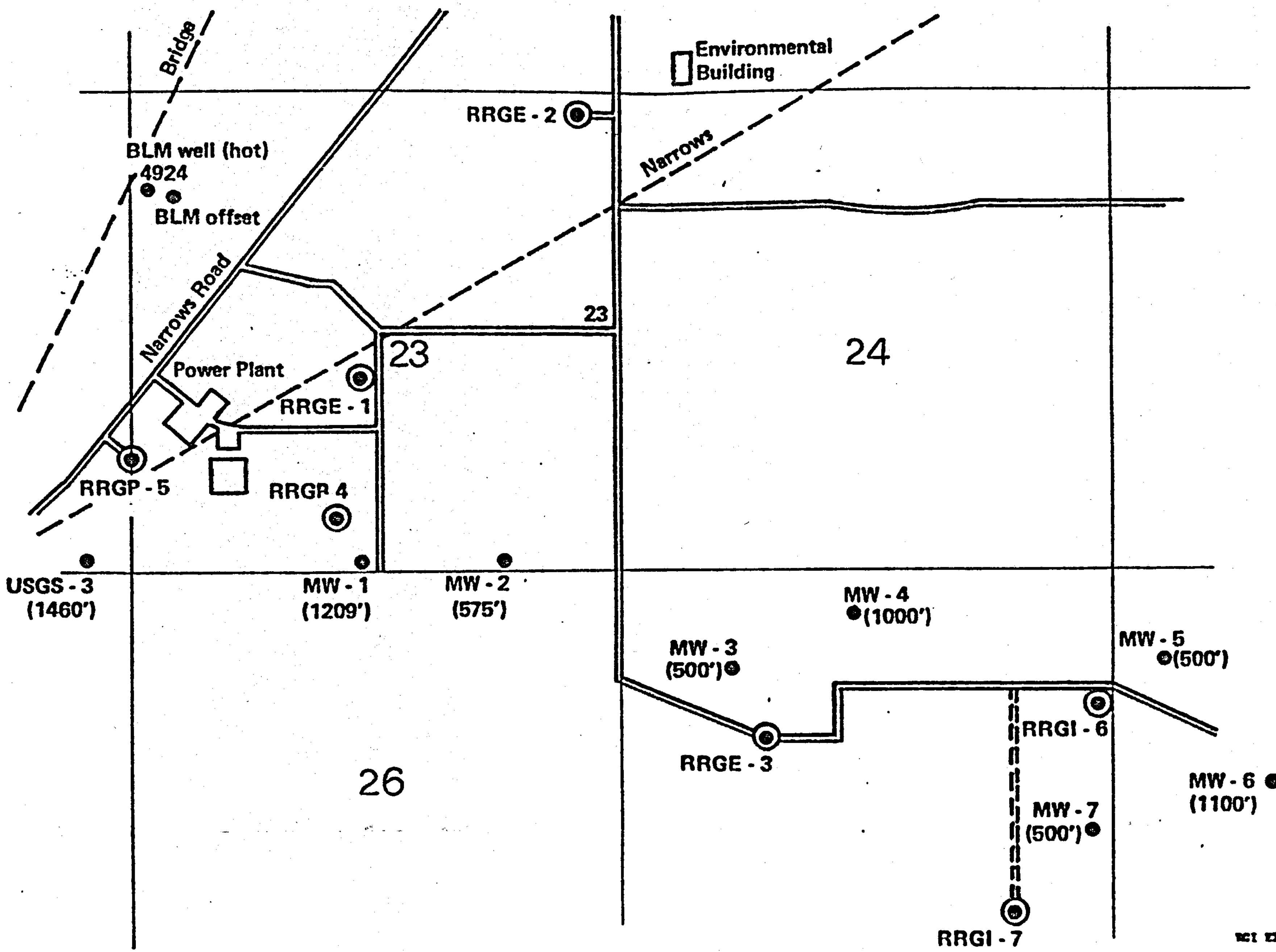
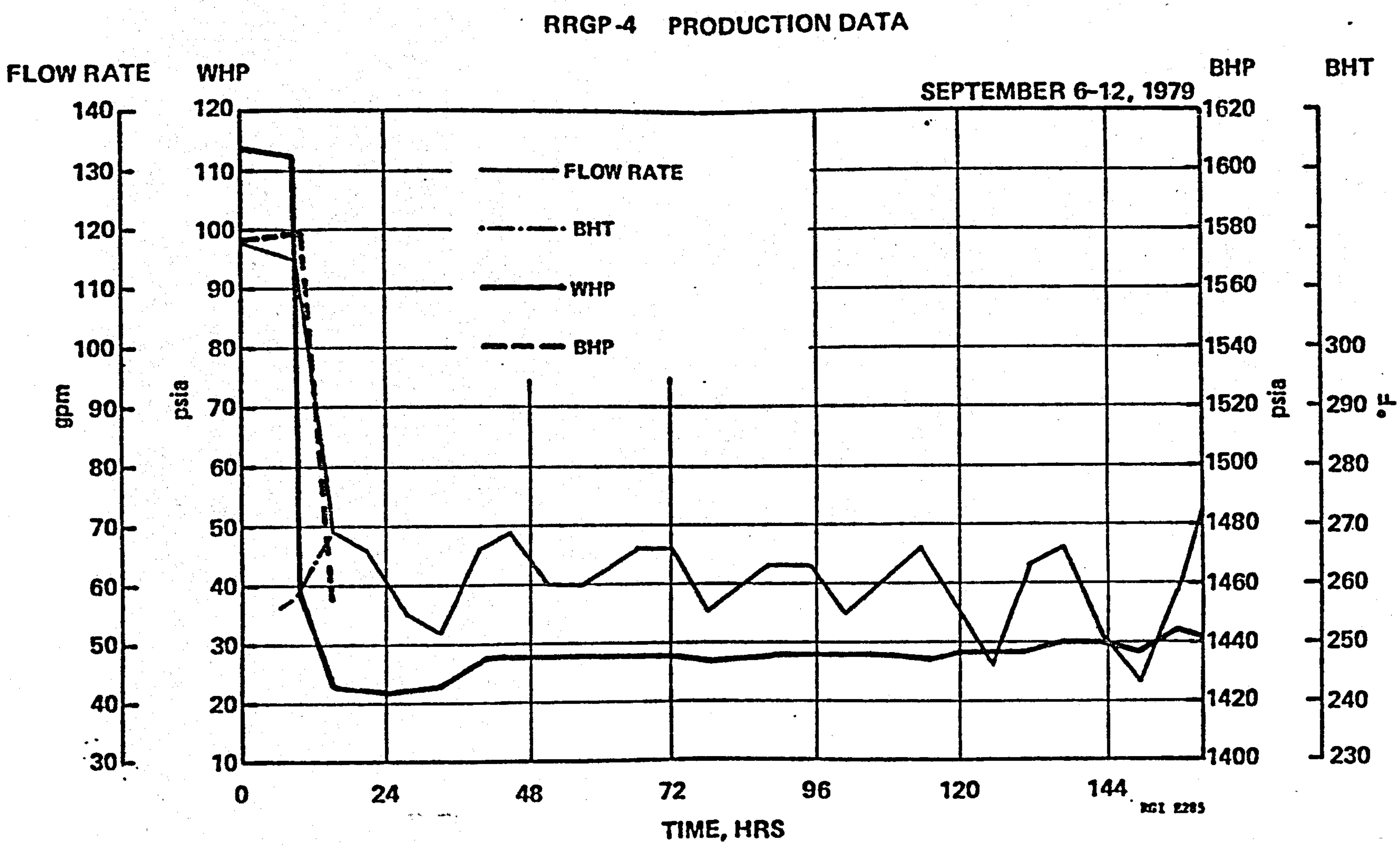
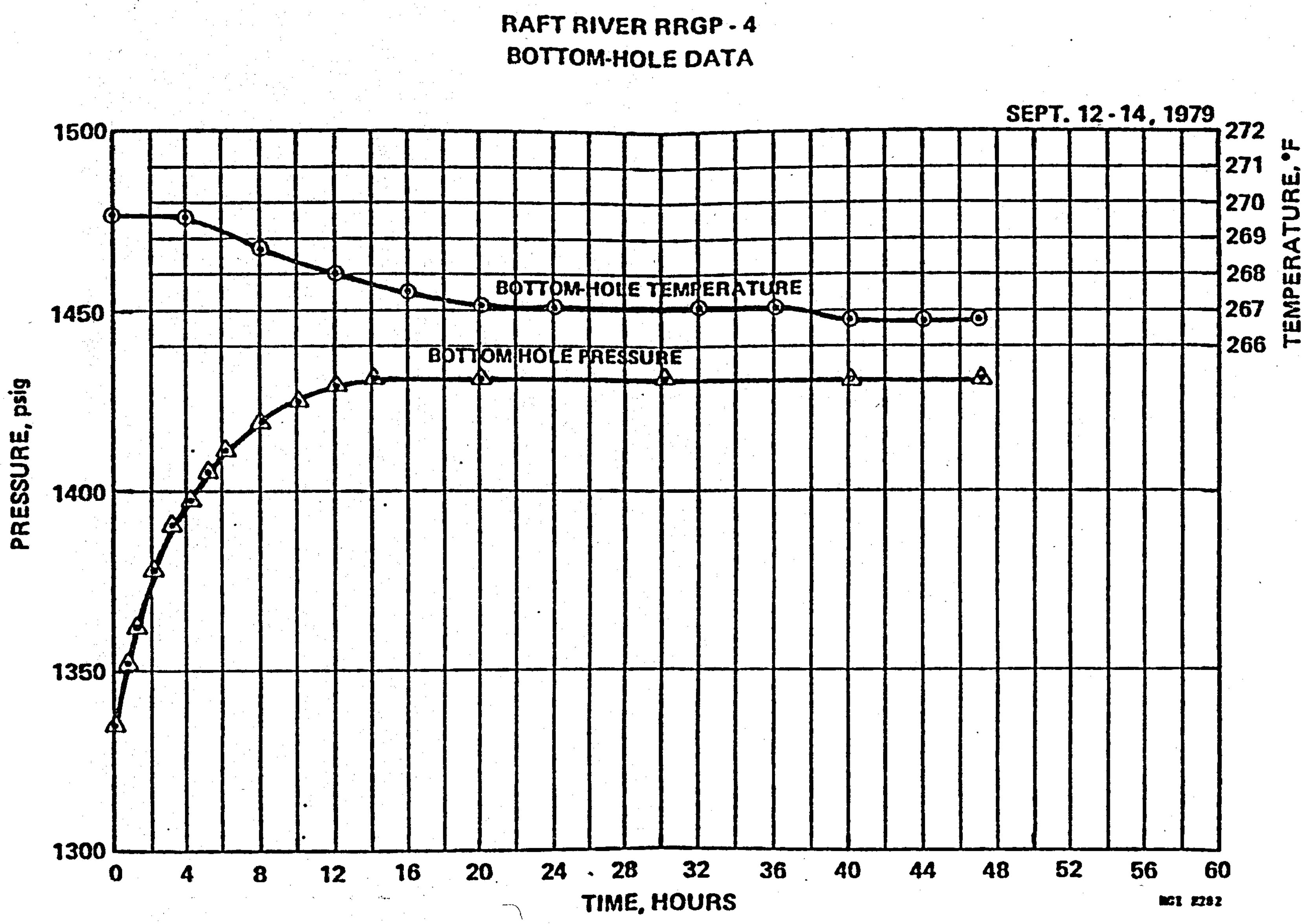


FIGURE 2



RRGP-4 PRODUCTION DATA
SEPTEMBER 6-12, 1979
FLOW RATE
WHP
BHP
BHT
FLOW RATE
BHT
WHP
BHP
gpm
psia
psia
°F
140
130
120
110
100
90
80
70
60
50
40
30
120
110
100
90
80
70
60
50
40
30
20
10
1620
1600
1580
1560
1540
1520
1500
1480
1460
1440
1420
1400
300
290
280
270
260
250
240
230
0
24
48
72
96
120
144
TIME, HRS

FIGURE 3



RAFT RIVER RRGP - 4
BOTTOM-HOLE DATA
SEPT. 12 - 14, 1979
1500
1450
1400
1350
1300
PRESSURE, psig
272
271
270
269
268
267
266
TEMPERATURE, °F
BOTTOM-HOLE TEMPERATURE
BOTTOM HOLE PRESSURE
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
TIME, HOURS

FIGURE 4

RRGP–4 BUILDUP DATA

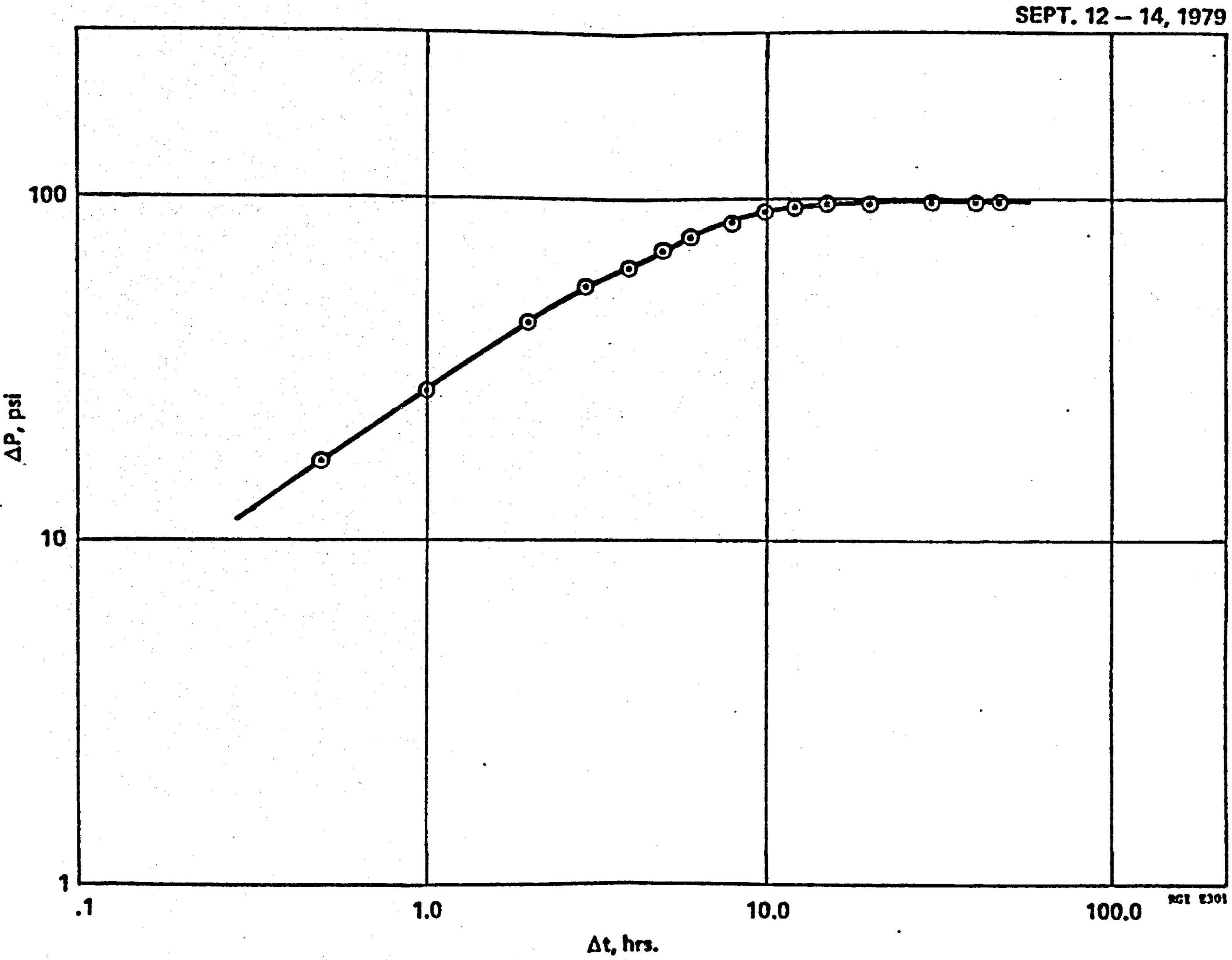


FIGURE 5

RRGP-4 BUILDUP DATA

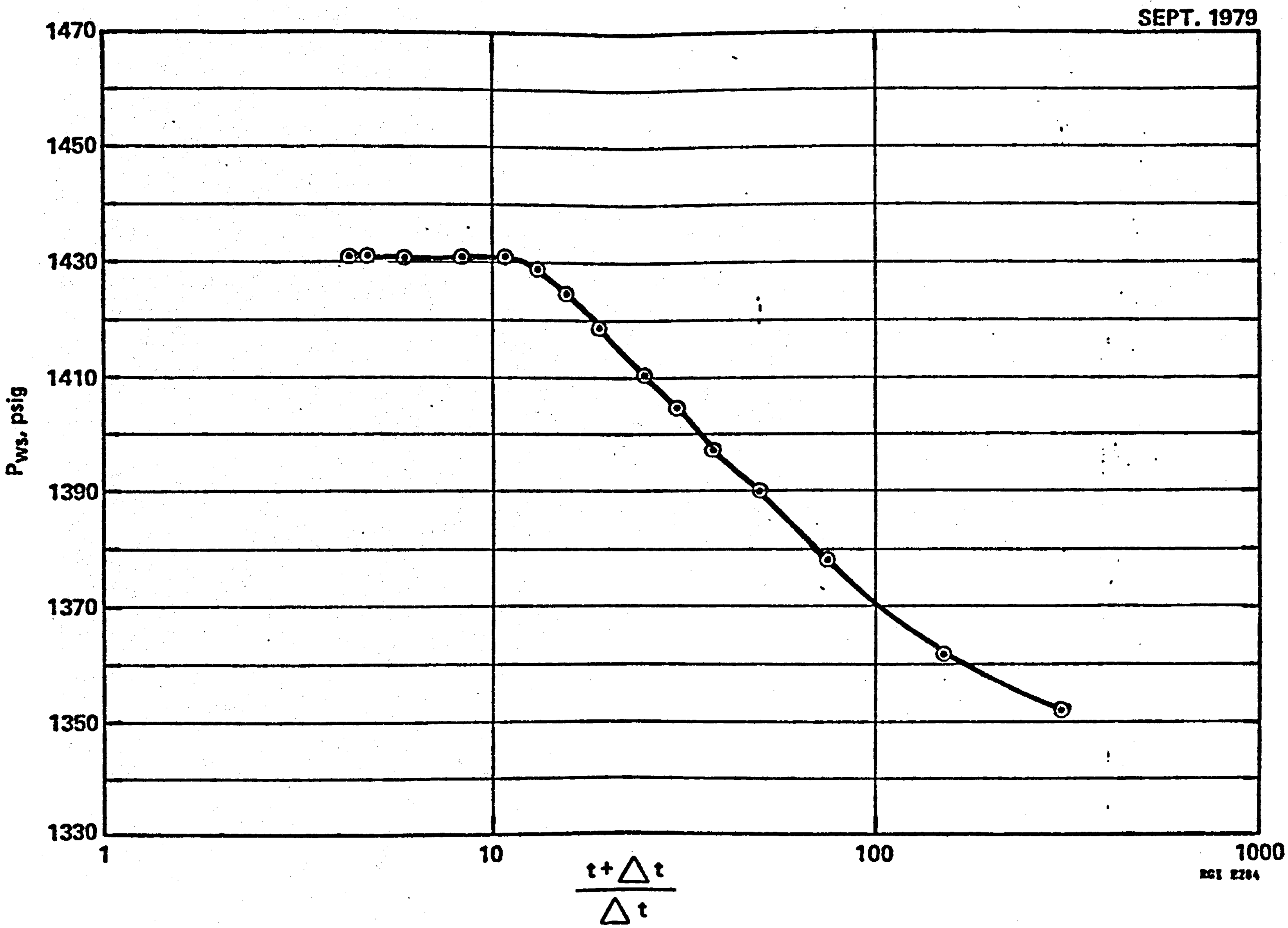


FIGURE 6

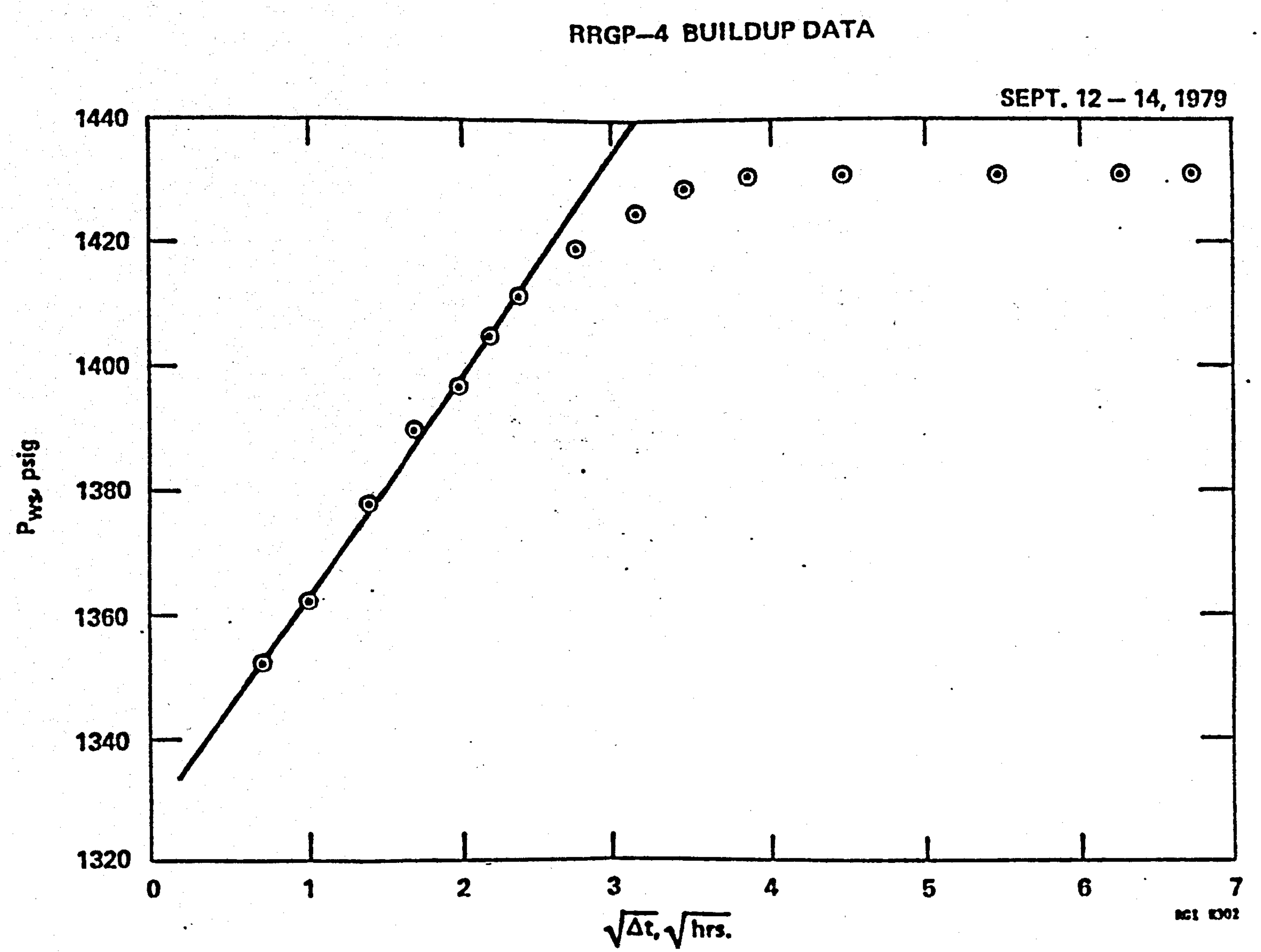

RRGP—4 BUILDUP DATA
SEPT. 12 – 14, 1979
1440
1420
1400
1380
1360
1340
1320
P_{ws}, psig
0
1
2
3
4
5
6
7
$\sqrt{\Delta t}, \sqrt{hrs.}$

FIGURE 7

RRGP-5 PRODUCTION DATA

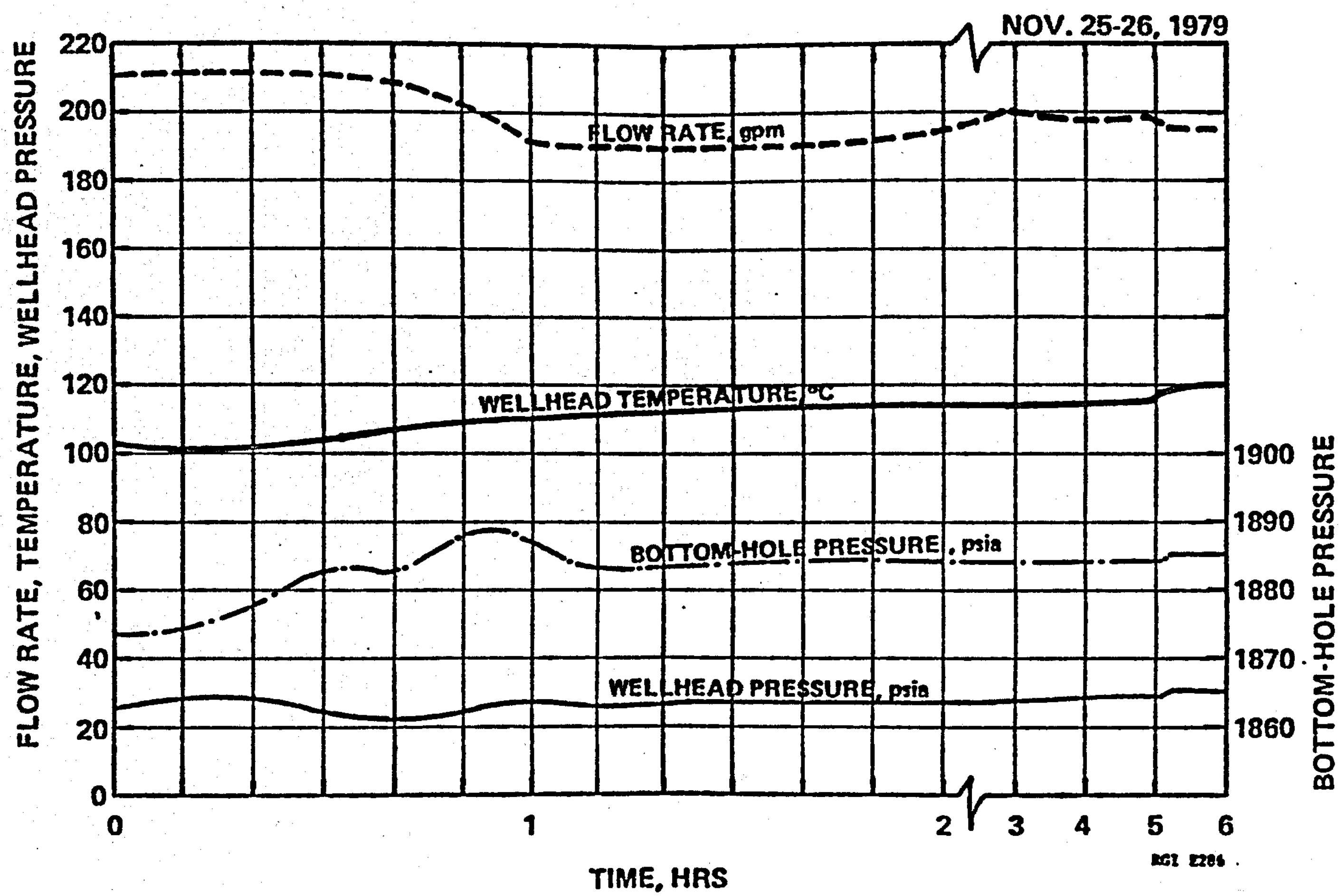


FIGURE 8

RRGP-5 BUILDUP DATA

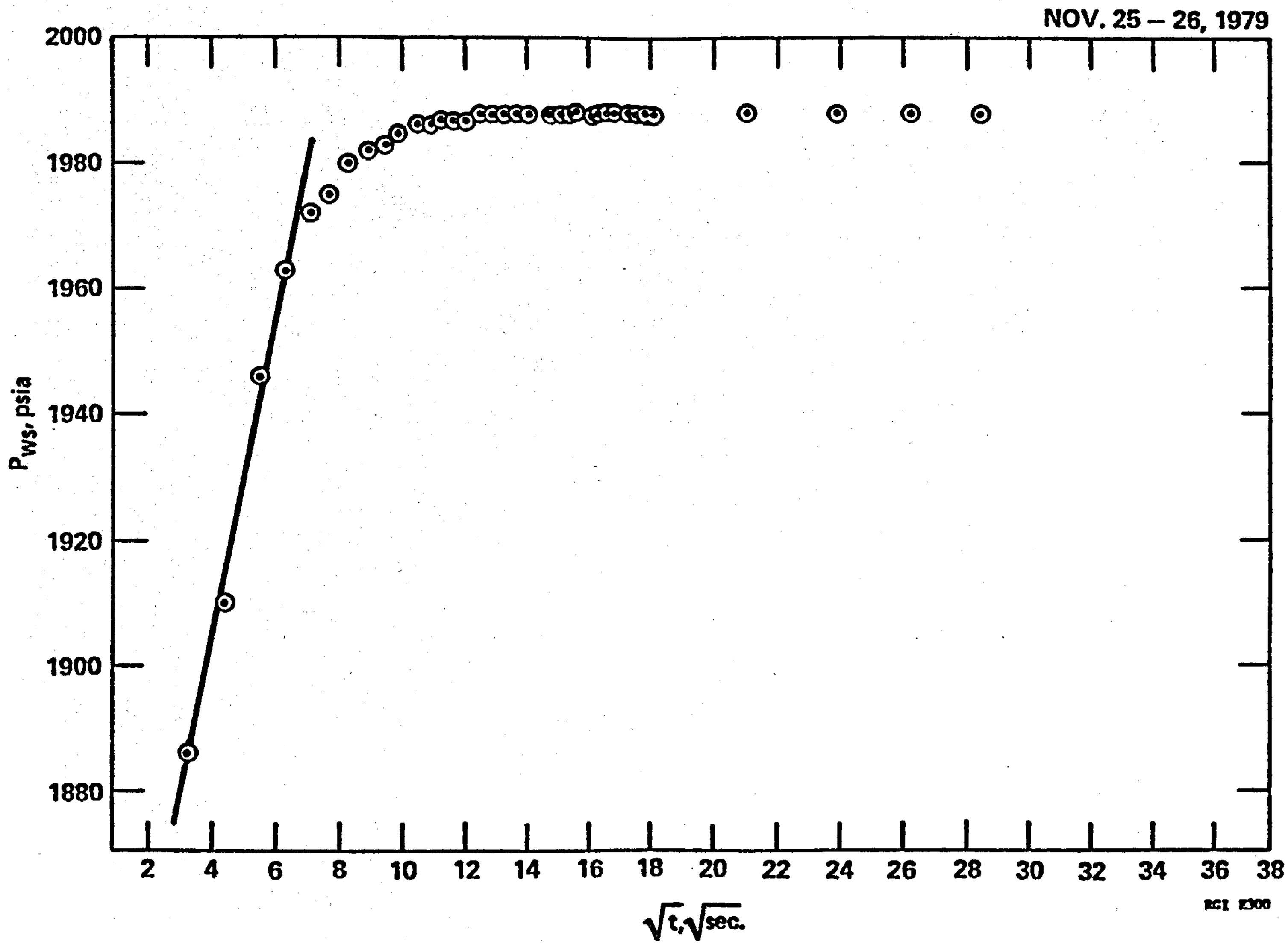
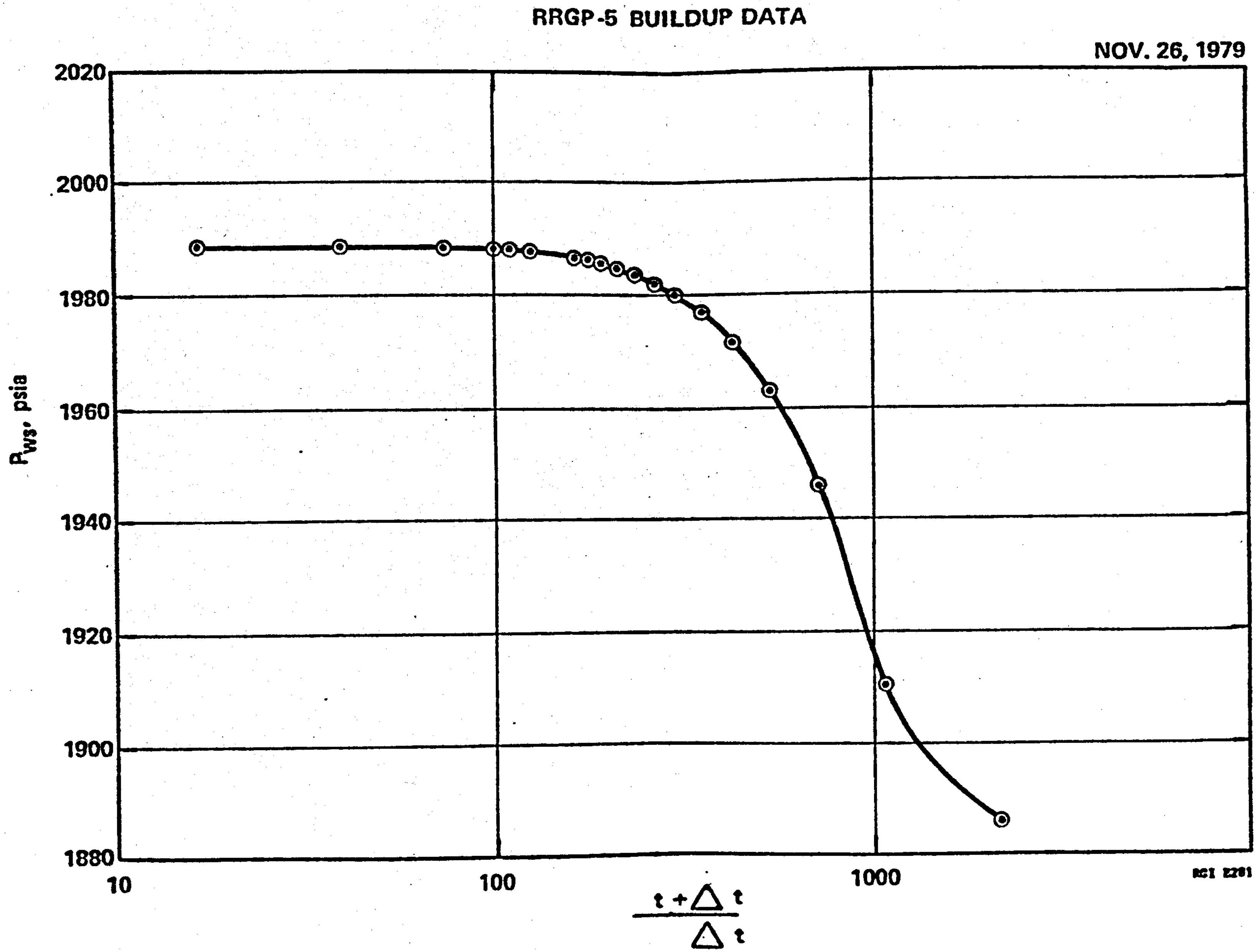


FIGURE 9



RRGP-5 BUILDUP DATA
NOV. 26, 1979
2020
2000
1980
1960
1940
1920
1900
1880
P_{ws}, psia
10
100
1000
$\frac{t + \Delta t}{\Delta t}$
RCI 2281

FIGURE 10

RRGP-5 BUILDUP DATA

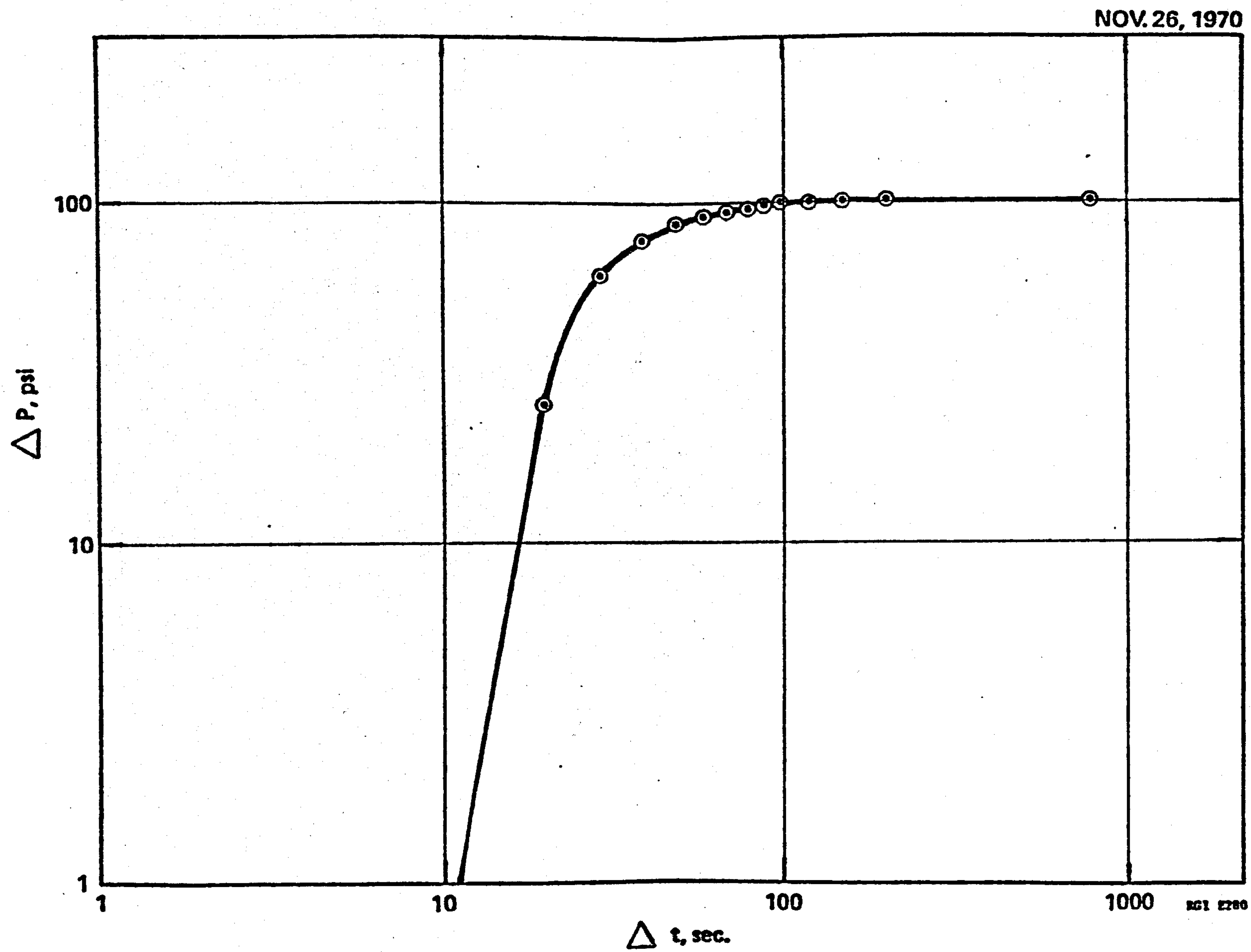


FIGURE 11

RRGP - 5
TEMPERATURE SURVEYS
RAFT RIVER, IDAHO

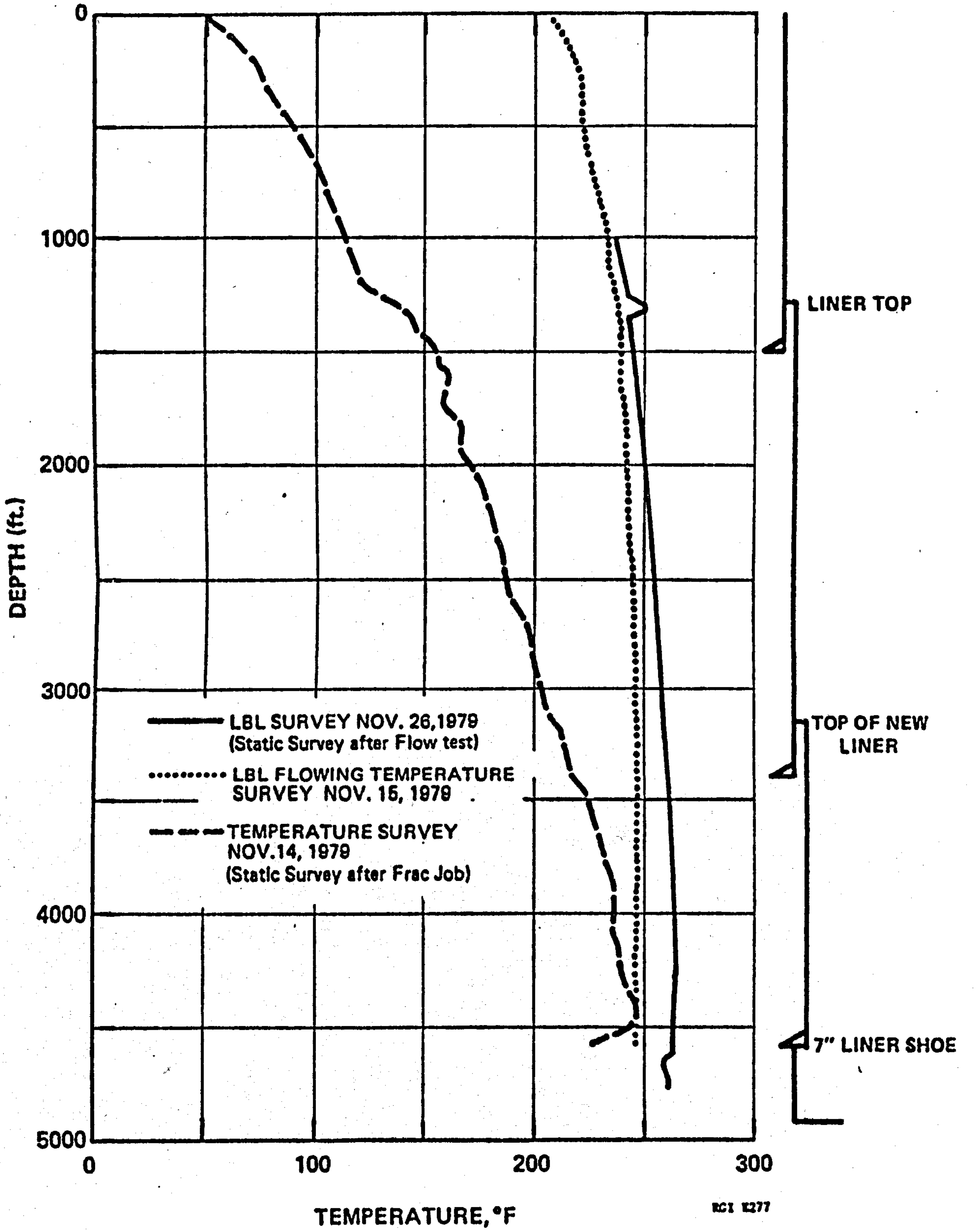


FIGURE 12

RESERVOIR SIMULATION

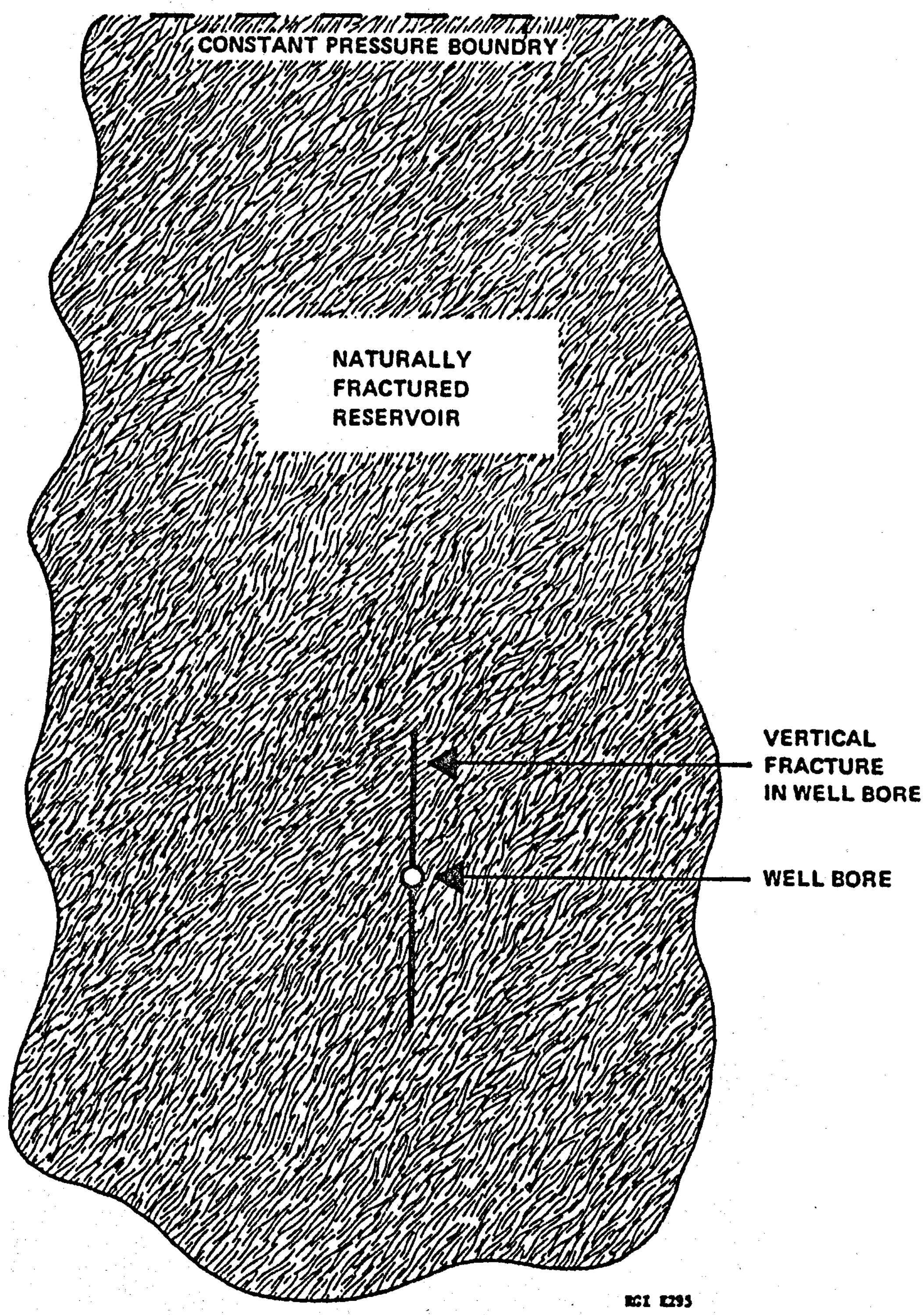


FIGURE 13

TOTAL ORGANIC CARBON AND CARBOHYDRATE CONCENTRATION OF RRGP-4 PRODUCED FLUID

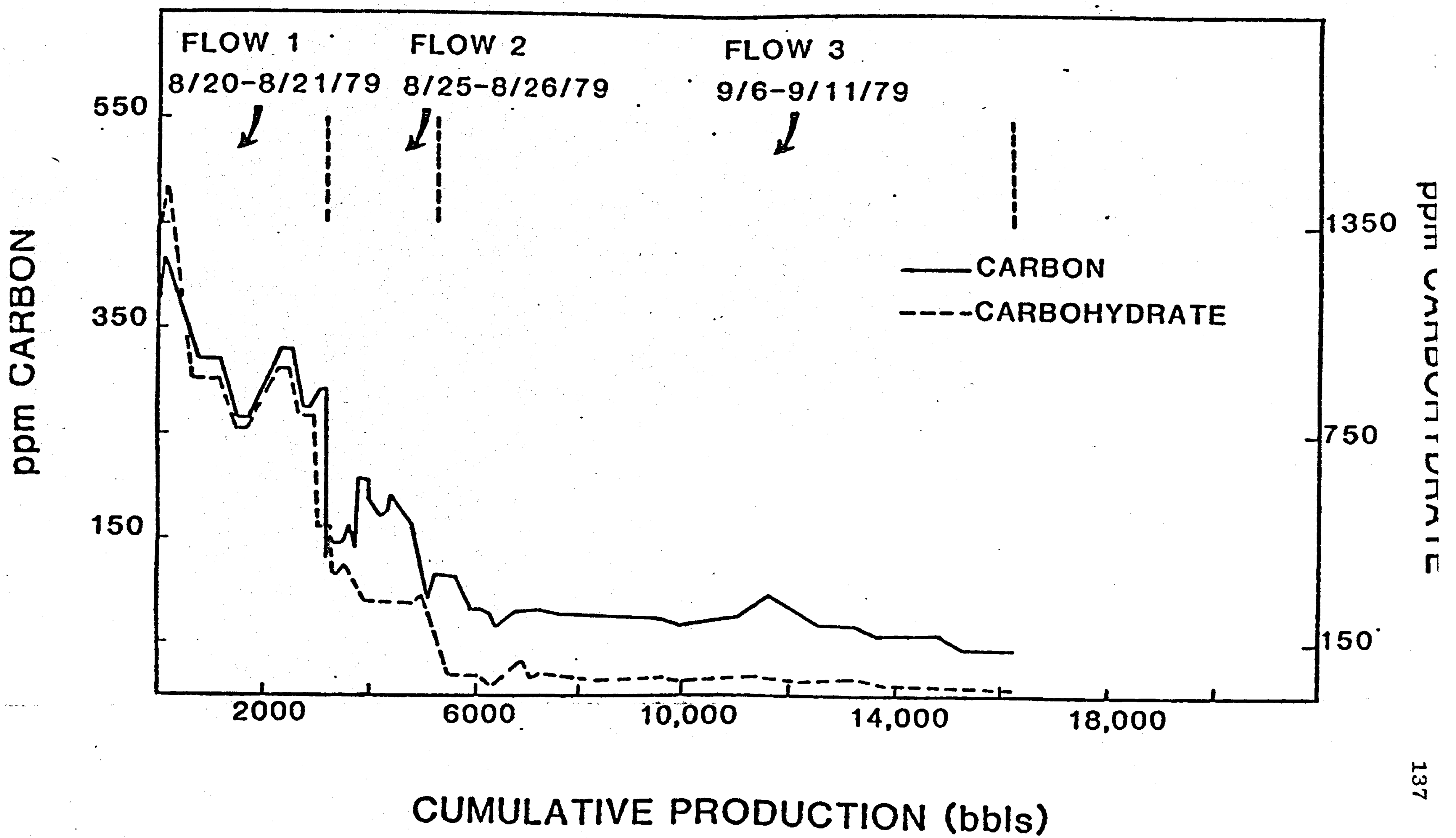


FIGURE 14

AMMONIUM AND NITRATE TRACER CONCENTRATION IN RRGP-5 PRODUCED FLUID

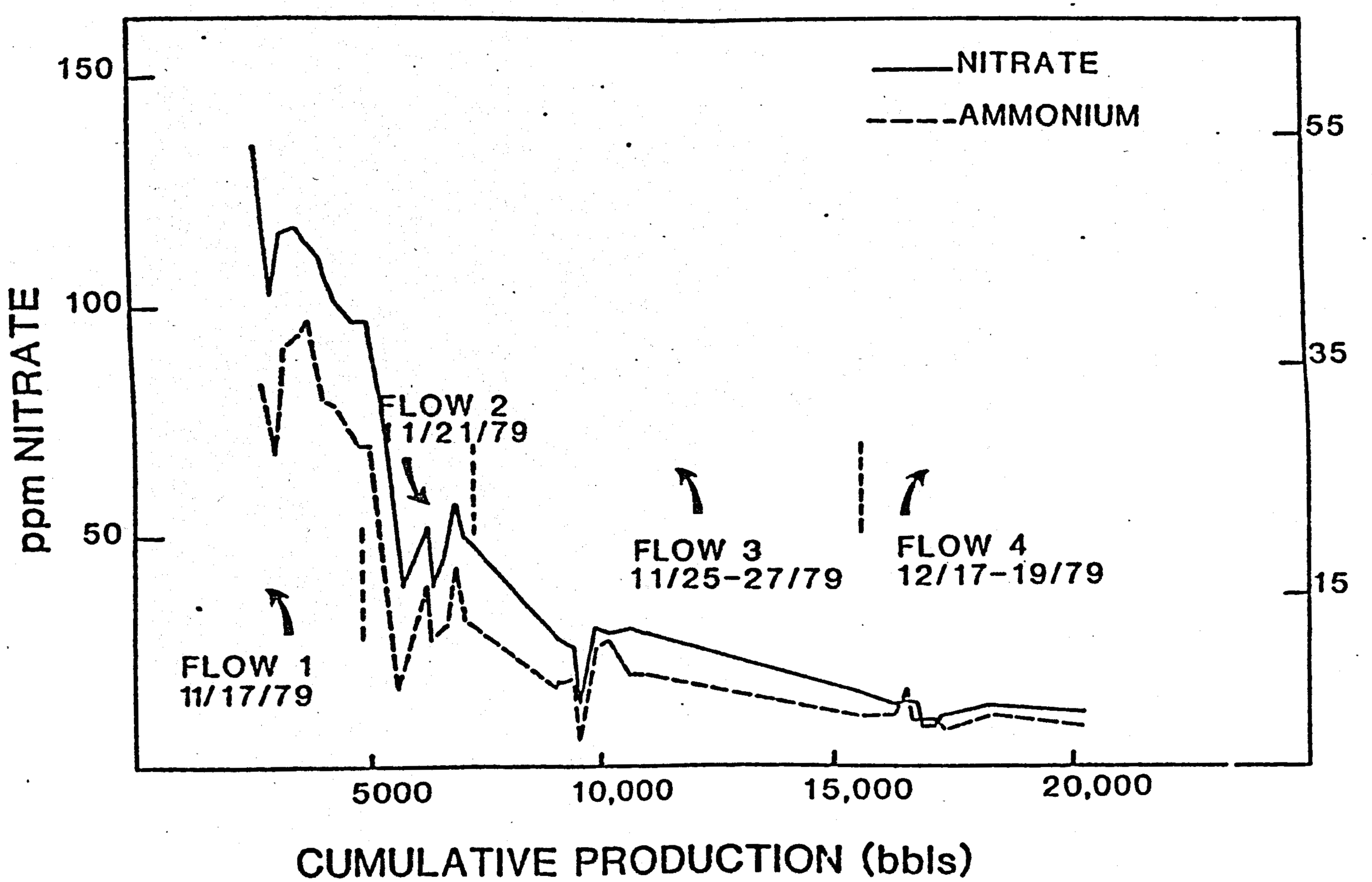


FIGURE 15

TOTAL ORGANIC CARBON AND CARBOHYDRATE CONCENTRATION OF RRGP-5 PRODUCED FLUID