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RESULTS AT RRGI-6 DURING JANUARY 1979

INJECTION FROM RRGE-2

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CONTENTS

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I. OBJECTIVES

The objectives of the January 1979 test of RRGI-6 included the determination of local aquifer boundaries, the estimation of aquifer transmissivity (T) and intrinsic transmissivity (kh), borehole flow characteristics, and well interfence; and the prediction of wellhead pressures after 5 years of injection. The test was used to permit RRFO to gain experience in operation of the injection system for upcoming Raft River tests.

II. SUMMARY OF RESULTS

Pulse test data prior to and following the ~72-hour injection did not indicate any well plugging during testing. Well losses are on the order of 69 kPa (10 psi) when injecting water with a temperature in excess of 104°C (220°F).

Injection at 44.16 l/s (700 gpm) indicates that the rate of pressure buildup of the cone of impression after ~ 100 minutes of injection was affected by a hydrologic phenomenon(a) that resulted in a reduced rate of pressure buildup. The rate of pressure buildup prior to ~ 100 minutes is 238.5 kPa/log cycle (34.59 psi/log cycle) as determined from semilogarithmic graphs of pressure versus time. The pressure buildup was only at a rate of 113.4 kPa/log cycle (16.44 psi/log cycle) after ~ 200 minutes with 125.6°C (258°F) water. Expected wellhead pressure after 5 years of continuous injection at 44.16 l/s (700 gpm) of 125.6°C (258°F) water with no additional boundary or well interference affects is 1984 kPaa (287.7 psia). The Hewlett-Packard (H-P) downhole pressure-temperature probe resulted in satisfactory pressure data only when the probe was subjected to temperature changes $<$ 0.0056°C/min. ($<$ 0.01°F/min.).

III. TEST PROCEDURE

Basically, the testing entailed stressing the Raft River geothermal aquifer(s) by producing deep geothermal fluid at RRGE-2 and reinjecting it into RRGI-6 at an intermediate depth.

The test involved two one-hour pulse injections in RRGI-6, each followed by a one-hour recovery. This was followed by a 72-hour injection and 72-hour recovery. The pulse injection rates were 51.73 l/s (820 gpm) and 47.31 l/s (750 gpm) respectively. The injection rate for the subsequent 72-hour duration test was 44.16 l/s (700 gpm). At the end of the 72-hour recovery, pulse injections were repeated at RRGI-6 at identical injection rates and as near identical pre-start conditions as possible. The intent here was to ascertain, if possible, any changes that may have occurred in the wellbore due to chemical precipitates or suspended solid invasion of the wellbore wall. Again each pulse was followed by a one-hour recovery.

A Peerless 15-stage 12-lb vertical turbine pump was installed at RRGE-2 to depth of 244.5m (802 ft.). At RRGI-6, a Johnson 9-stage 14BC vertical turbine pump was used as the injection pump.

To measure drawdown within the wellbore, a bubbler tube was installed to a depth of 244.1m (801 ft.). A 0-6895 kPag Heise gauge (PI-2-4) was attached to the bubbler system at the surface. The tube was periodically purged with nitrogen gas and the pressure allowed to equilibrate with the weight of the fluid column above the exit of the tube in the wellbore.

Control for the entire supply and injection system relied on the flow control apparatus at RRGI-6. It consisted of a 0.152m (6-inch) Fisher valve with Cavitrol trim. The valve opening was maintained automatically by sensing a differential pressure across an orifice with a Rosemont differential pressure transmitter (FT-6-9). Pressure differential across the orifice was recorded on a Hewlett-Packard strip chart recorder (FR-6-3). Ultimately, flow was maintained to within an estimated 0.5% with the system. Pipeline pressure between RRGE-2 and RRGI-6 was maintained within specified limits by valving at RRGE-2.

Due to the design of the entire supply and injection system, flow was gradually increased to a specified rate at the start of an injection and gradually decreased at the end. This technique is reflected in the data and will be discussed later.

Wellhead pressure buildup and falloff at RRGI-6 was measured with a 0-6895 kPag (0-1000 psig) Heise gage (PI-6-1), a Rosemont 0-6895 kPag (0-1000 psig) pressure transmitter (PT-6-2) interfaced to a Hewlett-Packard strip chart recorder (PR-6-3) and a 0-1379 kPaa (0-200 psia) digiquartz pressure transducer. When the injection pressure at RRGI-6 eventually exceeded 1379 kPaa (200 psia), the digiquartz transducer was valved out.

In addition to the surface instrumentation, a Hewlett-Packard downhole pressure-temperature probe was installed in the wellbore at 612.0 m (2008 ft.). The downhole probe,which ultimately failed during the 72-hour portion of the test, was removed and not reinstalled.

To monitor injection water temperature at RRGI-6, a Type K thermocouple (TE-6-4) was installed at the wellhead. Temperature was recorded with a Soltec strip chart recorder (TR-6-5). The Hewlett-Packard downhole probe recorded temperature while in operation.

Wells MW 3 through 7, RRGI-7, RRGE-1, and RRGE-3 were used as observation wells. Transient water level changes at these wells were measured at the MW wells and RRGI-7 with Stevens Type F water level recorders. Transient wellhead pressure was monitored with digiquartz pressure transducers at RRGE-1 and RRGE-3. Other experiments under way at RRGE-1 required that the well be flowing during the test. Discharge was held constant at approximately 13.12 l/s (208 gpm).

An attempt was made to obtain a temperature profile from RRGI-6 during the 72-hour portion of the test. However, the temperature probe was unable to get deeper than 6.09.6 M (2000 ft.).

113°C (235°F) during the 47.3 lps (750 gpm test, and from 109°C (228°F to 123°C (254°F) during the 51.7 lps (820 gpm) test. Water was injected for only 53 minutes during the 47.3 lps (750 gpm) test because the RRGI-6 injection pump had to be shutin due to smoking packer in the pump.

Figure 1 graphs the wellhead pressure, recorded by Heise gauge P16-1, versus the logarithm of injection time. A straight line is apparently formed by the data after approximately three minutes. The u assumption, inherent in modified nonequilibrium analysis, is satisfied in less than a minute, assuming a transmissivity of 3.16 x 10^{-4} square meters per second (m^2/s) [2200 gallons per day per foot of drawdown (gpd/ft.)], a storage coefficient of 0.005 and an effect radius of RRGI-6 of 0.3048 metres (1 ft.). The data were found to be thermally effected for approximately 300 minutes, during the 72-hour test. No boundaries are apparent on Figure 1.

The H-P temperature-pressure probe was used in collecting data during the January 9 pulse tests and the initial 72-hour test attempt. Corrosion of conducters within the probe resulted in failure on January 12. The probe was unavailable for further testing following failure.

The pressure at 612 metres (2008 ft.) increased from 5530 kPaa (kilopascals absolute) (814 psia [pounds per square inch absolute]) to 6830 kPaa (991 psia) during the 51.7 lps (820 gpm) test, and from 5530 kPaa (815 psia) to 6750 kPaa (979 psia) during the 47.9 lps (760 gpm) test. The temperature at 612 metres (2008 ft.) increased from 92°C (198°F) to 106°C (222°F) during the 51.7 lps (820 gpm) test, and from 103°C (217°F) to 112°C (234°F) during the 47.9 lps (760 gpm) test.

The H-P pressure and temperature data are indicated in Figure 2. The H-P data were thermally effected. The temperature change must be less than 0.021°C (0.01°F) per minute for the H-P probe to record reliable pressures. Temperature changes were greater than 0.021°C (0.01°F) during the initial 300 min. of injection. The H-P temperature decreased during the initial 20 minutes of injection, reflecting "cool" water at a depth less than 612.0 metres (2008 ft.) being forced down the wellbore by the injection water.

Calculated falloff graphs (Figure 3), of calculated falloff "s" versus the logarithm of shutin time "t", were believed to be thermally effected. The calculated falloff "s" is the difference between the values extrapolated from the linear pressure buildup data minus the observed wellhead pressure data. The u assumption is satisfied in less than a minute. The break in slope after 16 minutes of shutin, following the 47.3 lps (750 gpm) pulse test January 19, 1979, is related to the artesian flow of 1.26 lps (20 gpm) from RRGI-6 in an attempt to maintain isothermal conditions within the wellbore.

The calculated recovery H-P data (Figure 4) were thermally effected and did not form a straight line. The data could not be interpreted. The steps in the data, occurring after 3 and 1.5 minutes, were related to the procedure during well shutin. The injection was initially stepped down to 25.2 lps (400 gpm) before shutin.

Values for Q/s_{10} (Table 2), the test injection rate, Q, divided by the change in wellhead pressure per log cycle of the straight line segment, s_{10}, were calculated for each buildup and falloff graph. The Q/s_{10} ranged from 0.2852 lps/kPag/log cycle (31.14 gpm/psig/log cycle) to 0.1344 lps/kPag/log cycle (14.69 gpm/psig/log cycle). The Q/s_{10} log mean was 0.1844 lps/kPag/log cycle (20.16 gpm/psig/log cycle). Graphing the Q/s_{10} on logarithmic probability paper (Figure 5) indicates that the highest values resulted during falloff. This is to be expected since the temporally increasing density of the wellbore water, which is declining in temperature results in a factor affecting the rate of falloff which is not considered in the mathematical model used to analyze the data. The rapid pressure decline results in a lower Q/s_{10} than is actually the case. A similar situation exists during buildup. The decreasing density of the increasingly hotter injection water causes wellhead pressure buildups exceeding those theoretically predicted. This results in overestimated values for Q/s_{10} values and, consequently, underestimated values for Q/s_{10} for both falloff and buildup data. The underestimations during buildup are greater than that during falloff.

The Q/s_{10} results were graphed vervus the test injection rate (Figure 6). The Q/s_{10} of an ideal well is independent of Q. A linear relationship is suggested at injection rates above 45.4 lps (720 gpm). The relationship may be caused by non-ideal groundwater flow within RRGI-6, such as turbulent flow and/or fracture controlled flow.

4.3 BOREHOLE FLOW CHARACTERISTICS

Specific injectability (Si) and well losses were determined to estimate the borehole flow characteristics of RRGI-6. The specific injectability of a well is the injection rate divided by the pressure buildup occurring at a certain time. The specific injectability is related to aquifer characteristics and well efficiency (well losses), and is analogous to the specific capacity of a production well. For wells having significant well losses, the specific injectability decreases with an increase in an injection rate. An increase in injection results in a decrease in the specific injectability. Ten minutes of injection was chosen for determining the specific injectability to assure that data were unaffected by aquifer boundaries. The data were thermally effected, resulting in slightly underestimated values for the specific injectabilities.

The specific injectabilities (Table 3) ranged from 0.0724 lps/kPag (7.91 gpm/psi) ot 0.0566 lps/kPag (6.19 gpm/psi) with a logarithmic mean of 0.0631 lps/kPag (6.90 gpm/psig). The specific injectabilities are low in comparison to those found in the water well industry. Well losses are pressure increases caused by factors such as drilling mud on the borehole well, turbulent flow in the aquifer(s) near the borehole, and turbulent flow in the borehole. The greater the well losses the less efficient the well. Well losses were estimated by two methods, by comparing buildup and calculated falloff when boundary effects are negligable, and by use of the Theis equation. The difference between the buildup and falloff curves is related to well losses, which occur during buildup but not during falloff. Pressure buildups calculated using the Theis equation were compared with pressure buildup observed during testing, with the difference being well loss. A transmissivity of 3.16×10^{-4} m^2/s (2200 gpd/ft) and a storage coefficient of 0.005 were assumed when using the Theis equation. The storage coefficient is high for an artesian aquifer system, but consistent results were obtained using 0.005. The geology penetrated by RRGI-6 indicates a possible high storage coefficient.

The well losses indicated by both methods ranged from 34 kPag (5 psig) to 100 kPag (15 psig). Seventy kilopascals (10 psig) appears to be a reasonable estimate of well losses occurring during the January 1979 testing. The well losses were estimated to be much greater for the May 1, 1978 injection test. The difference in apparent well losses appears to be related to injection water temperature. The May test injected 43.3°C (110°F) water, viscosity 0.6178 centipoise (cp), while the January 1979 test injected over 104°C (220°F) water, having a viscosity of less than 0.3 cp. The lower viscosity of the hotter injection water resulted in decreased well losses during the January test. It is still believed that well losses will be quite high in RRGI-6 during injection of power plant effluent of 60°C (150°F). Additional testing, at lower temperatures will further define well losses.

4.4 EFFECTS OF 72-HOUR TEST ON RRGI-6

The pulse tests conducted before the 72-hour test were compared with those conducted after. It was hoped to determine the effect of the 72-hour test upon RRGI-6. No conclusions could be rendered due to inconsistent data. Figure 7 compares the pressure buildup occurring after 10 minutes of injection. The data implies that larger pressure buildups occurred following the 72-hour test. Figure 8 graphs pressure buildups, proportioned to 44.2 lps (700 gpm) vs injection time. The lps (650 gpm) test indicates that RRGI-6 injectibility decreased following the 72-hour test, while the 50.5 lps (800 gpm) test indicates it improved. The initial pulse test conducted on January 9, 1979 (45.4 lps) and January 19 (41.0 lps) resulted in the highest wellhead pressures, as the wellbore and injection water were relatively "cold". The 49.2 lps and 53.0 lps pulse tests resulted in lower wellhead pressures due to the lower viscosities of the hotter water injected during these tests. It can be concluded from Figure 8 that the pulse test data are thermally effected.

4.5 700 GPM TEST BEGINNING JANUARY 9, 1979

4.5.1.1 Wellhead

The first attempted 44.16 lps (700 gpm) 72-hour injection test began on January 9, 1979 and continued for 224 minutes until a fire resulted in pump shut down. A pump shut down for 2 minutes also occurred at 42 minutes after pumping began. Figure 9 is a semilogarithmic graph of wellhead pressure buildup versus the time since injection began. Wellhead pressure had declined to approximately 426.8 kPaa (61.9 psia) immediately prior to pump start-up which occurred 172 minutes after pump shut down for the preceeding 47.31 l/s (750 gpm) injection test. The equations defining wellhead pressure and Hewlett-Packard downhole pressures along with other pertinent data are listed in Table 4. The data segment following temporary pump shut down is displaced approximately 34.5 kPa (5 psi) below the extrapolated position of the data segment from 4 to 41 minutes. However, the ratios of Q/s_{10} for the data segments prior to and following the 2 minute pump shutdown, 0.2309 l/s/kPa/log cycle (25.24 gpm/psi/log/ cycle) and p.2120 l/s/kPa/log cycle (23.17 gpm/psi/log cycle) respectively, are similar. An effective injection rate of 45.42 l/s (720 gpm) was assumed for calculating the Q/s_{10} ratio when injecting at 44.16 l/s (700 gpm). The 1.26 l/s (20 gpm) warm-up flow from the well continued for such long periods of time prior to the 44.16 l/s (700 gpm) tests that the buildup slope would be very small and could be neglected in calculations for s_{10}. The maximum wellhead pressure observed was 1455 kPaa (211 psia). The wellhead pressure buildup during the first attempt at a 44.16 l/s (700 gpm) injection rate resulted in a log mean of 0.2212 l/s/kPa/ log cycle (24.18 gmp/psi/log cycle) for the ratio Q/s_{10} for the two data segments.

4.5.1.2 Downhole

The Hewlett-Packard downhole pressure-temperature probe, at a depth of 612.0 m (2008 ft.), was used to collect the pressure and temperature data in Figures 10, 11, and 12 concurrent with the wellhead pressure data. The pressure prior to injection was approximately 5605 kPaa (813 psia). Maximum observed pressure during injection was 6616 kPaa (959.54 psia). The pressure buildup data in Figure 10 exhibit such large fluctuations in pressure that an accurate estimate for the ratio Q/s_{10} is not possible. Previous experience with the Hewlett-Packard (H-P) probe indicates that accurate pressure data result only when the probe is subjected to low rates of temperature change. Figure 11 is a graph of the reported H-P temperature. The initial temperature, which was 108.9°C (228°F), declined to 104.4°C (220°F) at 20 minutes and then increased in an irregular manner to 122.8°C (253°F) after 213 minutes of injection. Figure 12 is a graph of the rate of temperature change during the test. The correlation between the fluctuations in pressure (Figure 10) and the fluctuations in temperature (Figure 11, 12) indicate that the reported pressure data are sensitive to temperature changes. Suspect pressure data even resulted when the reported rate of temperature change was 0.11°C/min. (0.2°F/min.). In conclusion, the H-P pressure data during buildup were affected by changing borehole fluid temperatures to such an extent that accurate estimates of the Q/s_{10} ratios are not possible.

4.5.2 FALLOFF

4.5.2.1 Wellhead

The wellhead pressure falloff data are plotted in Figure 13, which is a graph of wellhead pressure, s, versus t/t'. The term t is the time since injection began, while t' is the time since well shutin. Figure 14 is a graph of calculated wellhead falloff pressure, s", versus t'. The wellhead pressure declined to 498.8 kPaa (72.34 psia) when t/t' = 2.13. The calculated wellhead falloff pressure reached a maximum value of 1025 kPaa (148.6 psia) when t' = 199 minutes. The slopes for the falloff data were determined for the segments $3.46 < t/t' < 6.46$ and $41 < t' < 91$ minutes. Data prior to 41 minutes exhibited an oscillatory tendency whereas data after 91 minutes exhibited a more rapid recovery than expected. The values for the ratio Q/s_{10} of 0.1955 l/s/kPa/log cycle) (21.37 gpm/psi/log cycle) and 0.1971 l/s/kPa/log cycle (21.54 gpm/psi/log cycle) are very similar for the data in Figures 13 and 14. In conclusion, the log mean value for the ratio Q/s_{10} is 0.2112 l/s/kPa/log cycle (23.08 gpm/psi/log cycle) for the wellhead falloff data with the data trends suggesting a recharge boundary effect on the data when $t' > 100$ minutes. The data perhaps deviates due to thermal effects related to the cooling of water within the wellbore.

4.5.2.2 Downhole

The H-P downhole pressure data during falloff are plotted in Figure 15. The pressure declined to 5604.7 kPaa (812.89 psia) when t/t' reached 1.90. The pressure fluctuations about the linear trend are related to the temperature changes occurring at a depth of 612.0 m (2008 ft.), Figure 16. Figure 17 is a graph of the rate of temperature change as sensed by the H-P probe. The plot indicates temperature changes generally in excess of 0.011°C/min. (0.02°F/min.) Temperature changes of this magnitude significantly affect the corresponding pressure data. As such, the value for the ratio Q/s_{10} of 0.2262 l/s/kPa/log cycle (24.92 gpm/psi/log cycle) (Table 4) can be expected to have greater associated errors than data affected by smaller temperature changes. However, the Q/s_{10} value of 0.2262 l/s/kPa/log cycle (24.72 gpm/psi/log cycle) is not unreasonable in comparison to other values (Table 4).

4.6 700 GPM TEST BEGINNING JANUARY 10, 1979

4.6.1 BUILDUP

4.6.1.1 Wellhead

Injection began 1065 minutes after terminating the preceeding 44.16 l/s (700 gpm) test and continued at 44.16 l/s (700 gpm) for 4378 minutes. Wellhead pressure was 376 kPaa (54.5 psia) 20 minutes prior to final pump start-up. Three false starts occurred during the 20 minutes preceeding the test start-up. Figure 18 depicts the wellhead pressure buildup. Approximately 7 minutes were required to reach the injection rate of 44.16 l/s (700 gpm). The pressure buildup graphed as a linear trend from 8 to 99 minutes after injection began. These data resulted in a Q/s_{10} ratio of 0.1624 l/s/kPa/log cycle (17.75 gpm/psi/log cycle) (Table 4). Between 100 and 200 minutes the pressure buildup data graphed above the trend from 8 to 99 minutes. From 200 to 4234 minutes the data also graphed as a linear trend resulting in a s_{10} value of 112.6 kPa/log cycle (16.33 psi/log cycle). Values of Q/s_{10} which may be used to calculate kh and T are not applicable once the cone of impression encounters hydrologic conditions which are dissimilar to those near the well. As a result, values for s_{10} will be used to describe additional linear data trends following the first linear segment. Because of apparent gage errors, data from 2344 to 4234 minutes which were collected with the Heise gage (PI 6-2), were corrected based on the data from a strip chart recorder (PR 6-3).

A wellhead pressure of 1972 kPaa (286 psia) can be expected after 5 years of continuous injection at 44.16 l/s (700 gpm) based on the extrapolation of the data collected between 200 and 4234 minutes after pumping began. This assumes injection of 258° water. In conclusion, the wellhead pressure buildup data resulted in a Q/s_{10} ration of 0.1624 l/s/kPa/log cycle (17.75 gpm/psi/log cycle) from 8 to 99 minutes after injection began, while from 200 to 4234 minutes the data followed a near linear trend having a s_{10} value of 112.6 kPa/log cycle (16.33 psi/log cycle) which extrapolated to a wellhead pressure of 1972 kPaa (286 psi) after 5 years of injection with no additional interference or boundary effects.

4.6.1.2 Downhole

The H-P downhole pressure data were spurious for approximately 300 minutes after pumping began (Figure 19). The pressure was 5560.6 kPaa (806.5 psia) immediately prior to pump start-up. Pertinent data and equations are contained in Table 4. The temperature as reported by the H-P probe (Figure 20) required approximately 300 minutes for the temperature changes to become less than 0.0056°C/min. (0.01°F/min.) (Figure 21). Matching of wellhead pressure data (Figure 18) and downhold pressure data (Figure 19), during the initial 5 minutes of injection, indicates a 10.3 kPa (15 psi) greater vertical displacement of the wellhead pressures when t is greater than 300 minutes. This displacement is on the order of that expected to result from temperature-induced density changes in the upper 612.0 m (2008 ft.) of the borehole (Figure 20). The s_{10} value of 114.2 kPa/log cycle (16.56 psi/log cycle) for the data for t greater than 300 minutes is very similar to the value of 112.6 kPa/log cycle (16.33 psi/log cycle) for the wellhead pressure data. This similarity, as well as the reasonable pressure differences between the H-P and wellhead pressures when t > 300 minutes, supports the contention that the H-P pressure sensor can compensate for temperature changes from 98.9°C (210°F) to 125.6°C (258°F) and can be used to define pressure trends under specified conditions. It appears that 0.0056°/Cmin. (0.01°F/min.) is the maximum rate of temperature change to which the H-P probe can be subjected and still result in acceptable precision in distinguishing pressure trends. In conclusion, the H-P downhole pressure data resulted in an estimate of 114.2 kPa/log cycle (16.56 psi/log cycle) for s_{10} from 304 to 3364 minutes after injection began.

The H-P data can be used to provide an estimate for the wellhead pressure after 5 years of continuous injection. The equation for the H-P downhole pressure for the period from 304 to 3364 minutes after pumping began (Table 4, Figure 19), results in a calculated downhole pressure of 7062.3 kPaa (1024.3 psia) after 5 years of continuous injection with no additional boundary or interference effects. Since the pressure prior to injection was 5560.6 kPaa (806.5 psia), the pressure buildup due to injection would be 1501.7 kPa (217.8 psi). With a wellhead pressure of 375.8 kPaa (54.5 psia) prior to injection and a 10.3 kPa (15 psi) increase in wellhead pressure above that observed at 612 m (2008 ft.) because of density changes during the test, the calculate wellhead pressure would be 1980.9 kPaa (287.3 psia). This value is in close agreement with the 1973.9 kPaa (286.14 psia) estimate derived from wellhead pressure buildup for the 44.16 1/s (700 gpm) test beginning January 10.

4.6.2 FALLOFF

4.6.2.1 Wellhead

Wellhead pressure falloff data are plotted in Figures 22 and 23. The initial time segments of the data have s_{10} values of 156.6 kPa/log cycle (22.71 psi/log cycle) and 155.0 kPa/log cycle (22.48 psi/log cycle) in Figures 22 and 23 respectively. The log mean s_{10} value for the initial time segment is 155.8 kPa/log cycle (22.59 psi/log cycle). The second segments have s_{10} values of 289.4 kPa/log cycle (41.18 psi/log cycle) and 251.9 kPa/log cycle (36.53 psi/log cycle) in Figures 22 and 23 respectively with a resulting log mean of 267.4 kPa/log cycle (38.79 psi/log cycle). No explanation for these slopes is readily available, but hydrologic heterogeneity in the various receiving zones and/or commingling effects between the various receiving zones may have resulted in the observed data. Additional tests are planned on RRGI-6 and will provide further insight into the hydrologic behavior of the receiving zones during long-term injection.

4.6.2.2 Downhole

Due to equipment malfunction, data were not collected using the H-P probe.

4.7 DISCUSSION

4.7.1 kh and T

The pulse tests, the first 44.16 l/s (700 gpm) test beginning January 9, and the first segment of the pressure buildup for the 44.16 l/s (700 gpm) test beginning January 10, can be used to provide an estimate of the kh (intrinsic transmissivity) and T (transmissivity) of the aquifer(s) penetrated by RRGI-6. The k is the intrinsic permeability and h is the aquifer thickness. Since h is not known, the product kh is calculated. The log mean Q/s_{10} values for the buildup and falloff data are 0.1699 l/s/kPa/log cycle (18.57 gpm/psi/log cycle) and 0.2002 l/s/kPa/log cycle (21.88 gpm/psi/log cycle) respectively. Wellbore fluid heat-up during injection would result in underestimation of actual Q/s_{10} values with wellbore fluid cooling during falloff also resulting in underestimated Q/s_{10} values, but to a lesser degree. Consequently, the falloff data is the best available estimator of Q/s_{10}.

By using the log mean Q/s_{10} for the falloff data, estimates for kh and T can be computed. The kh can be computed using the following equation:

$$kh = \frac{5759 \times Q \times \mu}{s_{10}}$$

where: kh is in md-ft
Q/s_{10} is in gpm/psi/log cycle
μ is the viscosity in centipoises.

Table 5 lists the estimated kh values which range from 26,116 md-m (85,682 md-ft) to 8872 md-m (29,107 md-ft) for assumed aquifer water temperatures ranging from 37.8°C (100°F) to 121.1°C (250°F) respectively. Corresponding estimates for T can be calculated using the following equation:

$$T = \frac{kh}{1000} \times 0.3284147 \frac{\gamma}{\mu}$$

where: T is in gal/d/ft
kh is in md-ft
γ is the specific gravity in lb/ft^3
μ is the viscosity in centipoises.

Table 5 lists the estimated T values which range from 3.688 x 10^{-4} m^2/sec (2566 gpd/ft) to 3.499 x 10^{-4} m^2/sec (2434 gpd/ft) for assumed aquifer temperatures ranging from 37.8°C (100°F) to 121.1°C (250°F) respectively. The receiving aquifer(s) effective temperature is probably in the range from 93.3°C (200°F) to 121.1°C (250°F). Thus, the aquifer kh and T values are on the order of 10,668 md-m (35,000 md-ft) and 3.550 x 10^{-4} m^2/sec (2470 gpd/ft) respectively.

4.7.2 Commingling/Boundary/Heterogeneity Effects

The buildup and falloff data (Figures 18, 22 and 23) for the 4378 minute (72.97 hour) injection test exhibited a marked decline in slope relative to the preceeding data trend. For the pressure buildup data in Figure 18, the change in slope from 279.7 kPa/log cycle (40.56 psi/log cycle) to 112.6 kPa/log cycle (16.33 psi/log cycle) occurred at t ≈ 100 minutes assuming a 10.3 kPa (15 psi) increase in wellhead pressure due to decreasing borehole water density from t ≈ 65 minutes for the data in Figure 22. The data during falloff (Figures

13 and 14) for the 44.16 l/s (700 gpm) test beginning January 9 also exhibit a change in slope after ≈ 100 minutes of falloff. Thus, it appears that after approximately 100 minutes of injection, the slope of the pressure buildup data deviates from the initial slope.

The slopes of the various segments on the buildup and falloff graphs do not provide sufficient information to delineate the type(s) of hydrogeologic phenomena responsible for the change in slopes. The slope, s_{10}, of 279.7 kPa/log cycle (40.56 psi/log cycle) for the data between t = 8 minutes and t = 99 minutes in Figure 18 is probably too high because of wellbore heatup during injection. The actual slope is probably less than 320 kPa/log cycle (35 psi/log cycle). The phenomenon(a) affecting the pressure buildup data results in an approximate halving of the slope for data collected when t is greater than 100 minutes. The phenomenon(a) affecting the slope is not an infinite linear constant head recharge boundary since the pressure continued to increase, rather than stabilize at a constant value. The falloff data in Figures 22 and 23 result in slopes of only 156.6 kPa/log cycle (22.71 psi/log cycle) and 155.0 kPa/log cycle (22.48 psi/log cycle) for the initial falloff data. A slope on the order of 207 to 276 kPa/log cycle (30 to 40 psi/log cycle) would normally be expected. The increase in slope for data when t' > 100 minutes suggest a phenomenon(a) that would result in a more rapid falloff of the wellhead pressure. If the spatially spreading cone(s) of impression encountered a volume of geologic material having a larger kh and/or larger storage coefficient than that of the material immediately surrounding the well, a decrease in the pressure buildup slope would result. The commingling effects of the hydrologically different receiving zones in the borehole could also result in the observed changes in slopes during buildup and falloff since these zones can be expected to have different temporally dependent water uptake rates. Additional data on this peculiar behavior of the buildup and falloff curves will be obtained in forthcoming tests.

4.8 INTERFERENCE EFFECTS

4.8.1 Observation Wells RRGE-3 and RRGE7

Figures 24 and 25 are graphs of wellhead pressure versus time for RRGE-3. The period during which injection occurred at RRGI-6 are also indicated. The injection at RRGI-6 did not result in a detectable change in wellhead pressure at RRGI-6.

Figures 26 and 27 are graphs of depth to water level at RRGI-7. The water level in the well increased at the average rate of 0.00278 m/hr or 0.0666 m/d (0.009105 ft/hr or 0.219 ft/d) from 0800 on December 30, 1978, to 2400 on January 9, 1979. The linear regression equation for this period is indicated in Figure 26. The linear regression approaches within approximately 0.12 m (0.4 ft) of the observed data on February 2, 1979. The calculated pressure buildup, s", at RRGI-7 was calculated as the difference between the observed depth to water minus the extrapolated values based on a linear regression through the preceding data. The maximum calculated pressure buildup, s", was 0.573 m (1.88 ft) at 1200 on January 15, approximately 34 hours after injection stopped. Figure 28 is a graph of calculated pressure buildup versus time in hours since 1800 on January 9, 1979. The injection at 820 gpm began at 1743 on January 9, 1979. Because of a varying and intermittent injection rate, as well as a heterogeneous aquifer system, a rigorous analysis of the interference data is not possible. However, an extrapolation of the steepest sloping data segment where $102 < t < 114$ hr results in a decrease in the depth to water of 9.98 m (32.74 ft) after five years of continuous injection. Because of the prolonged 6.30 l/sec (100 gpm) injection to warm the pipeline and RRGI-6 wellbore, it is assumed that this decrease in depth to water, 97.9 kPa (14.2 psi), resulted because of injection at 37.85 l/s (600 gpm). This is a preliminary estimate only. Injection at a constant rate for a period greater than 73 hr is required before the interference effects can be quantified with reasonable confidence levels.

The buildup data in Figure 28 may be interpreted as indicating the presence of a high transmissivity zone. The abrupt increase in slope at approximately 90 hr after pulse testing began can be interpreted as indicating that the pressure buildup at RRGI-6 was being transmitted to RRGI-7 via a high transmissivity zone after 90 hr. This high transmissivity zone could also result in the observed decline in pressure buildup at RRGI-6 (Figure 18). Additional data regarding the hydrologic conditions in the vicinity of RRGI-6 and RRGI-7 will be obtained in future injection tests of longer duration currently being planned.

4.8.2 Monitor Wells 3, 4, 5, 6, and 7

The monitor wells exhibited different apparent water level responses to the injection test. Monitor well 3, Figures 29 and 30, did not exhibit any distinguishable response to the test. The depth to water level in MW-1 was decreasing before testing and continued to decrease at approximately the same rate, after testing concluded. The sudden rise in water level on February 5, when MW-3 was pumped, is caused by inducing hot water into the wellbore and destroying thermal equilibrium. However, monitor wells 4 to 7, Figures 31 to 38, all exhibited a rise in water levels beginning approximately 2400 on January 14. The maximum water level rise above a linear water level trend beginning January 1 for MW 4, 5, 6, and 7 is estimated to be 0.18 m (0.6 ft), 0.12 m (0.4 ft), 0.030 m (0.1 ft), and < 0.030 m (< 0.1 ft), respectively.

A major stream runoff event may have recharged aquifers and been responsible for the observed decreases in depth to water levels. The runoff event, caused by rapidly melting snow, began on January 10. There are no data available on the response of the water table to this runoff event. However, a shallow monitor well network shall be placed in operation in the near future. Based on the data available, it is inconclusive whether the observed increases in well water levels resulted because of injection or because of regional ground water recharge. Additional data for the monitor wells will be available in forthcoming injection tests.

TABLE 1

INJECTION RATES RRGI-6, JANUARY 9 TO 19, 1979

Actual Rate	Test Rate	Test Type
51.7 lps (820 gpm)	45.4 lps (720 gpm)	Pulse Buildup
---------	51.7 lps (820 gpm)	Pulse Falloff
47.9 lps (760 gpm)	49.2 lps (780 gpm)	Pulse Buildup
---------	47.9 lps (760 gpm)	Pulse Falloff
44.2 lps (700 gpm)	45.4 lps (720 gpm)	72-hour Buildup
	44.2 lps (700 gpm)	72-hour Falloff
44.2 lps (700 gpm)	45.4 lps (720 gpm)	72-hour Buildup
---------	44.2 lps (700 gpm)	72-hour Falloff
47.3 lps (750 gpm)	41.0 lps (650 gpm)	Pulse Buildup
	47.3 lps (750 gpm)	Pulse Falloff
51.7 lps (820 gpm)	53.0 lps (840 gpm)	Pulse Buildup
---------	51.7 lps (820 gpm)	Pulse Falloff

TABLE 2

RRGI-6 Q/s_{10}, JANUARY 1979

Analysis Q	Test Type	Q/s_{10}
45.4 lps (720 gpm)	Buildup[1]	0.1344 lps/kPag/log cycle (14.69 gpm/psig/log cycle)
51.7 lps (820 gpm)	Falloff[2]	0.1899 lps/kPag/log cycle (20.76 gpm/psig/log cycle)
49.2 lps (780 gpm)	Buildup	0.1876 lps/kPag/log cycle (20.52 gpm/psig/log cycle)
47.9 lps (760 gpm)	Falloff	0.2042 lps/kPag/log cycle (22.35 gpm/psig/log cycle)
45.4 lps (720 gpm)	Buildup	0.2307 lps/kPag/log cycle (25.23 gpm/psig/log cycle)
44.2 lps (700 gpm)	Falloff	0.1918 lps/kPag/log cycle (20.95 gpm/psig/log cycle)
45.4 lps (720 gpm)	Buildup	0.1622 lps/kPag/log cycle (17.75 gpm/psig/log cycle)
44.2 lps (700 gpm)	Falloff	0.2852 lps/kPag/log cycle (31.14 gpm/psig/log cycle)
41.0 lps (650 gpm)	Buildup	0.1382 lps/kPag/log cycle (15.11 gpm/psig/log cycle)
47.3 lps (750 gpm)	Falloff	0.2048 lps/kPag/log cycle (22.39 gpm/psig/log cycle)
53.0 lps (840 gpm)	Buildup	0.1921 lps/kPag/log cycle (21.00 gpm/psig/log cycle)
51.7 lps (820 gpm)	Falloff	0.1929 lps/kPag/log cycle (21.08 gpm/psig/log cycle)

[1] Buildoff Q/s_{10} using wellhead pressure.

[2] Falloff Q/s_{10} using calculated recovery data.

TABLE 3

RRGI-6 SPECIFIC INJECTABILITY JANUARY 1979

Analysis Q	Pressure Buildup 10 Minutes	Specific Injectability
45.4 lps (720 gpm)	772 kPag (112 psig)	0.0588 lps/kPag (6.43 gpm/psig)
49.2 lps (780 gpm)	724 kPag (105 psig)	0.0680 lps/kPag (7.43 gpm/psig)
45.4 lps (720 gpm)	696 kPag (101 psig)	0.0652 lps/kPag (7.13 gpm/psig)
45.4 lps (720 gpm)	627 kPag (91 psig)	0.0724 lps/kPag (7.91 gpm/psig)
41.0 lps (650 gpm)	724 kPag (105 psig)	0.0566 lps/kPag (6.19 gpm/psig)
53.0 lps (840 gpm)	896 kPag (130 psig)	0.0591 lps/kPag (6.46 gpm/psig)

TABLE 4

PERTINENT DATA FOR LINEAR REGRESSIONS ON SEMILOGARITHMIC

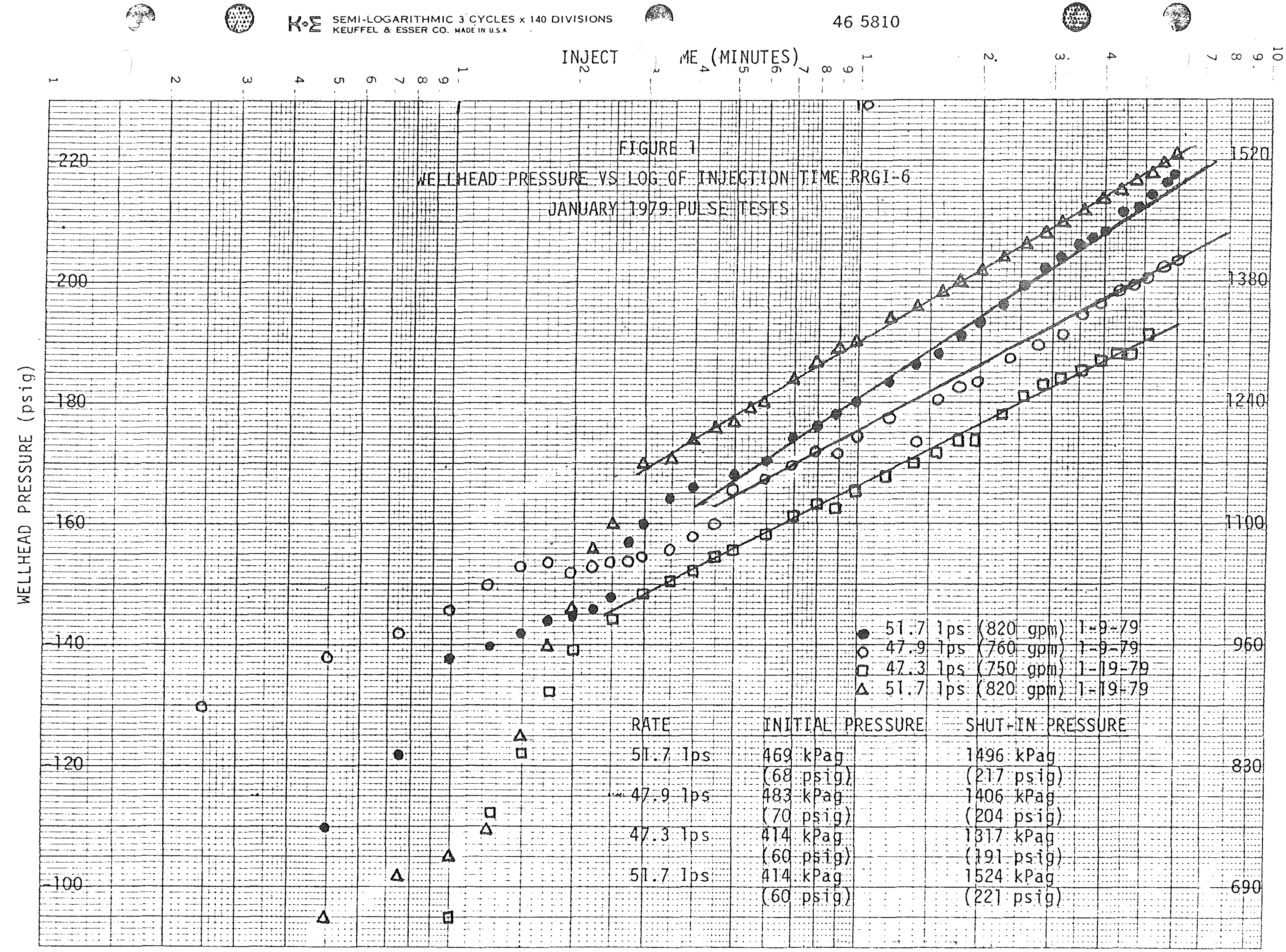
DATA PLOTS FOR 700 GPM INJECTION ON RRGI-6 BEGINNING JANUARY 9 AND 10, 1979

Date Test Began	LINEAR REGRESSION: Time Period Since Injection Began or Stopped: From Min.	To Min.	EQUATION FOR PRESSURE PSIA	Buildup	Falloff	H-P	Wellhead	Wellhead Pressure After 5 Yrs. With No Interference PSIA	Q/s_{10} GPM/PSI/LOG CYCLE
1-9	4	41	150.04 + 28.53 Log t	X			X	----	25.24
1-9	52	203	139.82 + 31.07 Log t	X			X	----	23.17
1-9	31	91	63.71 + 33.69 Log t/t'		X		X	----	20.78
1-9	41	91	69.48 + 33.42 Log t'		X		X	----	20.95
1-9	9	249	805.17 + 29.13 Log t/t'		X	X		----	24.03
1-10	8	99	119.34 + 40.56 Log t	X			X	----	17.75
1-10	200	4234	181.33 + 16.33 Log t	X			X	286.14	----
1-10	304	3364	917.99 + 16.56 Log t	X		X		287.3	----
1-10	1.5	10.25	80.61 + 22.71 Log t/t'		X		X	----	----
1-10	1.5	10.25	77.66 + 22.48 Log t'		X		X	----	----
1-10	185.25	3870	46.60 + 41.18 Log t/t'		X		X	----	
1-10	185.25	3870	55.17 + 36.53 Log t'		X		X	289.7	

TABLE 5

ESTIMATES FOR AQUIFER INTRINSIC TRANSMISSIVITY AND TRANSMISSIVITY AS A FUNCTION OF ASSUMED AQUIFER TEMPERATURE

Temperature °F	Intrinsic Transmissivity kh	Transmissivity T
100	85682 md-ft	2566 gal/d/ft
150	54055 md-ft	2533 gal/d/ft
200	38179 md-ft	2488 gal/d/ft
250	29107 md-ft	2434 gal/d/ft


K+E SEMI-LOGARITHMIC 3 CYCLES × 140 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 5810
INJECTION TIME (MINUTES)
FIGURE 1
WELLHEAD PRESSURE VS LOG OF INJECTION TIME RRGI-6
JANUARY 1979 PULSE TESTS
WELLHEAD PRESSURE (psig)
51.7 lps (820 gpm) 1-9-79
47.9 lps (760 gpm) 1-9-79
47.3 lps (750 gpm) 1-19-79
51.7 lps (820 gpm) 1-19-79
RATE
INITIAL PRESSURE
SHUT-IN PRESSURE
51.7 lps
469 kPag
(68 psig)
1496 kPag
(217 psig)
47.9 lps
483 kPag
(70 psig)
1406 kPag
(204 psig)
47.3 lps
414 kPag
(60 psig)
1317 kPag
(191 psig)
51.7 lps
414 kPag
(60 psig)
1524 kPag
(221 psig)

21

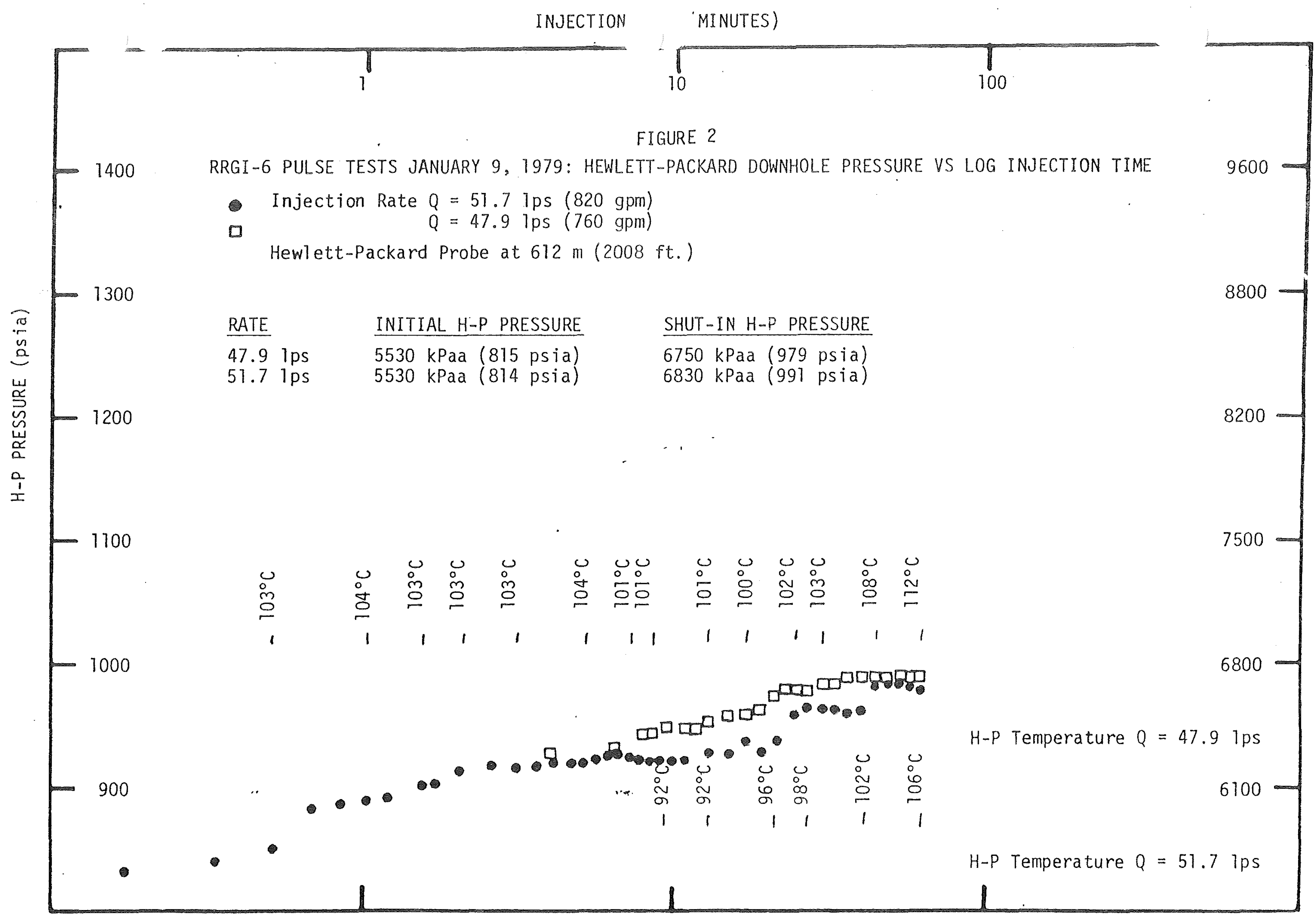
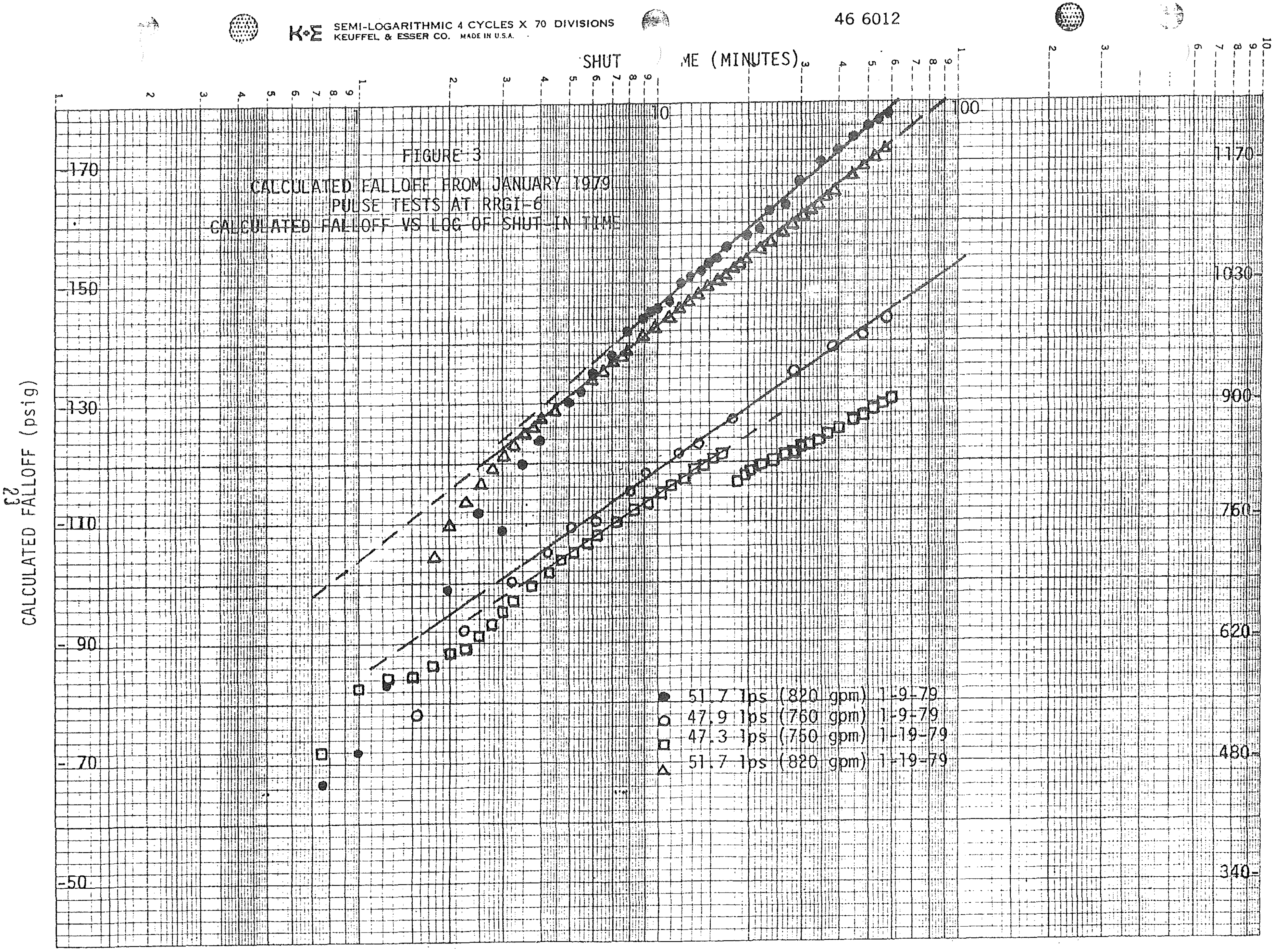


FIGURE 2

RRGI-6 PULSE TESTS JANUARY 9, 1979: HEWLETT-PACKARD DOWNHOLE PRESSURE VS LOG INJECTION TIME


K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6012
FIGURE 3
CALCULATED FALLOFF FROM JANUARY 1979
PULSE TESTS AT RRGI-6
CALCULATED FALLOFF VS LOG OF SHUT-IN TIME
SHUT ME (MINUTES)
CALCULATED FALLOFF (psig)
1
10
100
170
150
130
110
90
70
50
1170
1030
900
760
620
480
340
51.7 lps (820 gpm) 1-9-79
47.9 lps (760 gpm) 1-9-79
47.3 lps (750 gpm) 1-19-79
51.7 lps (820 gpm) 1-19-79

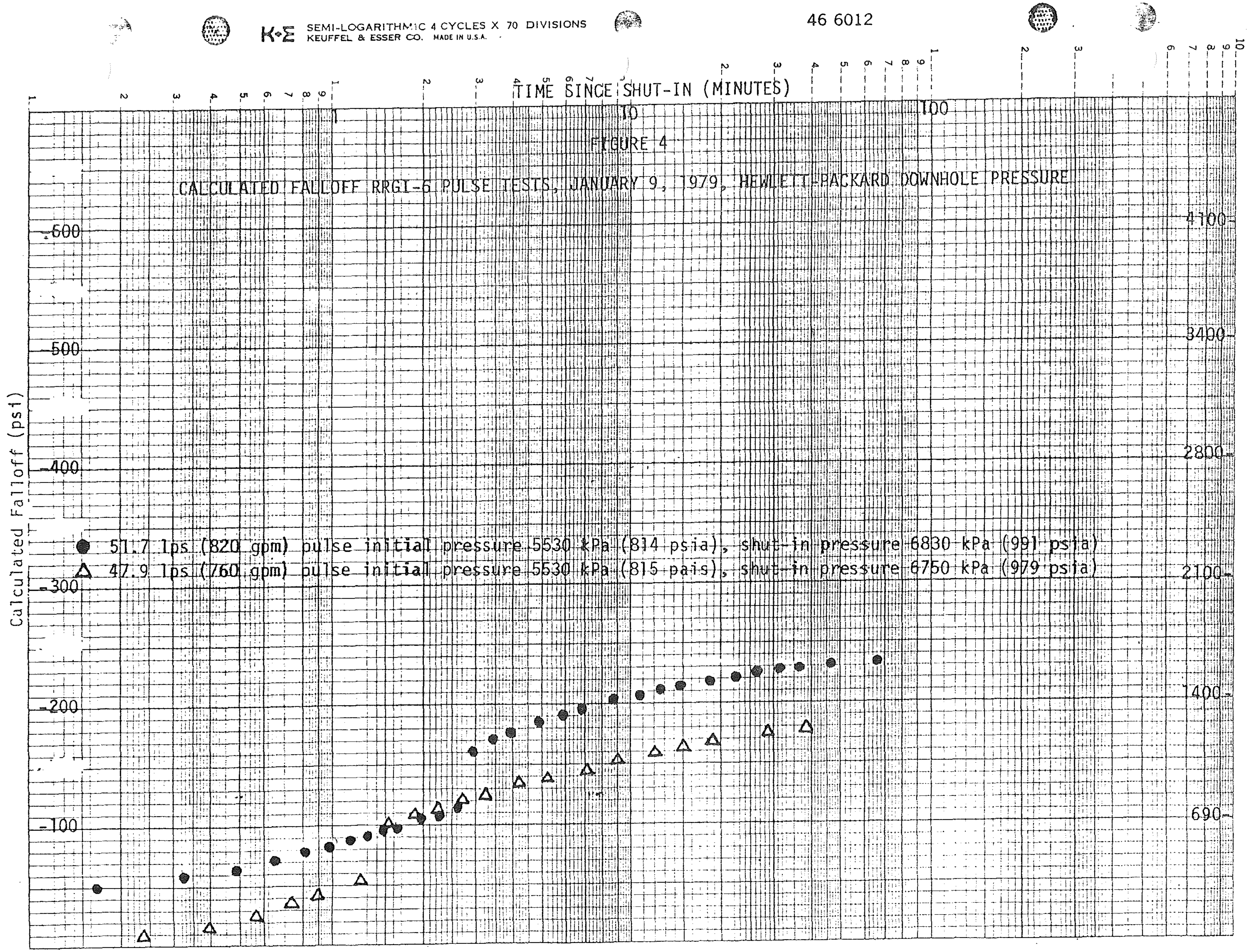


FIGURE 4

CALCULATED FALLOFF RRGI-6 PULSE TESTS, JANUARY 9, 1979, HEWLETT-PACKARD DOWNHOLE PRESSURE

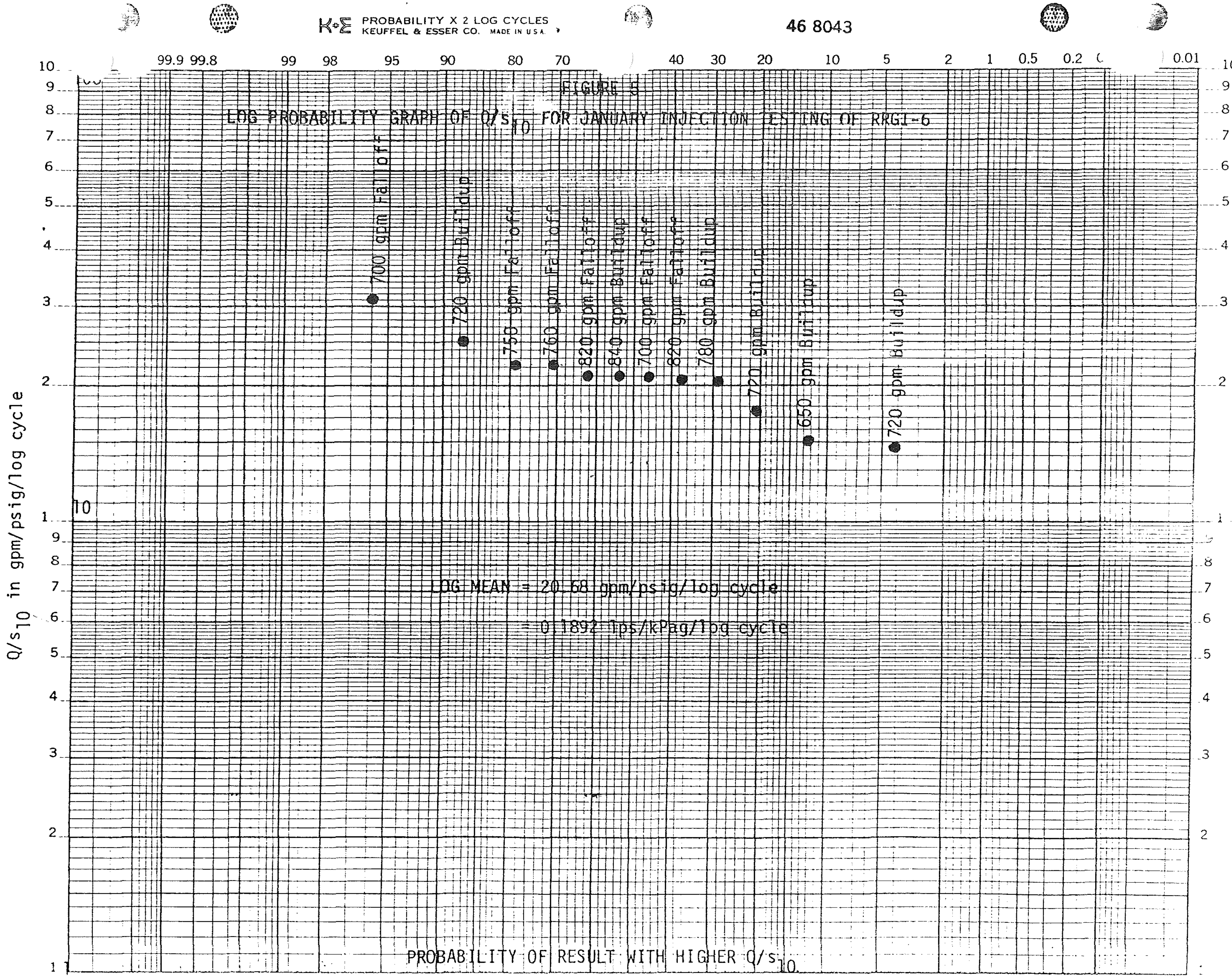


FIGURE 5

LOG PROBABILITY GRAPH OF Q/s_{10} FOR JANUARY INJECTION TESTING OF RRGI-6

Figure 6
RRGI-6, Jan. 9-19, 1979
Q/s_{10} vs Q
Q in l/s

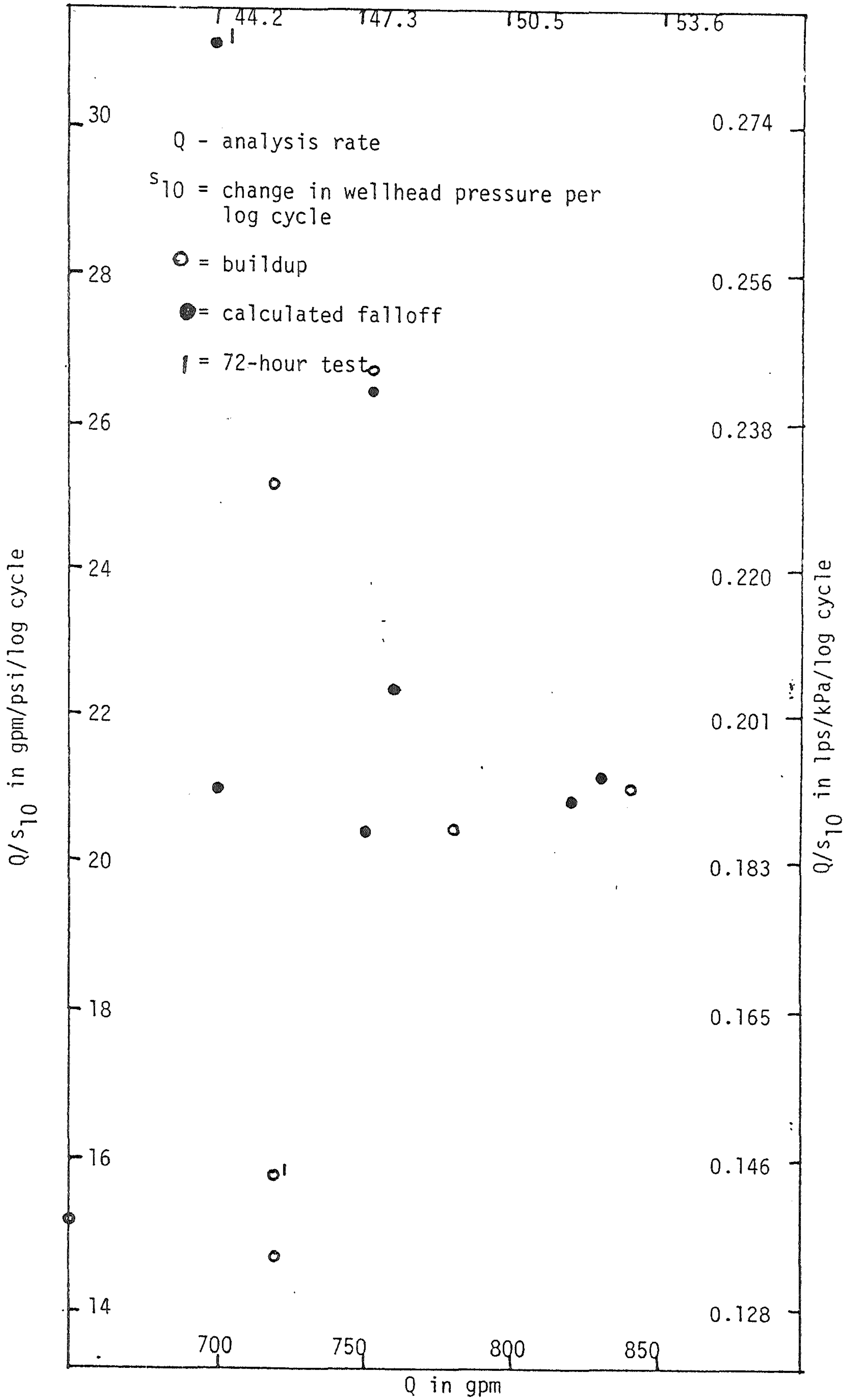
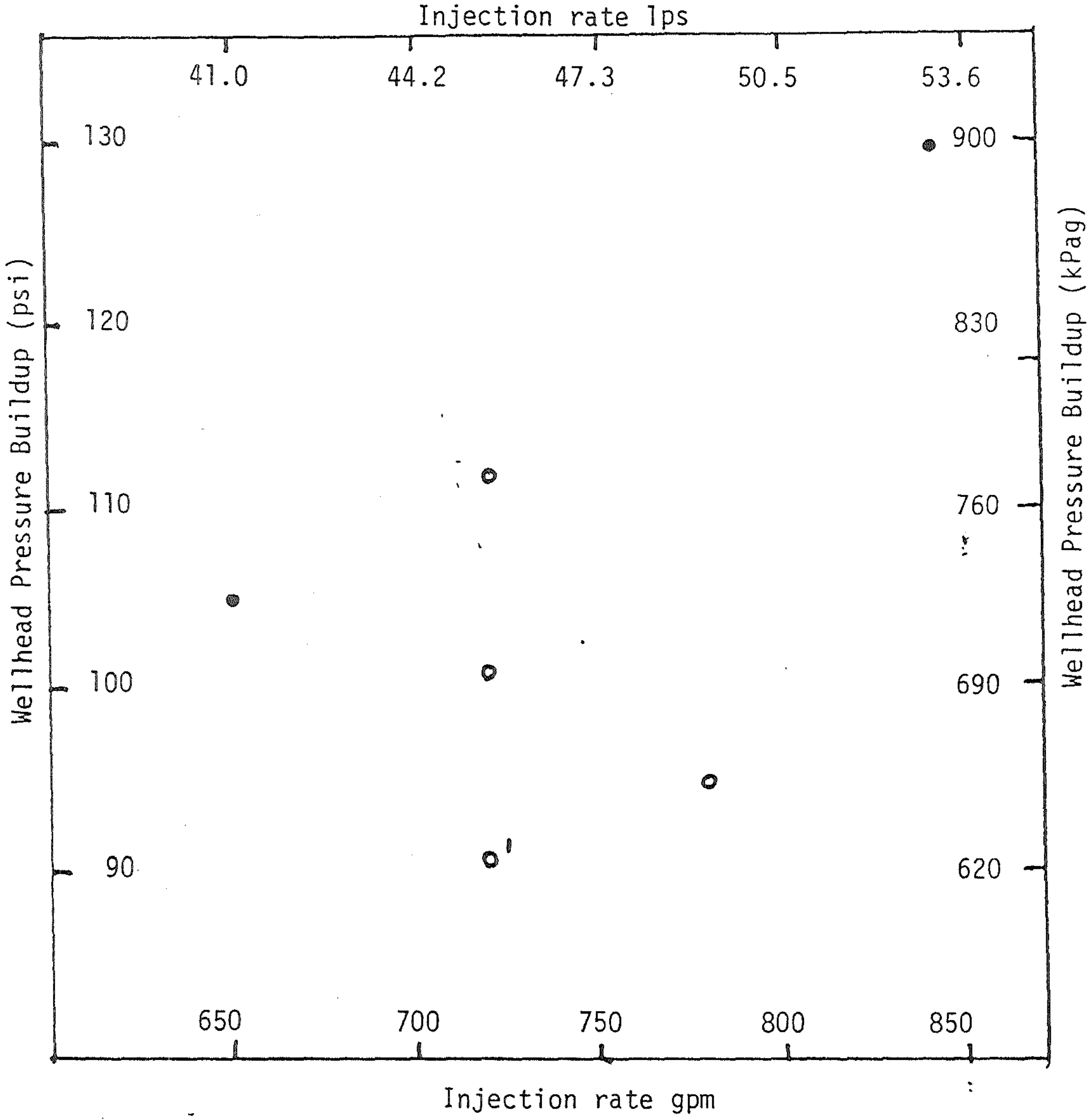


Figure 7

RRGI-6 January 9-19, 1979

Wellhead pressure buildup after 10 minutes vs test analysis rate

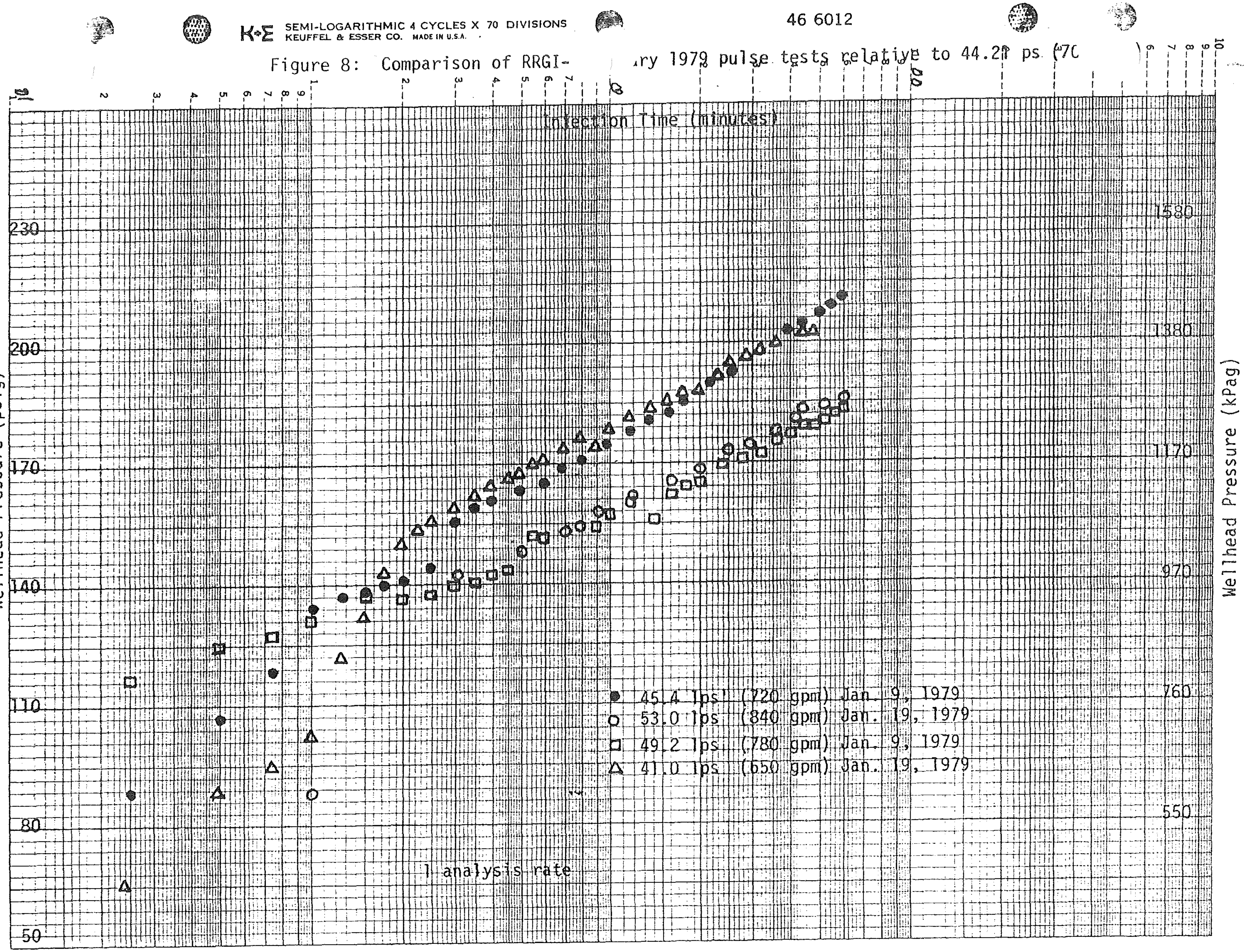


o Jan. 9-10, 1979

● Jan. 19, 1979

' Seven minutes of injection was required before reaching desired rate.

Figure 8: Comparison of RRGI- ry 1979 pulse tests relative to 44.2 ps (70



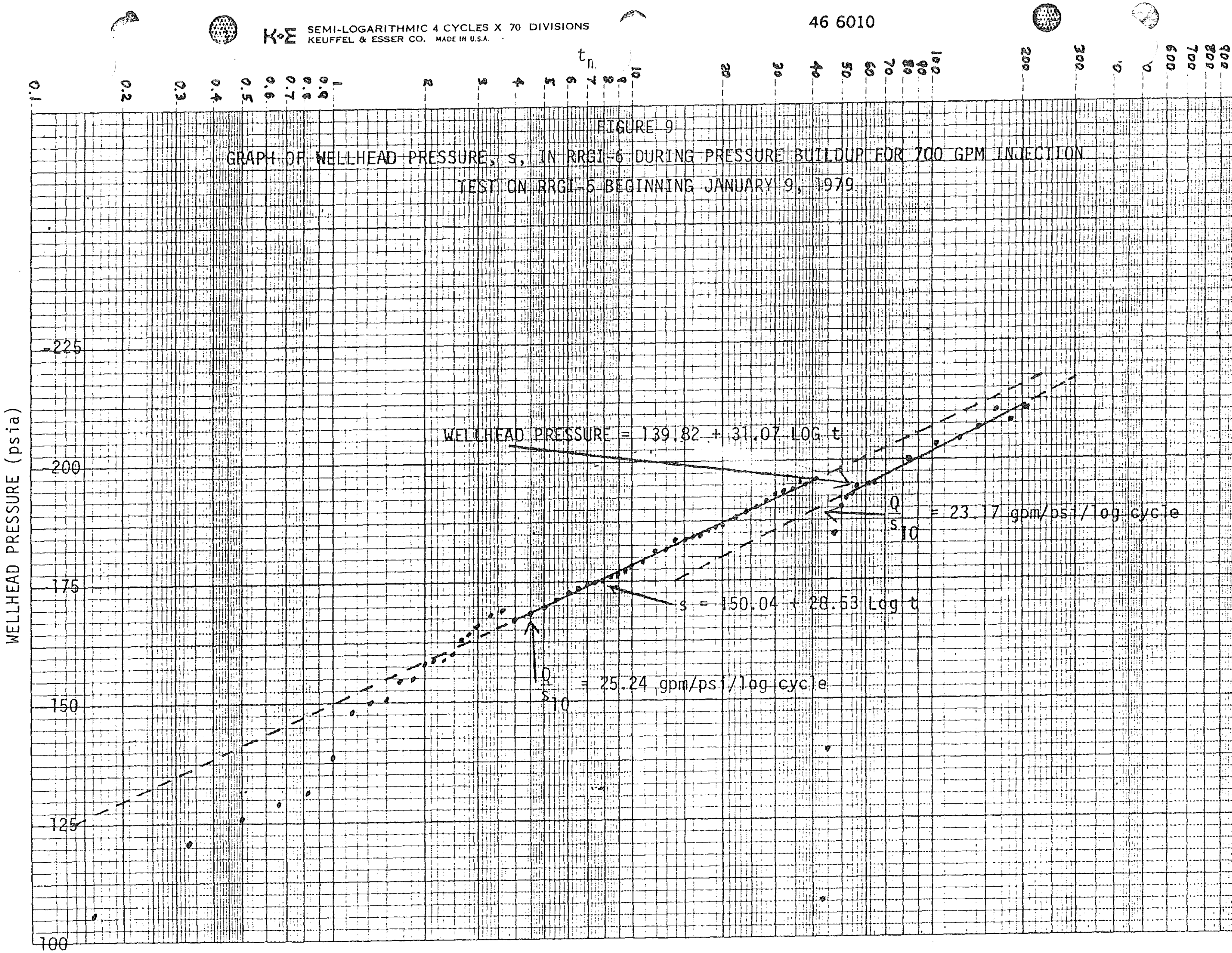


FIGURE 9

GRAPH OF WELLHEAD PRESSURE, s, IN RRGI-6 DURING PRESSURE BUILDUP FOR 700 GPM INJECTION

TEST ON RRGI-6 BEGINNING JANUARY 9, 1979

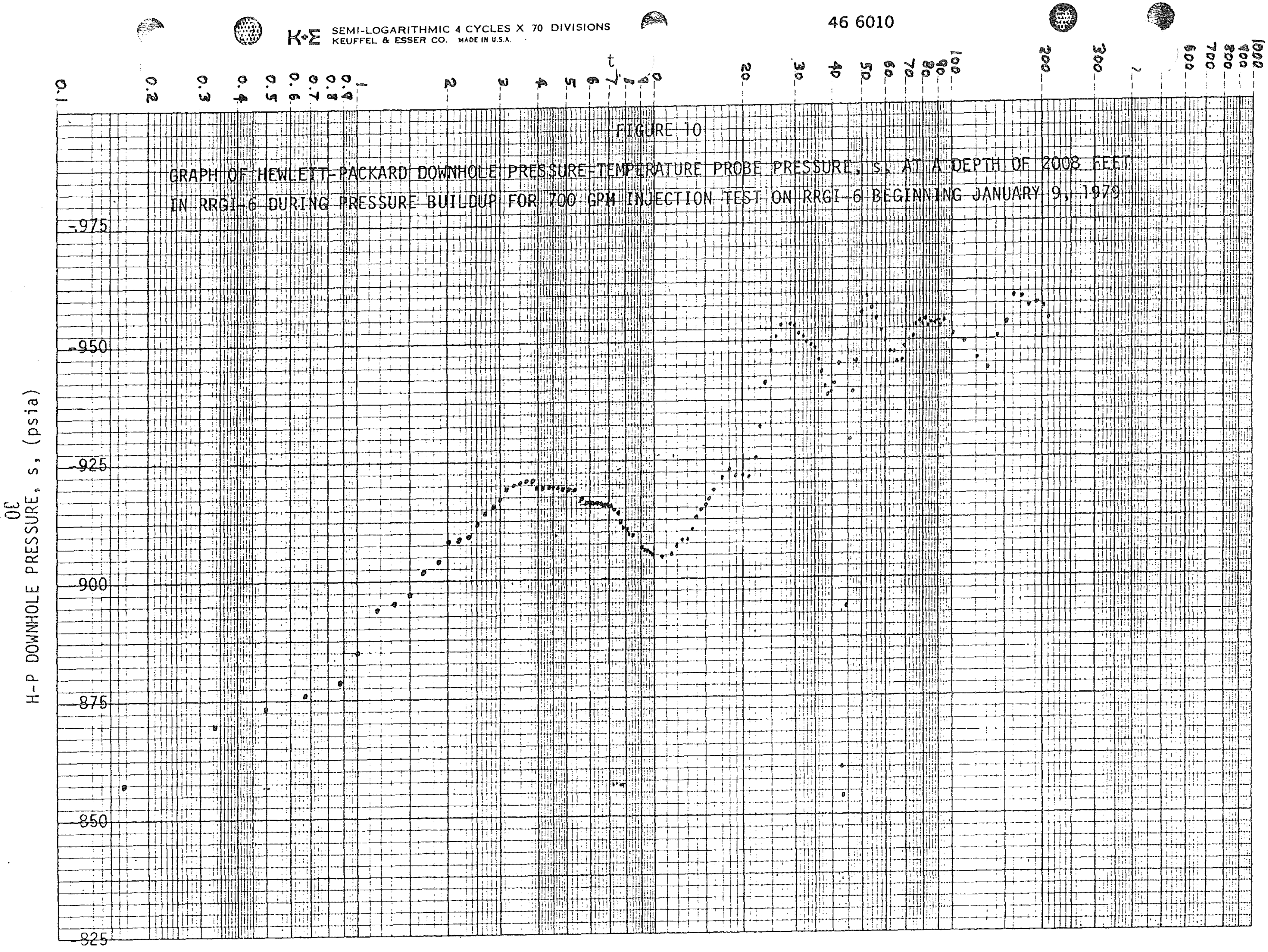


FIGURE 10

GRAPH OF HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE PRESSURE, s, AT A DEPTH OF 2008 FEET IN RRGI-6 DURING PRESSURE BUILDUP FOR 700 GPM INJECTION TEST ON RRGI-6 BEGINNING JANUARY 9, 1979

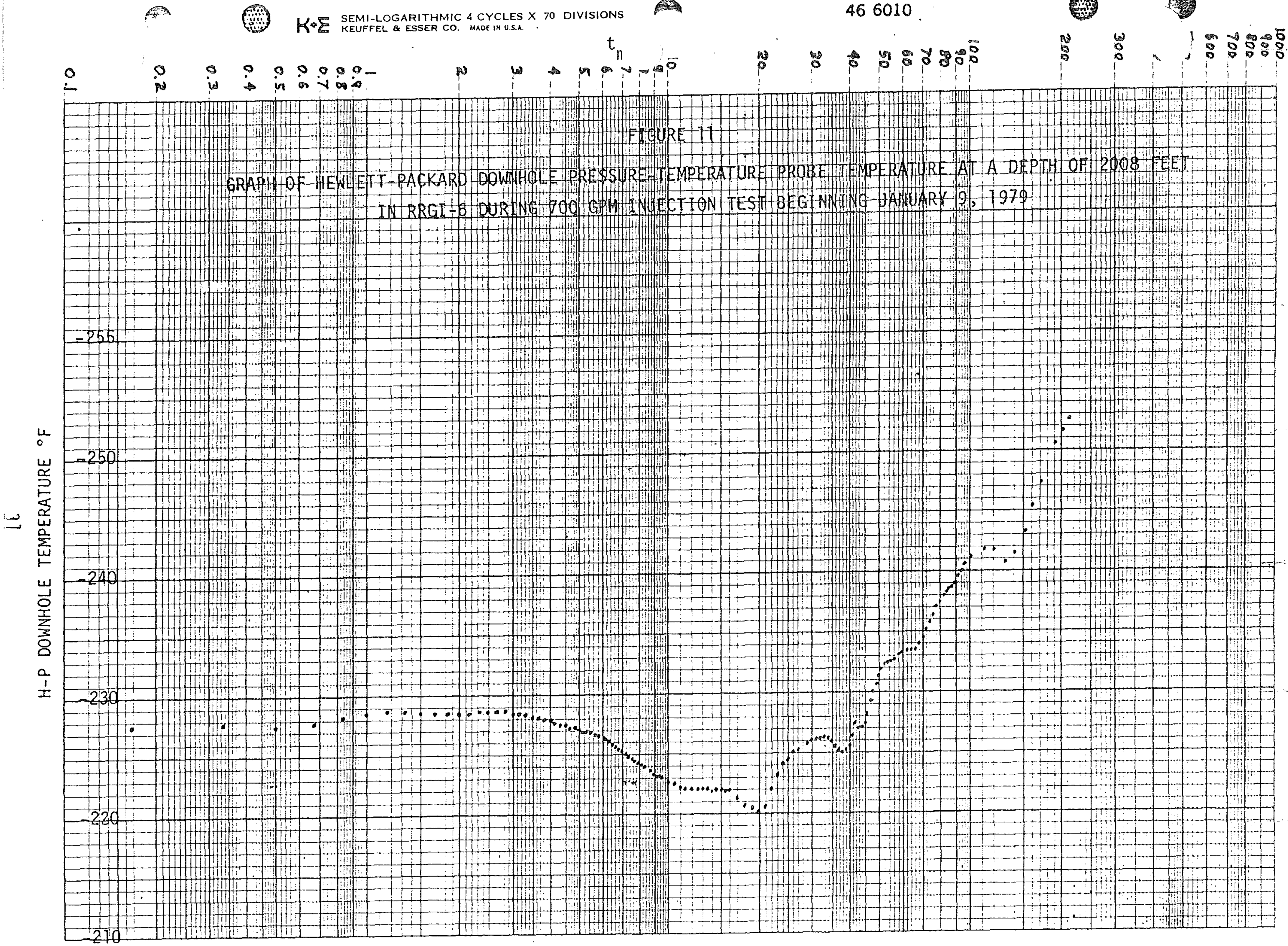


FIGURE 11
GRAPH OF HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE TEMPERATURE AT A DEPTH OF 2008 FEET
IN RRGI-6 DURING 700 GPM INJECTION TEST BEGINNING JANUARY 9, 1979
H-P DOWNHOLE TEMPERATURE °F
t_n
-255
-250
-240
-230
-220
-210
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
9
10
20
30
40
50
60
70
80
90
100
200
300
600
700
800
900
1000
K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6010

K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

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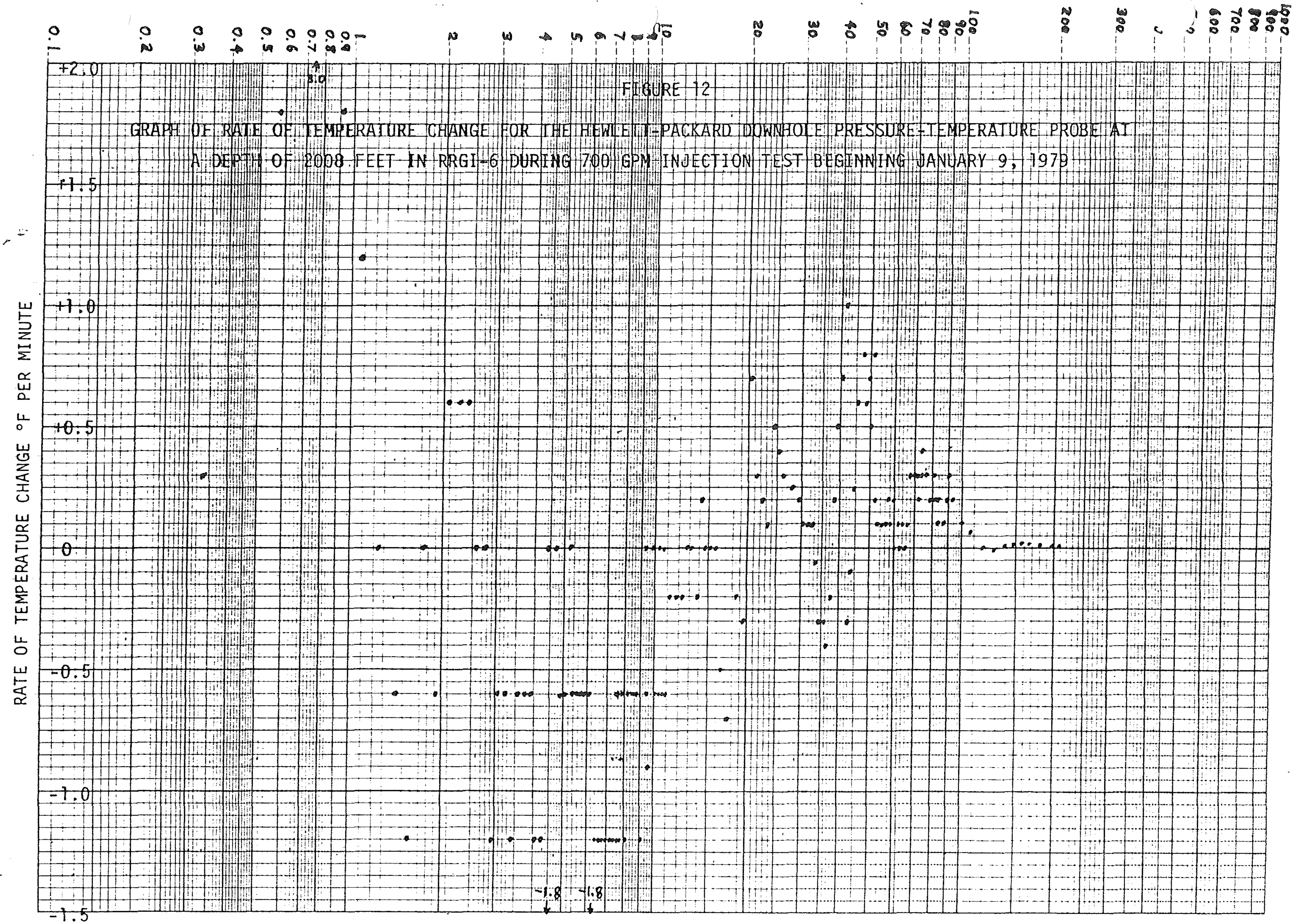


FIGURE 12

GRAPH OF RATE OF TEMPERATURE CHANGE FOR THE HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE AT A DEPTH OF 2008 FEET IN RRGI-6 DURING 700 GPM INJECTION TEST BEGINNING JANUARY 9, 1979

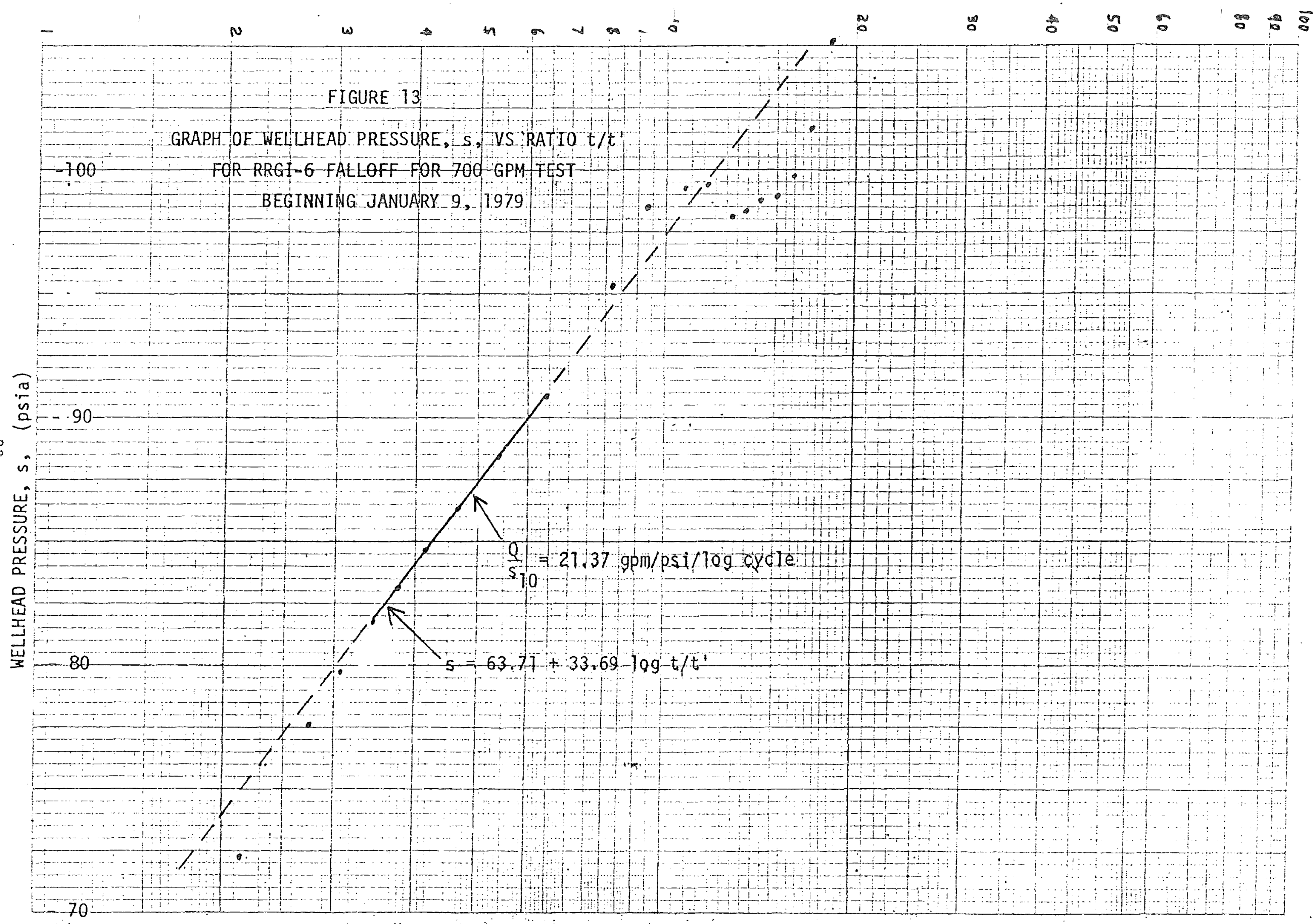
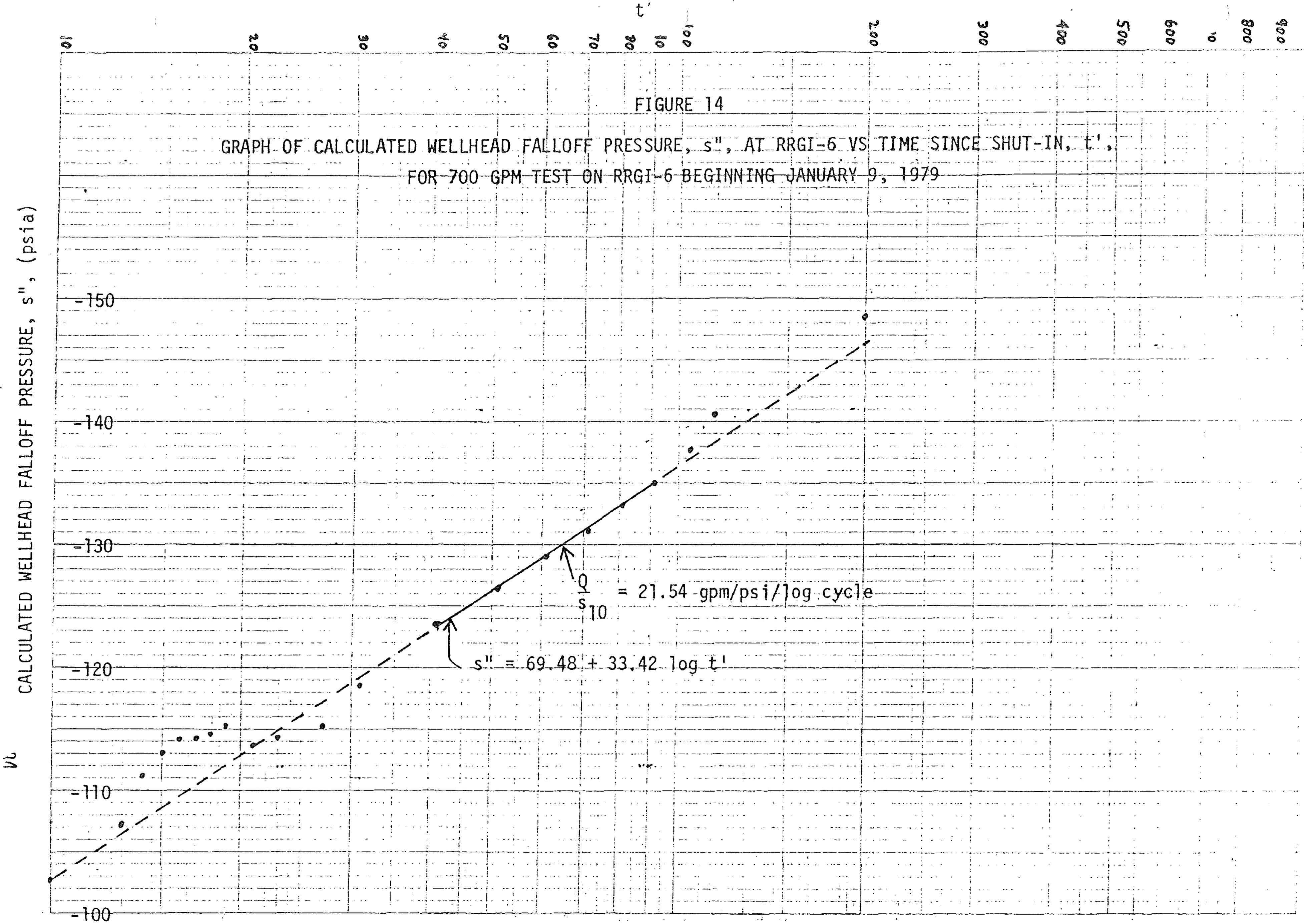


FIGURE 13

GRAPH OF WELLHEAD PRESSURE, s, VS RATIO t/t'
FOR RRGI-6 FALLOFF FOR 700 GPM TEST
BEGINNING JANUARY 9, 1979

FIGURE 14

GRAPH OF CALCULATED WELLHEAD FALLOFF PRESSURE, s", AT RRGI-6 VS TIME SINCE SHUT-IN, t', FOR 700 GPM TEST ON RRGI-6 BEGINNING JANUARY 9, 1979



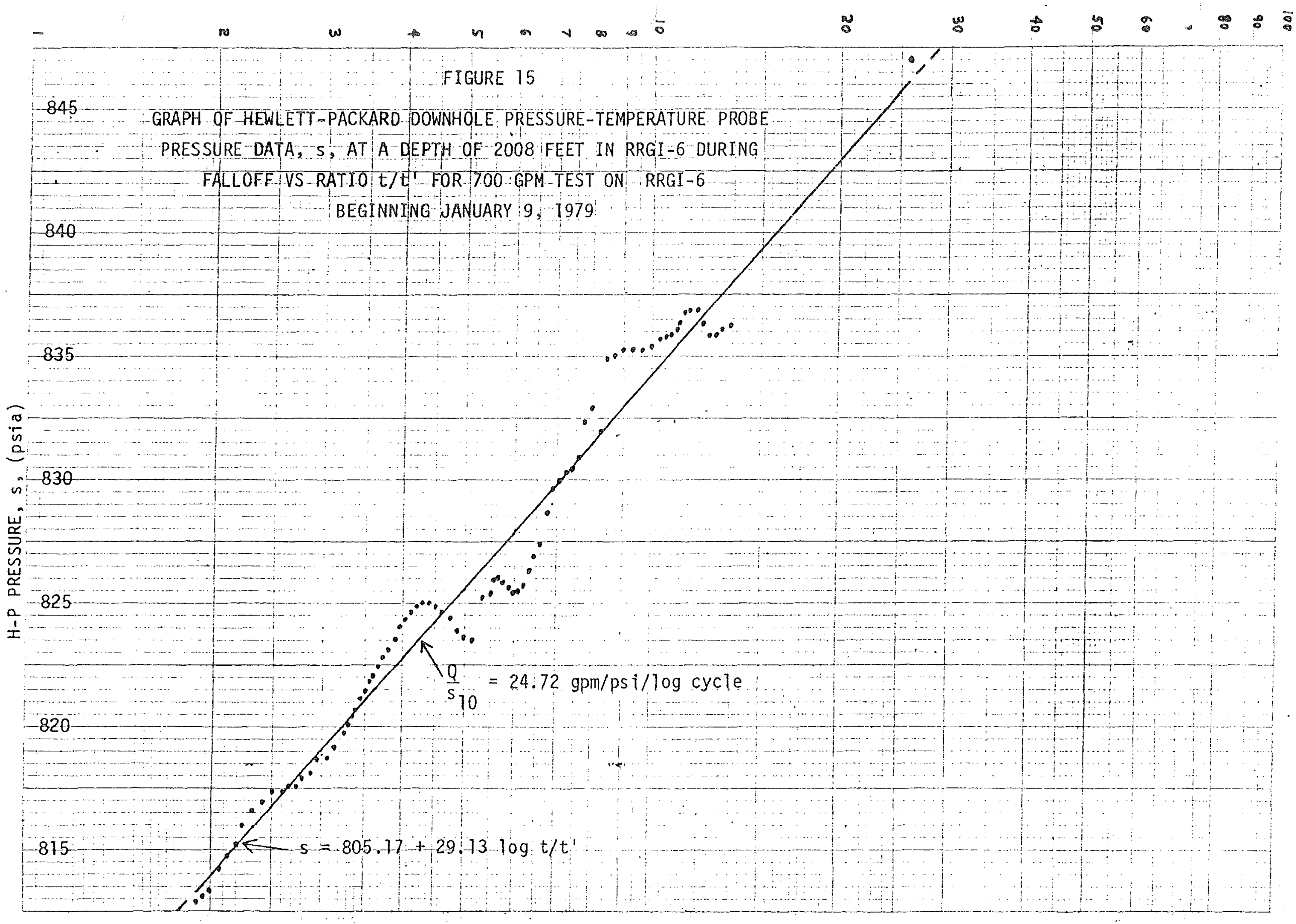


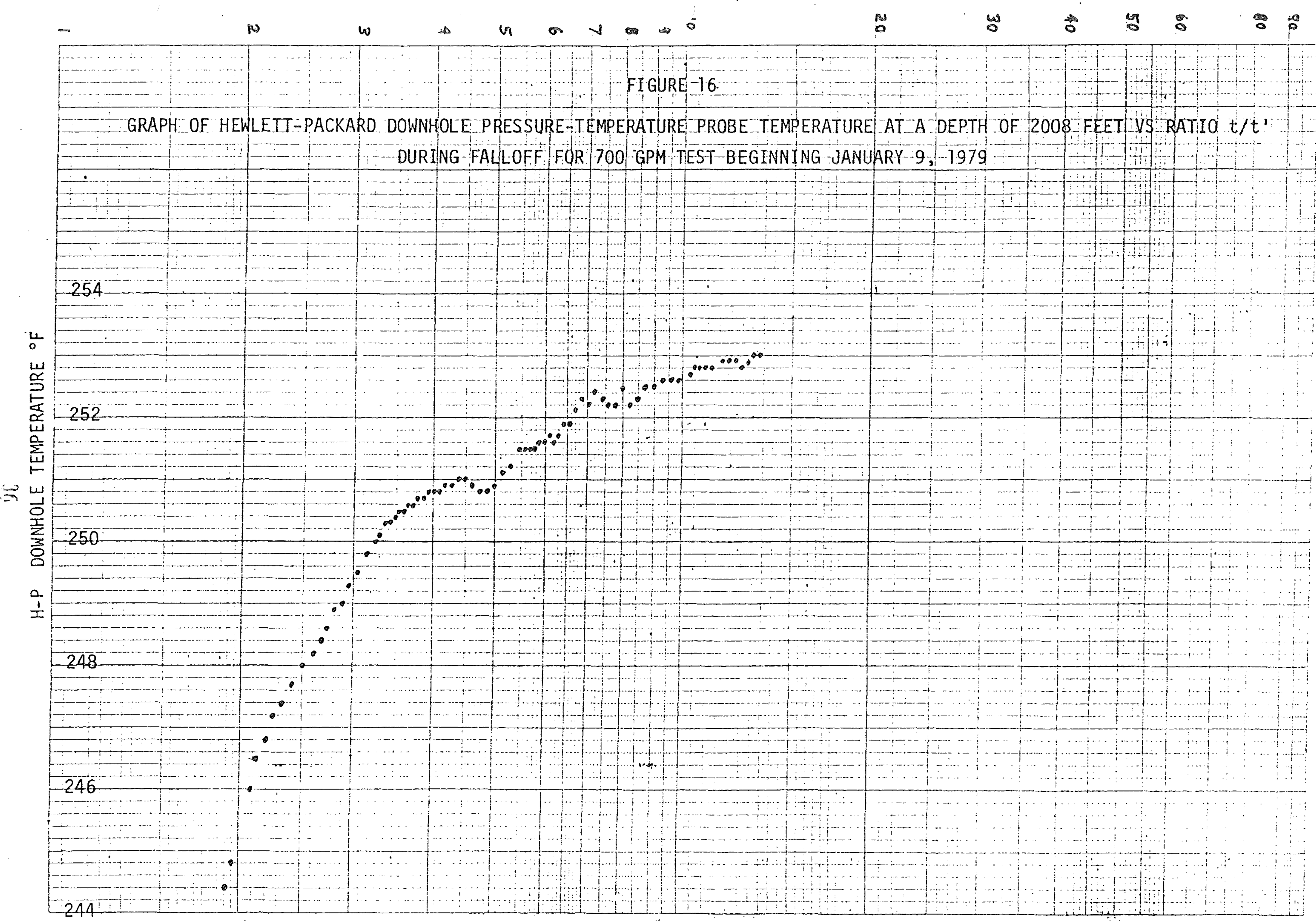
FIGURE 15

GRAPH OF HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE PRESSURE DATA, s, AT A DEPTH OF 2008 FEET IN RRGI-6 DURING FALLOFF VS RATIO t/t' FOR 700 GPM TEST ON RRGI-6 BEGINNING JANUARY 9, 1979

FIGURE 16

GRAPH OF HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE TEMPERATURE AT A DEPTH OF 2008 FEET VS RATIO t/t'

DURING FALLOFF FOR 700 GPM TEST BEGINNING JANUARY 9, 1979



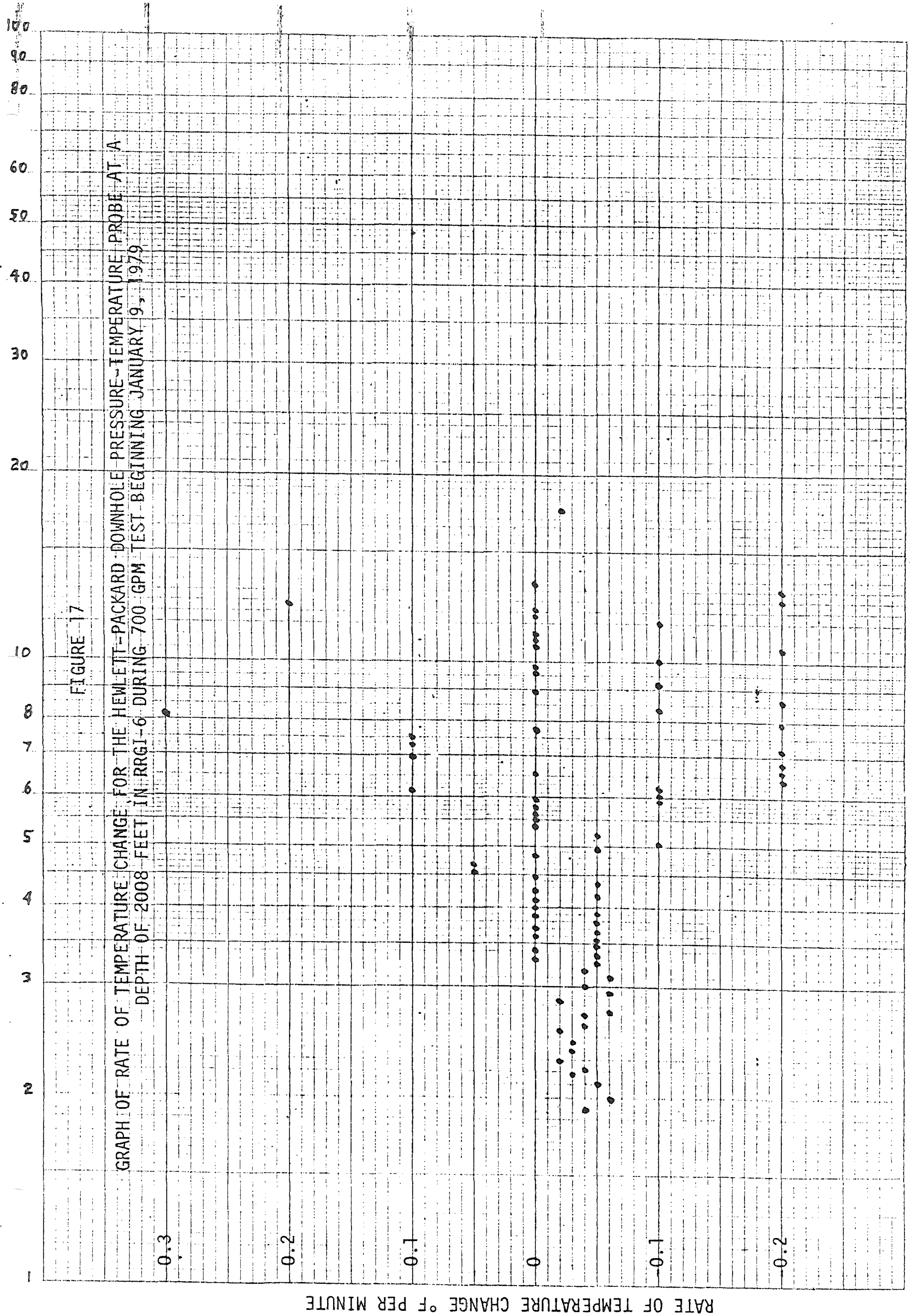


FIGURE 17

GRAPH OF RATE OF TEMPERATURE CHANGE FOR THE HEWLETT-PACKARD DOWNHOLE PRESSURE-TEMPERATURE PROBE AT A DEPTH OF 2008 FEET IN RRGI-6 DURING 700 GPM TEST BEGINNING JANUARY 9, 1979

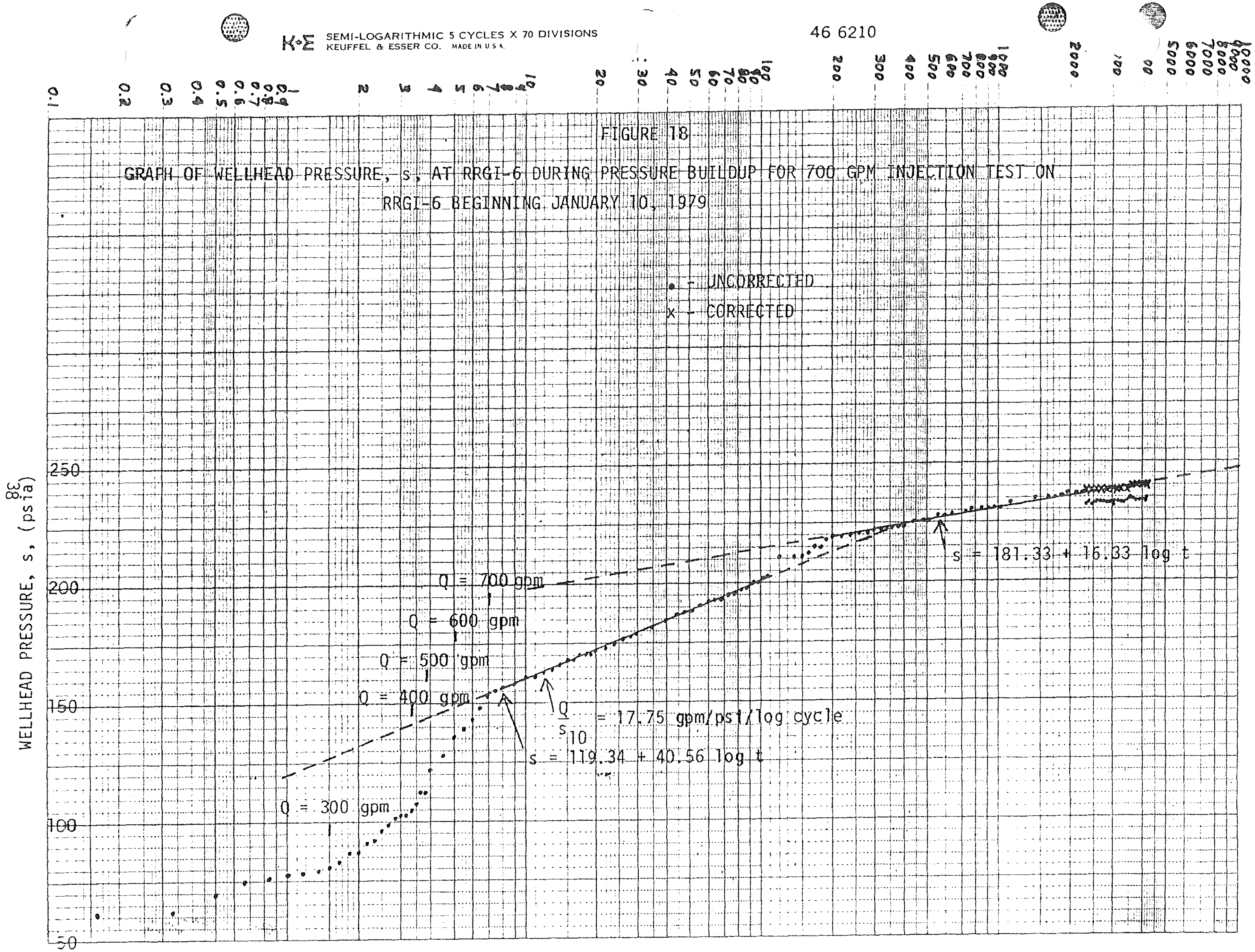
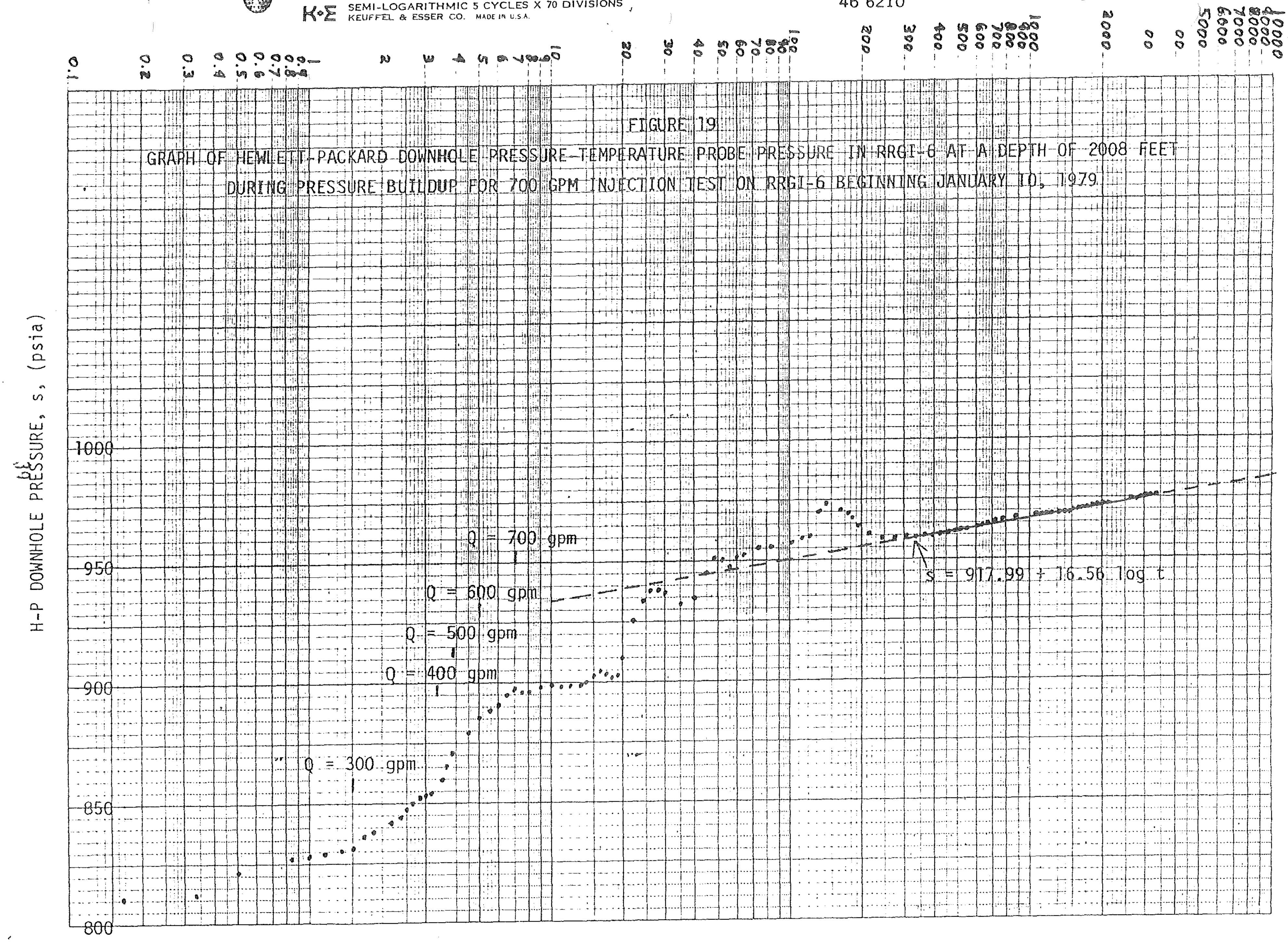


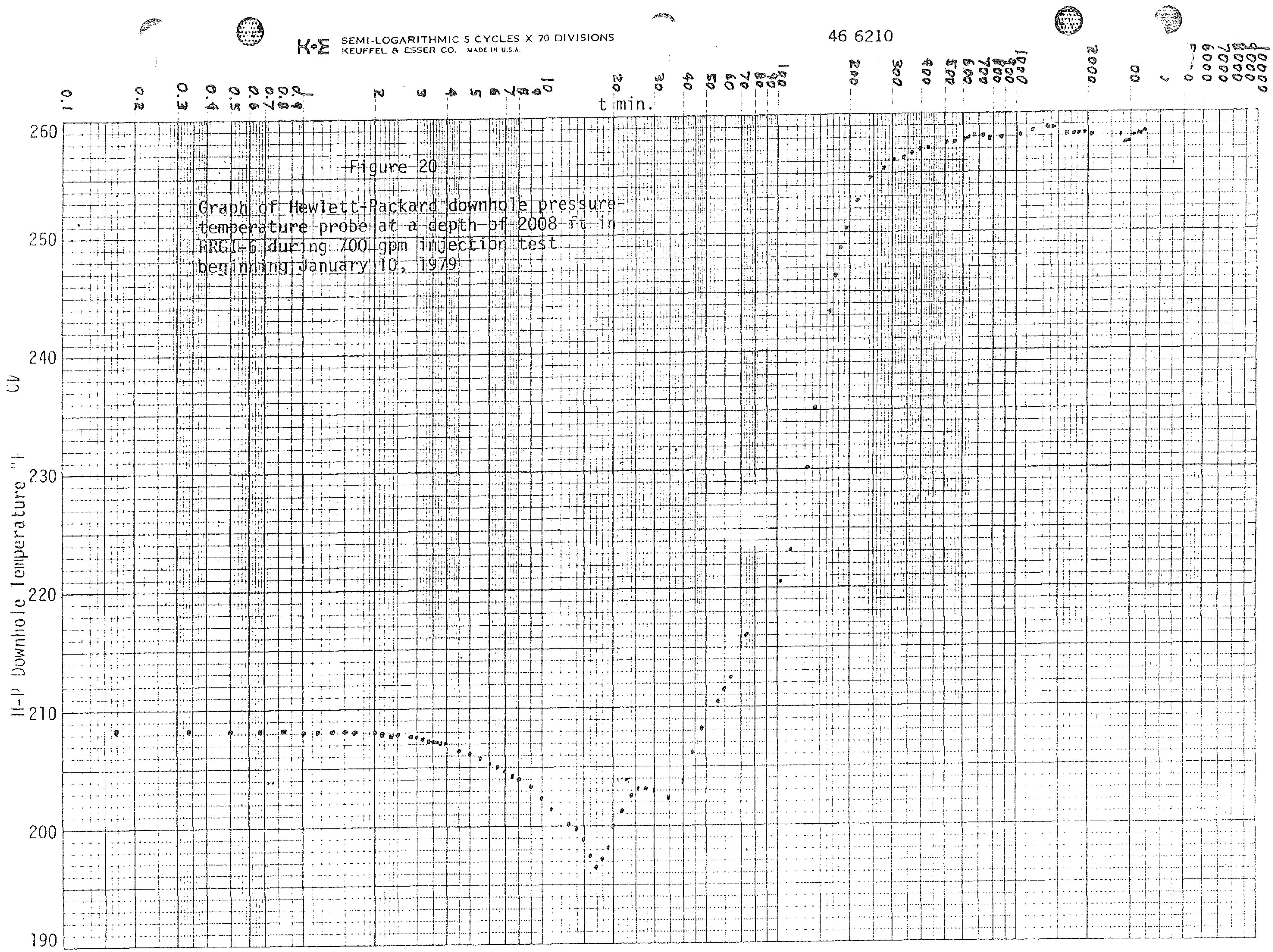
FIGURE 18

GRAPH OF WELLHEAD PRESSURE, s, AT RRGI-6 DURING PRESSURE BUILDUP FOR 700 GPM INJECTION TEST ON RRGI-6 BEGINNING JANUARY 10, 1979

K+E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 6210





K+E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6210
Figure 20
Graph of Hewlett-Packard downhole pressure-temperature probe at a depth of 2008 ft in RRGI-6 during 700 gpm injection test beginning January 10, 1979
t min.
H-P Downhole Temperature °F
190
200
210
220
230
240
250
260

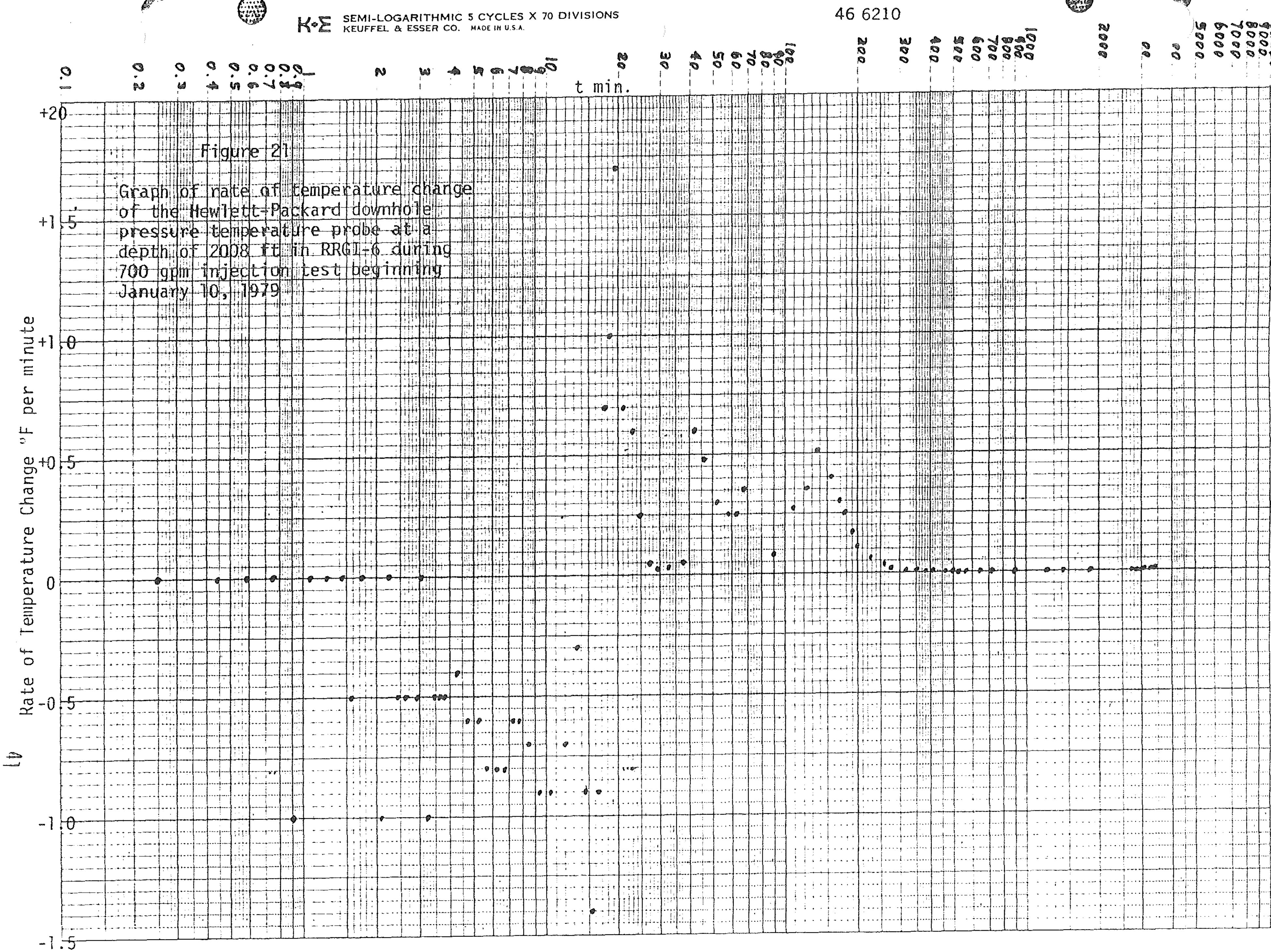


Figure 21

Graph of rate of temperature change of the Hewlett-Packard downhole pressure temperature probe at a depth of 2008 ft in RRGI-6 during 700 gpm injection test beginning January 10, 1979

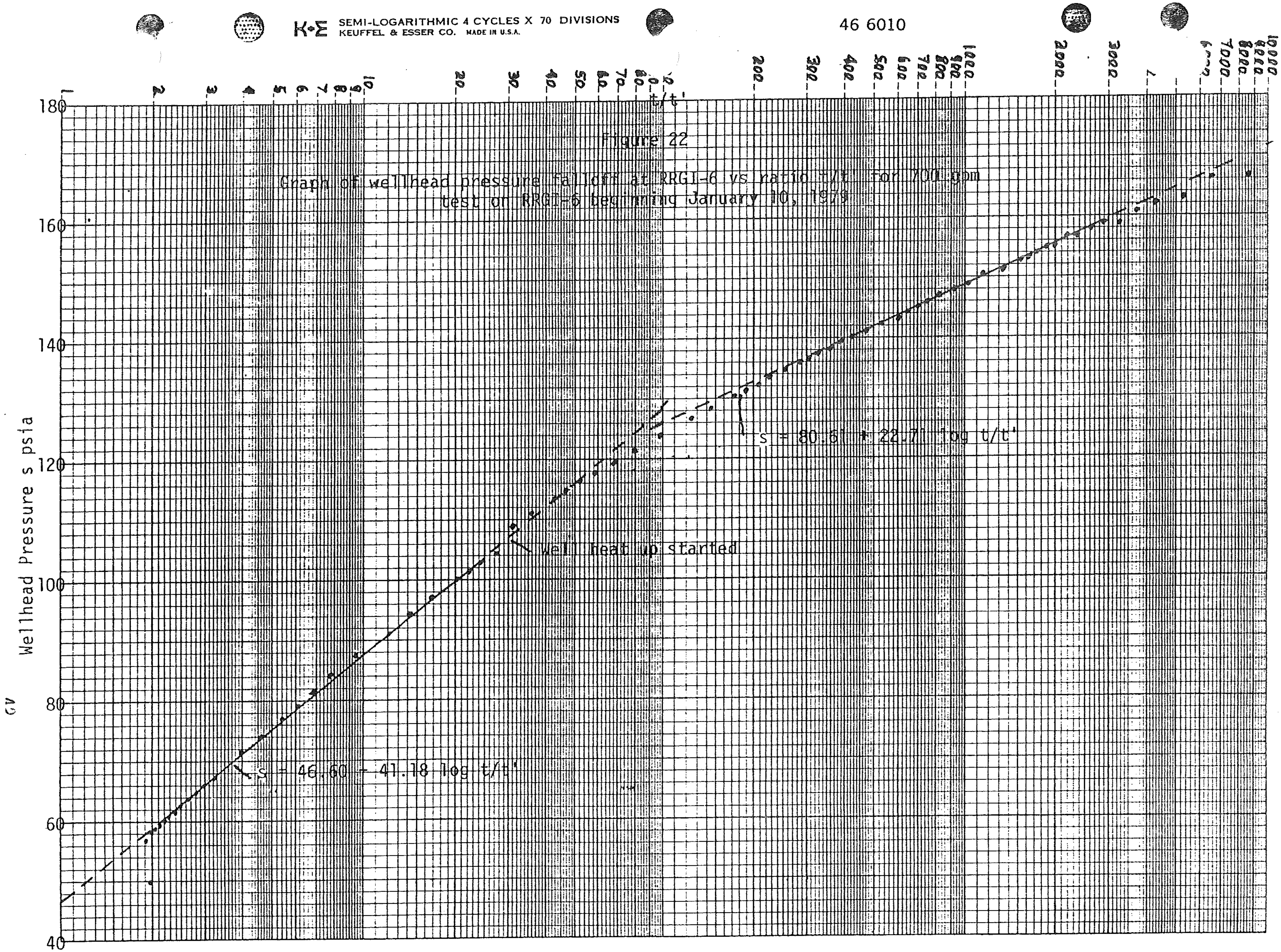


Figure 22

Graph of wellhead pressure falloff at RRGI-6 vs ratio t/t' for 700 gpm test on RRGI-6 beginning January 10, 1979

KE SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 6010

Figure 23

Graph of calculated wellhead falloff pressure, s", at RRGI-6 vs time since shutin for 700 gpm test on RRGI-6 beginning January 10, 1979

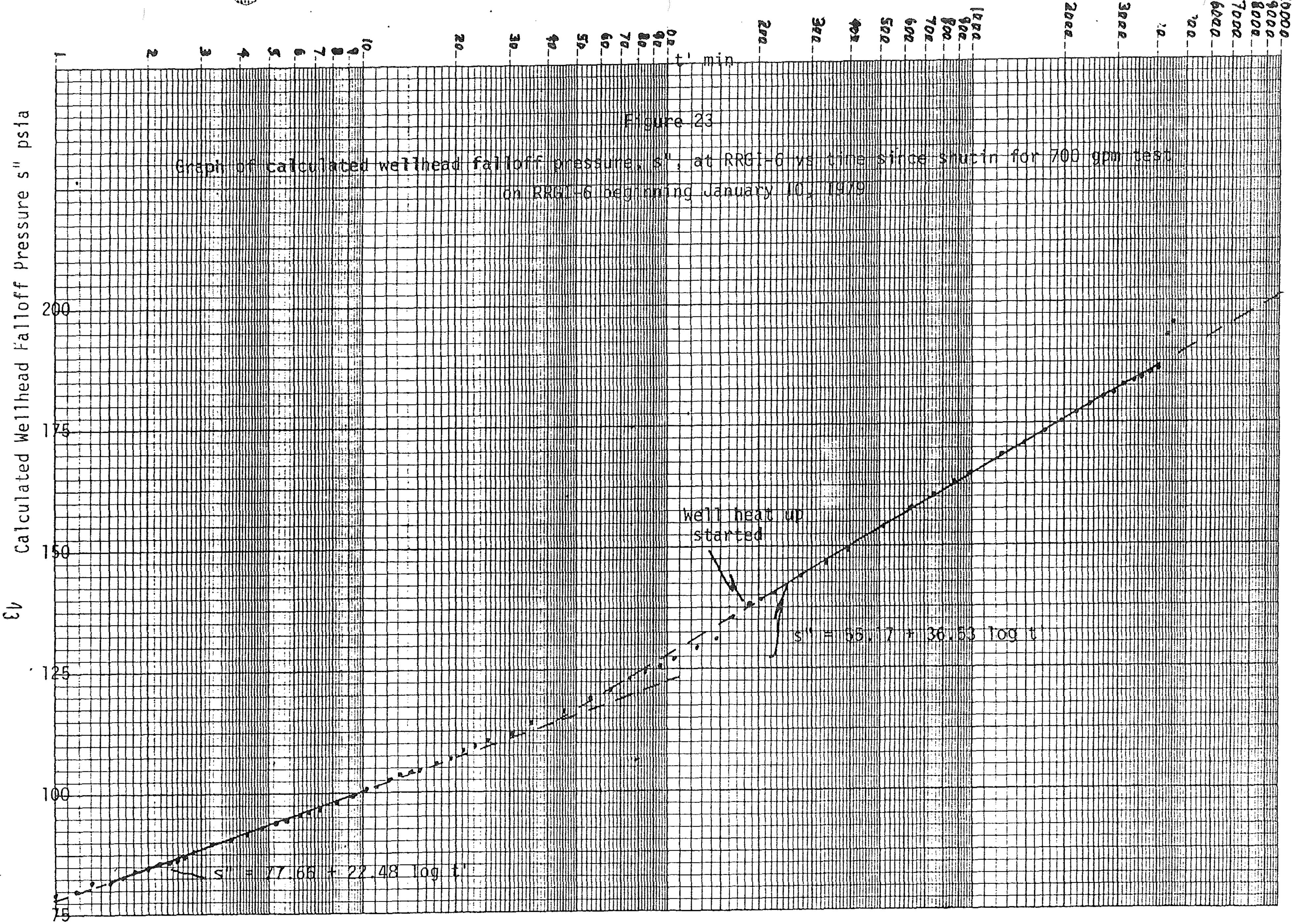


Figure 24

Graph of wellhead pressure vs time for RRGE-3

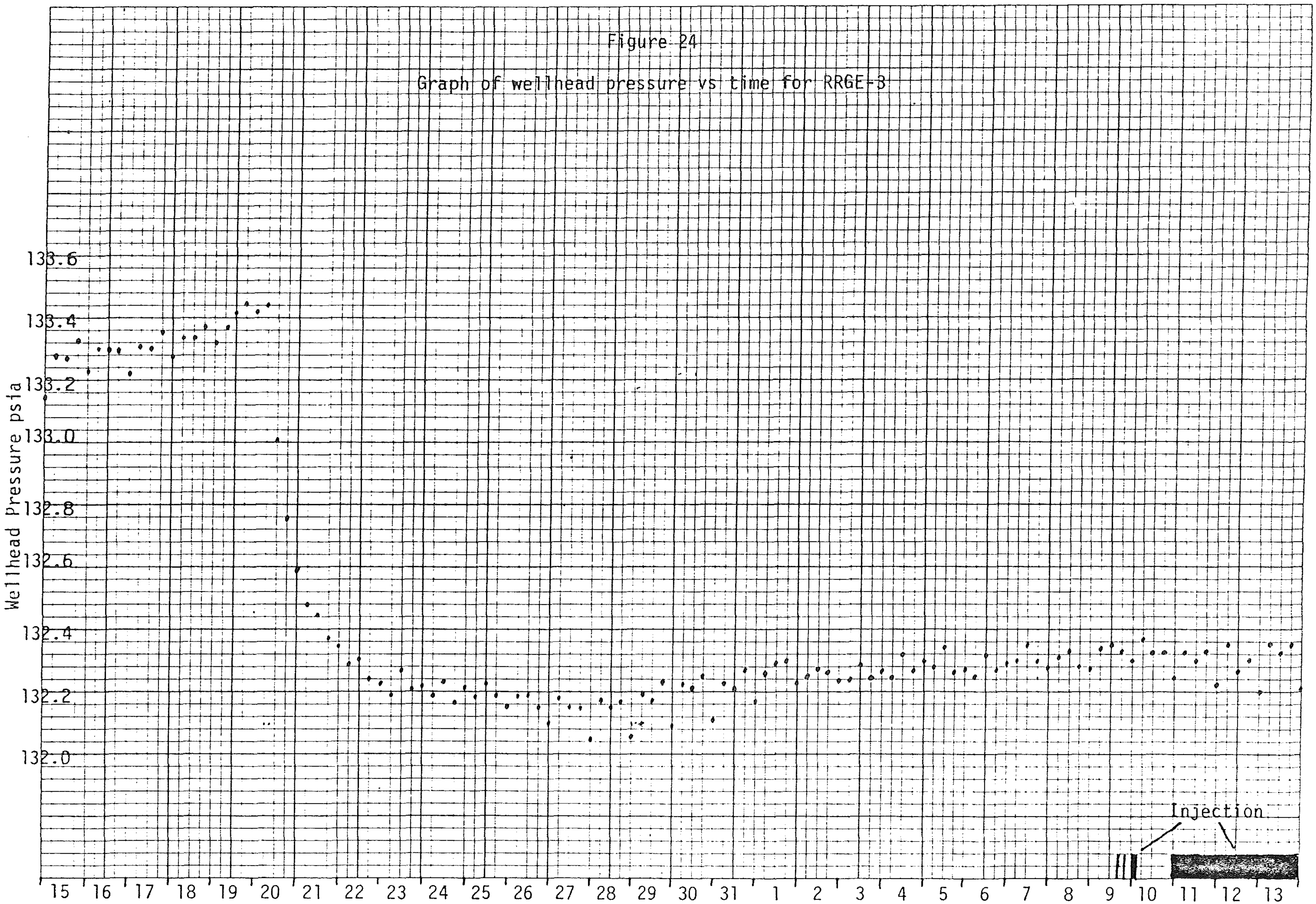
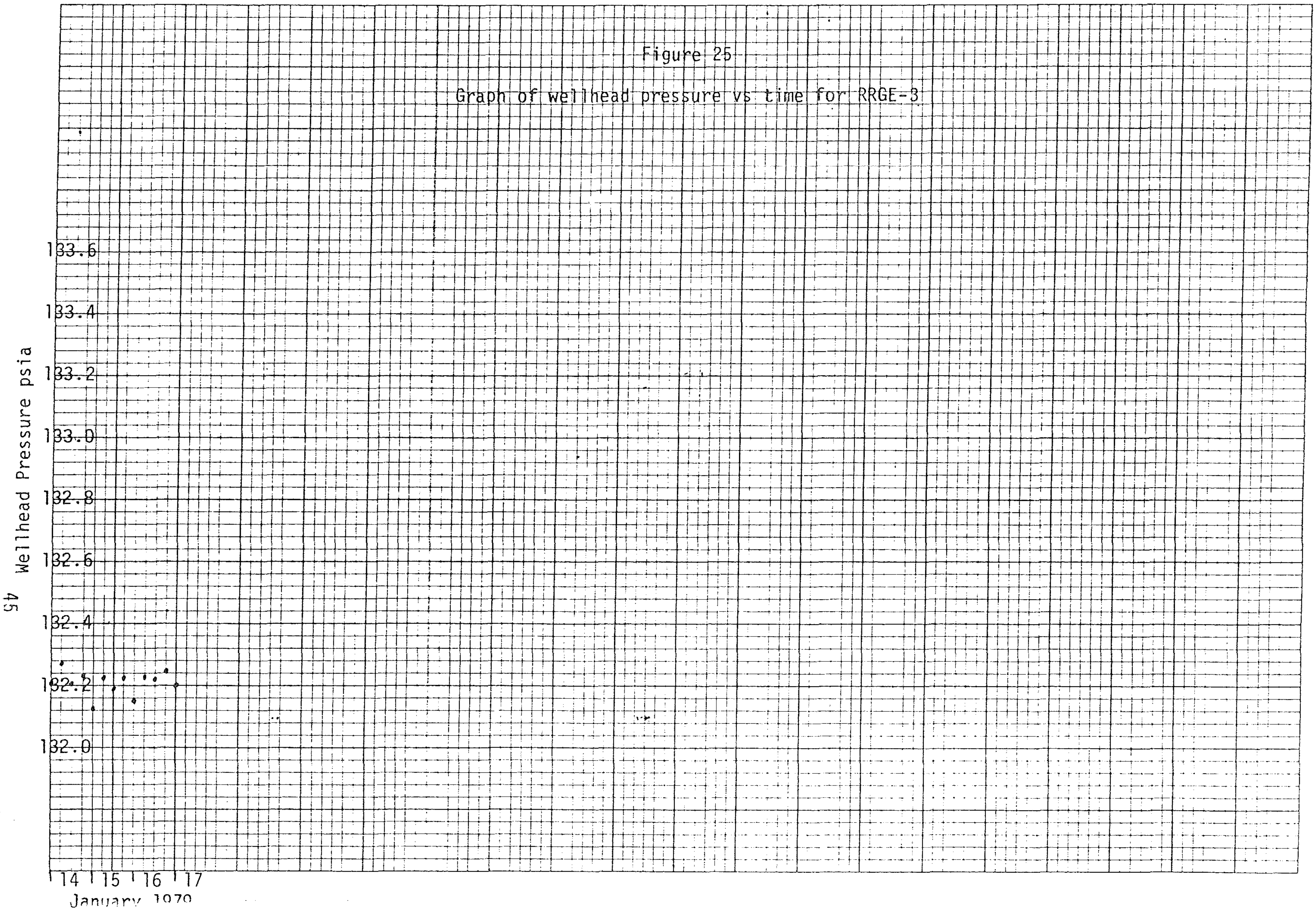


Figure 25

Graph of wellhead pressure vs time for RRGE-3



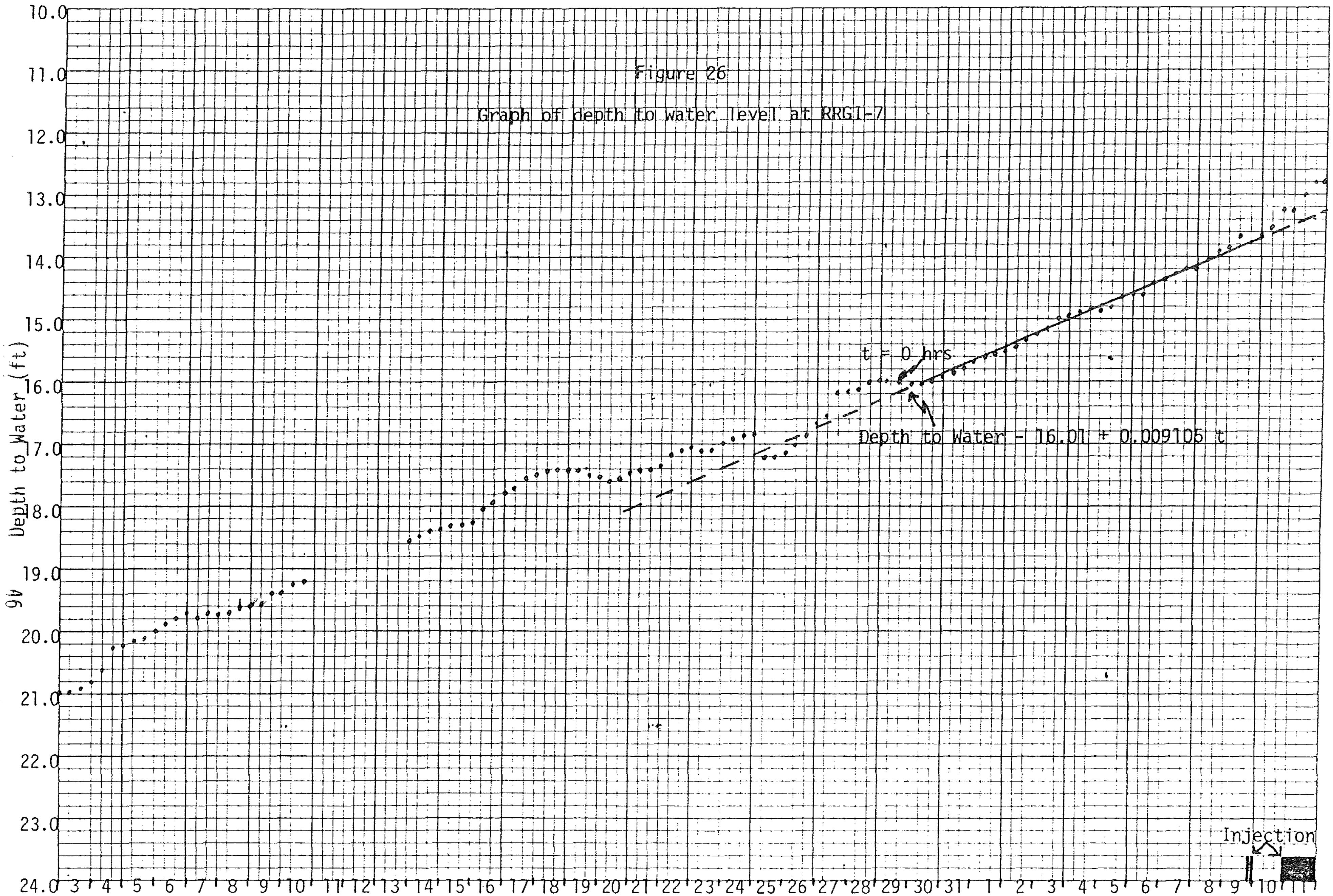


Figure 26

Graph of depth to water level at RRGI-7

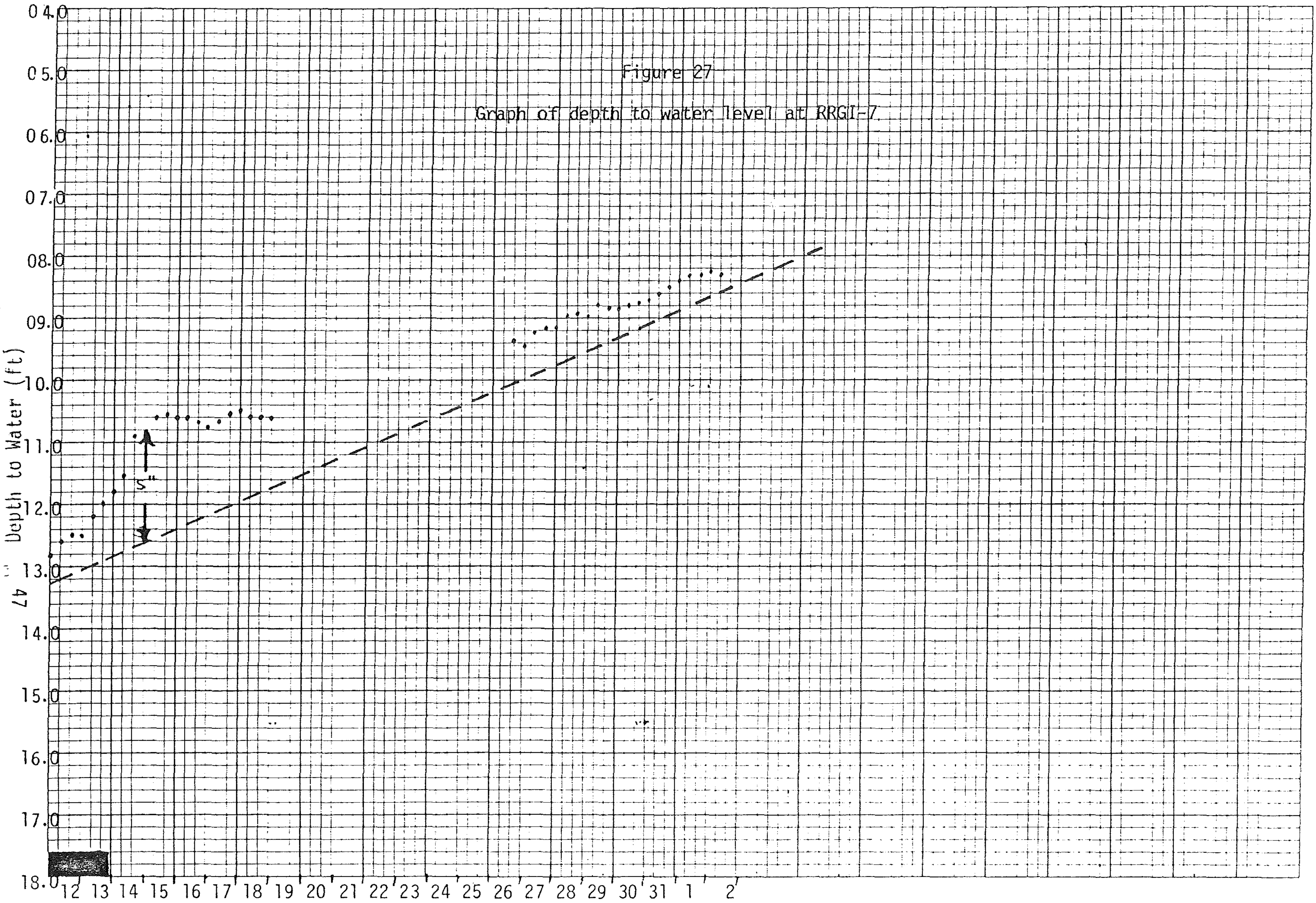


Figure 27

Graph of depth to water level at RRGI-7

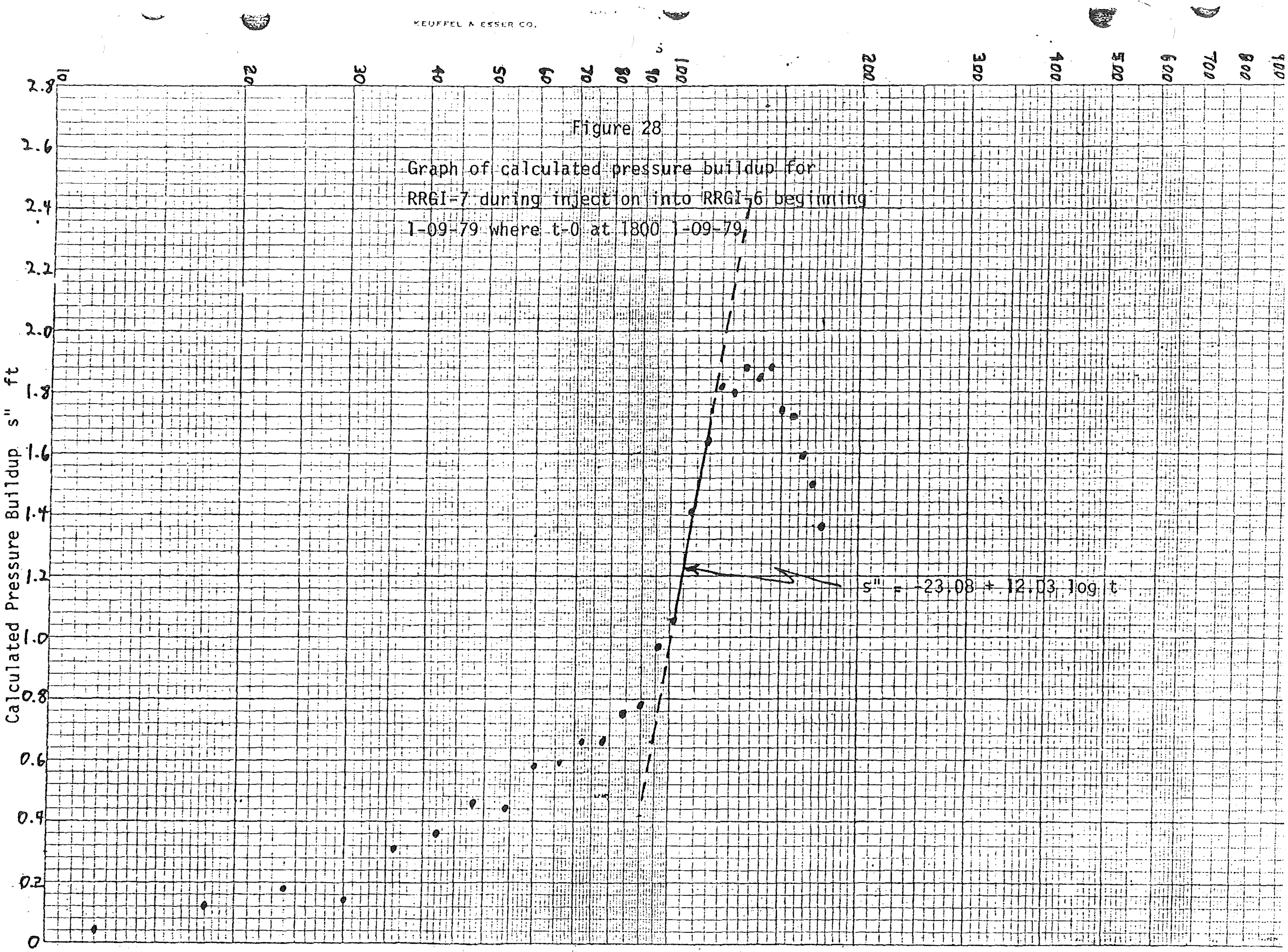


Figure 28

Graph of calculated pressure buildup for RRGI-7 during injection into RRGI-6 beginning 1-09-79 where t-0 at 1800 1-09-79

Figure 29

Graph of depth to water in monitor well 3

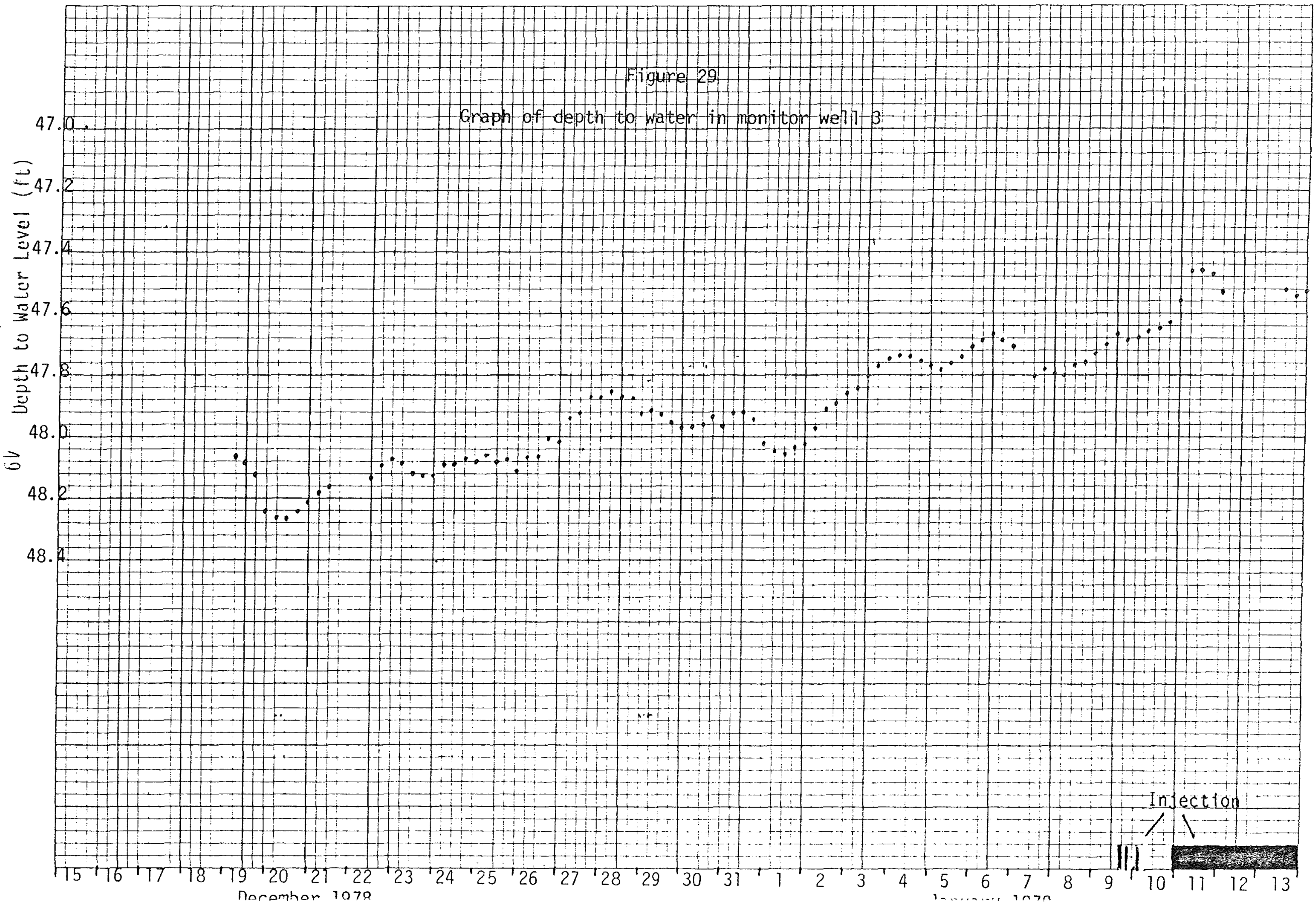


Figure 30

Graph of depth to water level monitor well 3

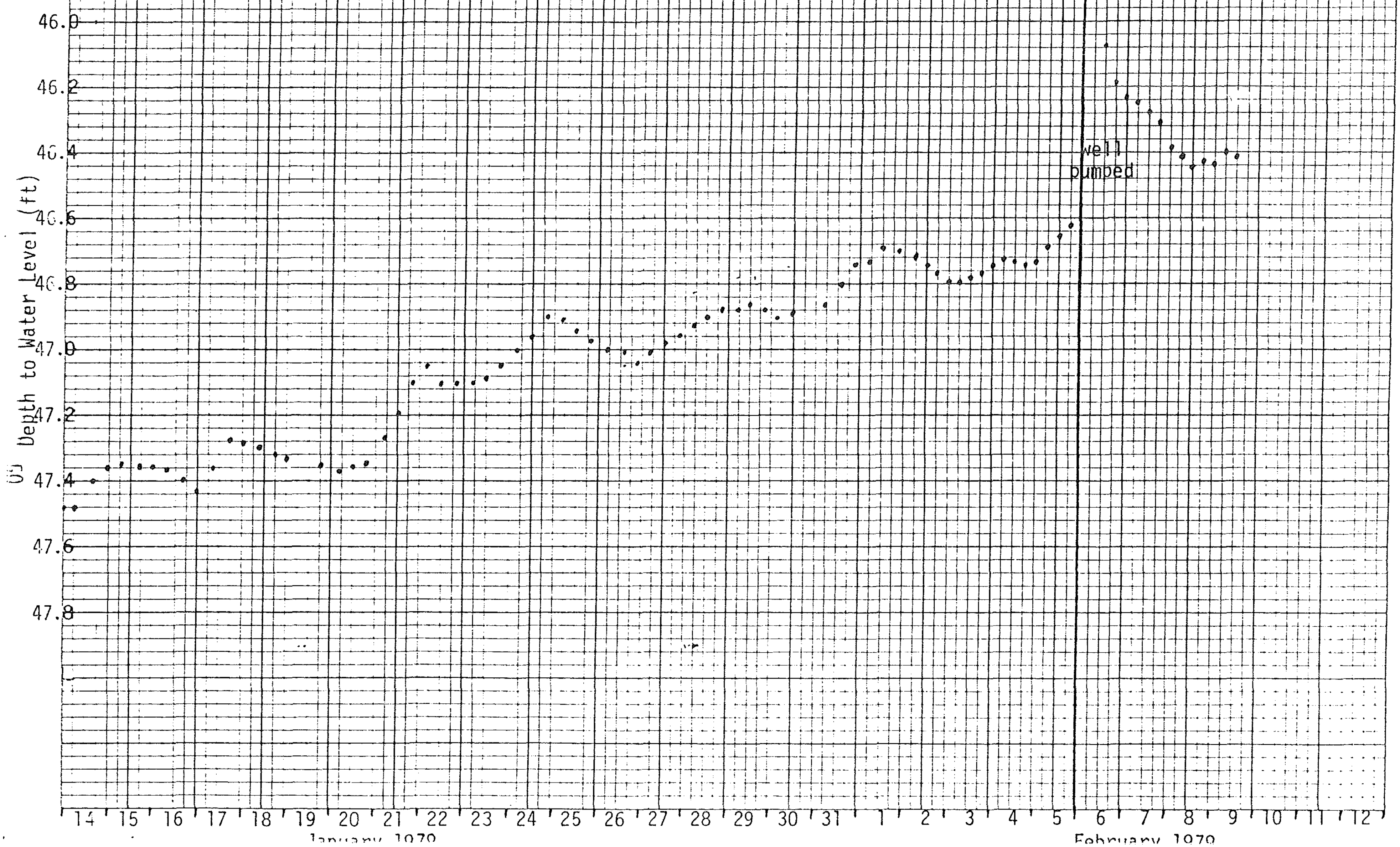
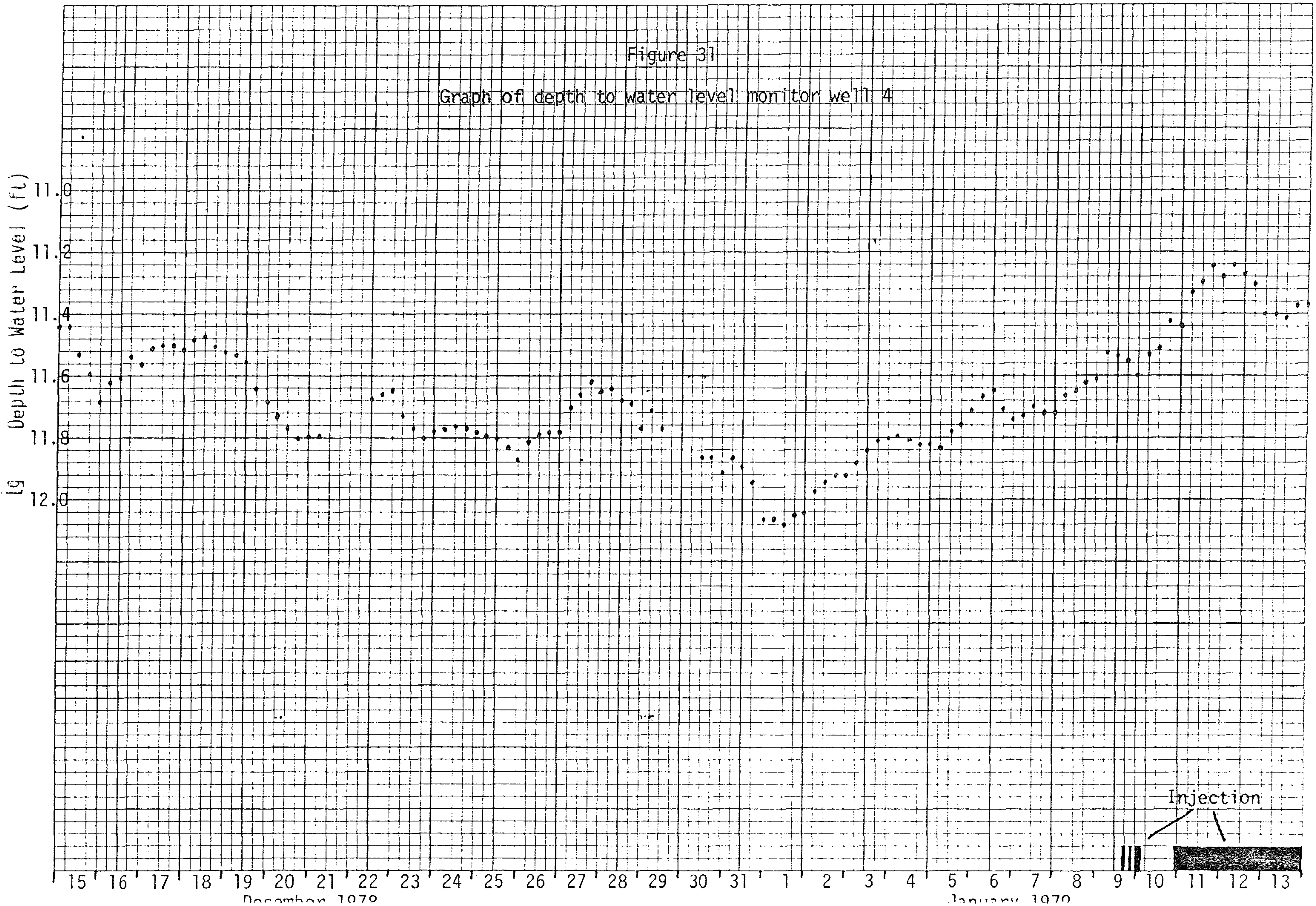


Figure 31

Graph of depth to water level monitor well 4



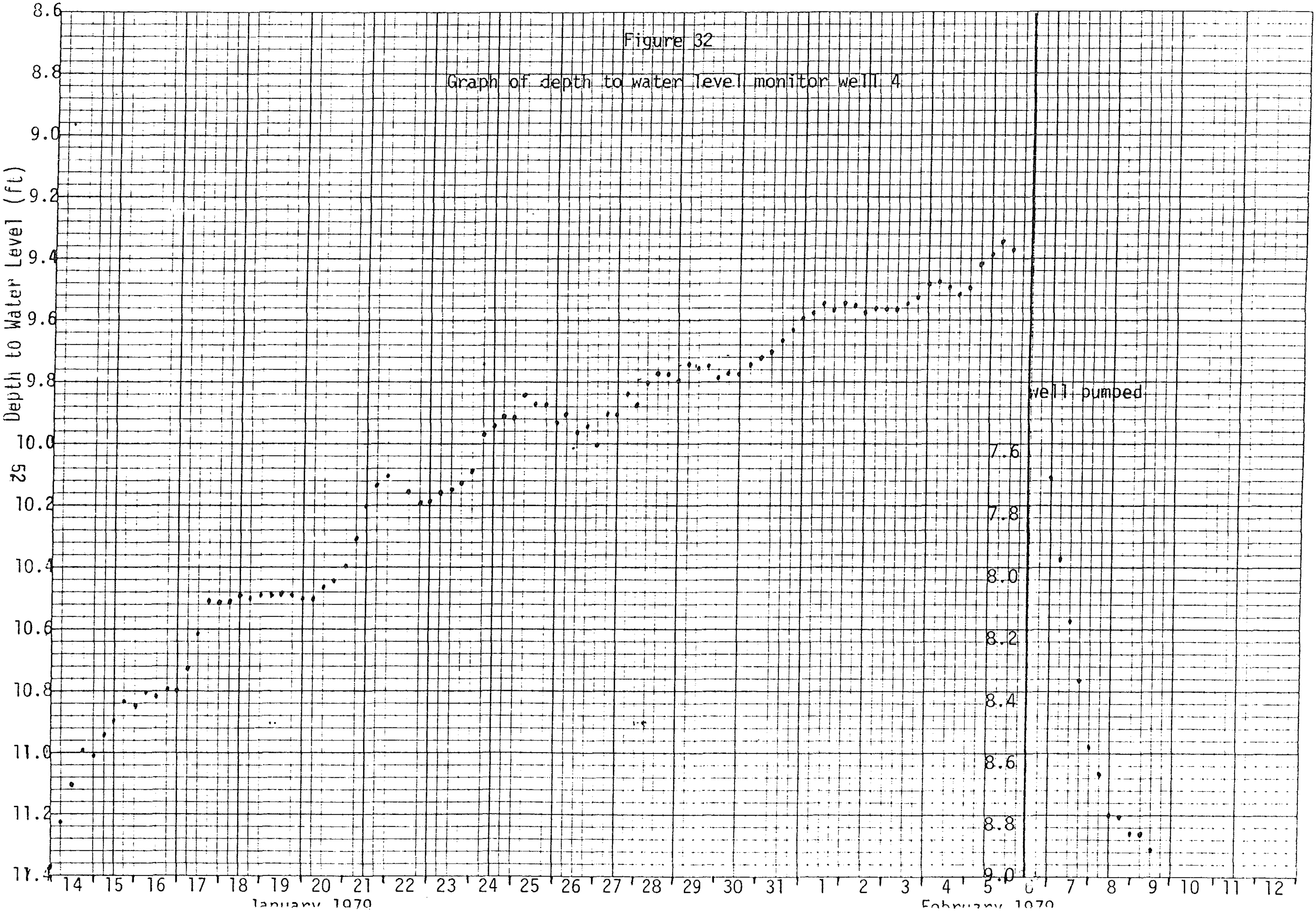


Figure 32

Graph of depth to water level monitor well 4

Figure 33

Graph of depth to water level monitor well 5

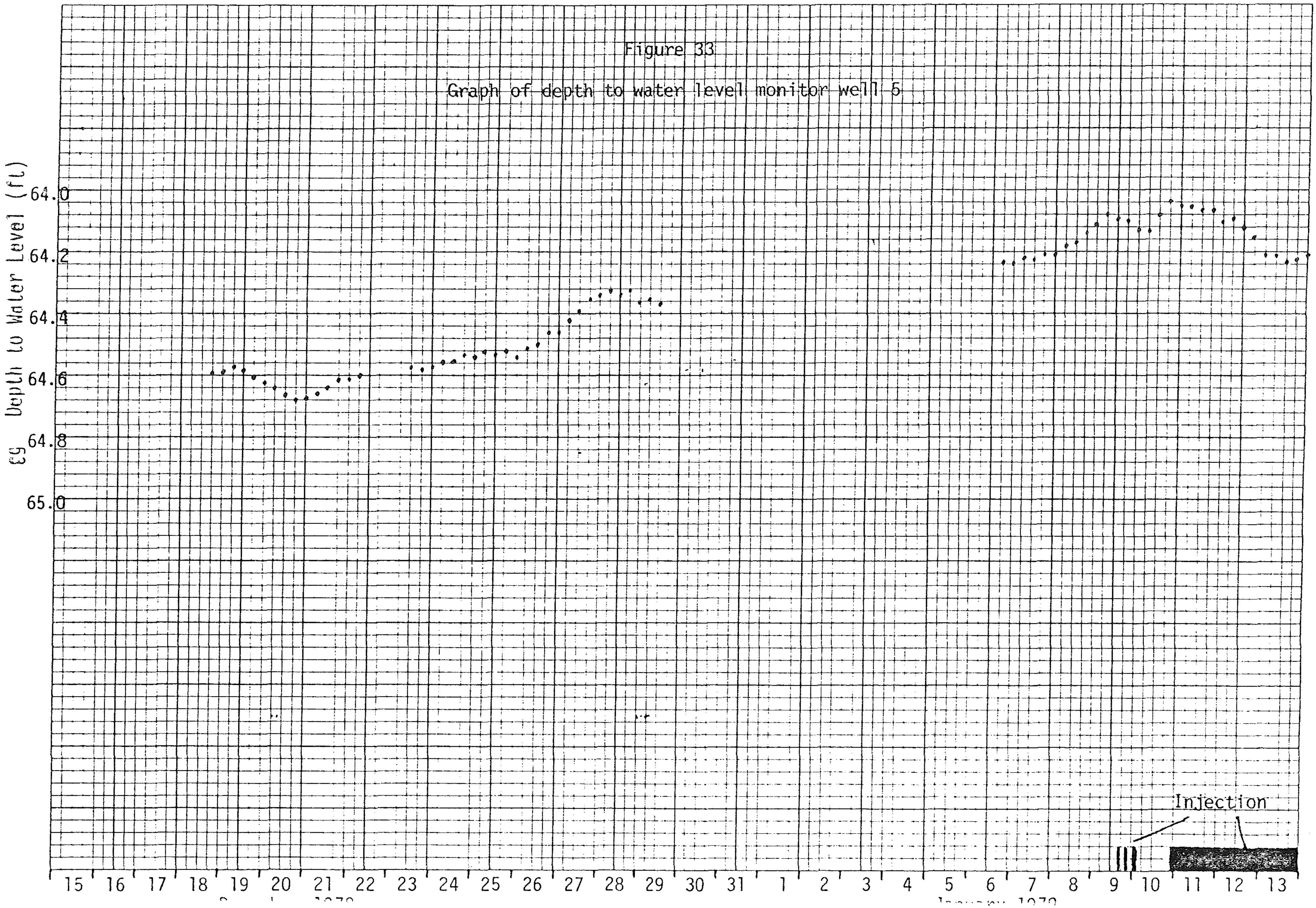
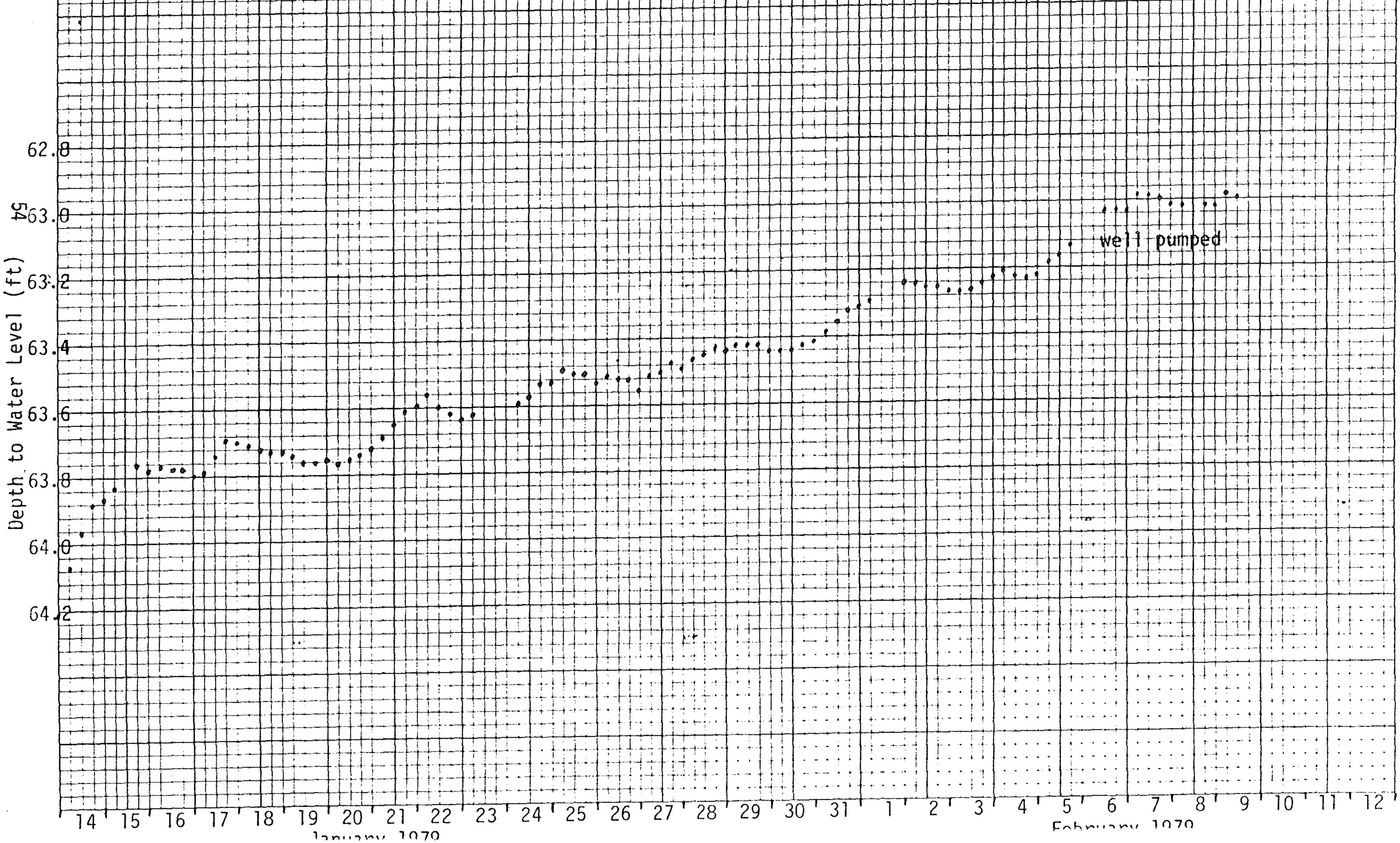


Figure 34

Graph of depth to water monitor well 5



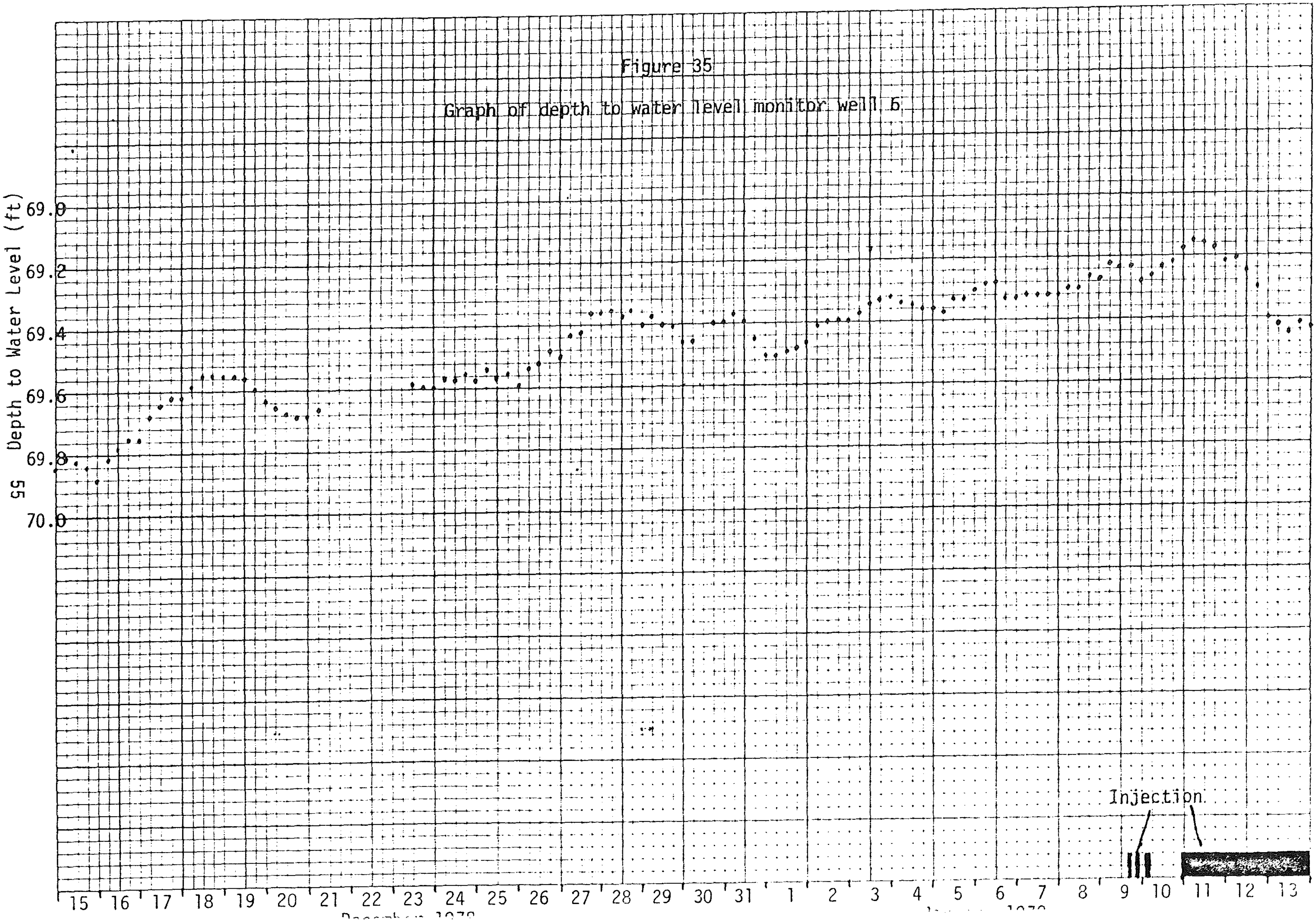


Figure 35

Graph of depth to water level monitor well 5

Figure 36

Graph of depth to water level monitor well 6

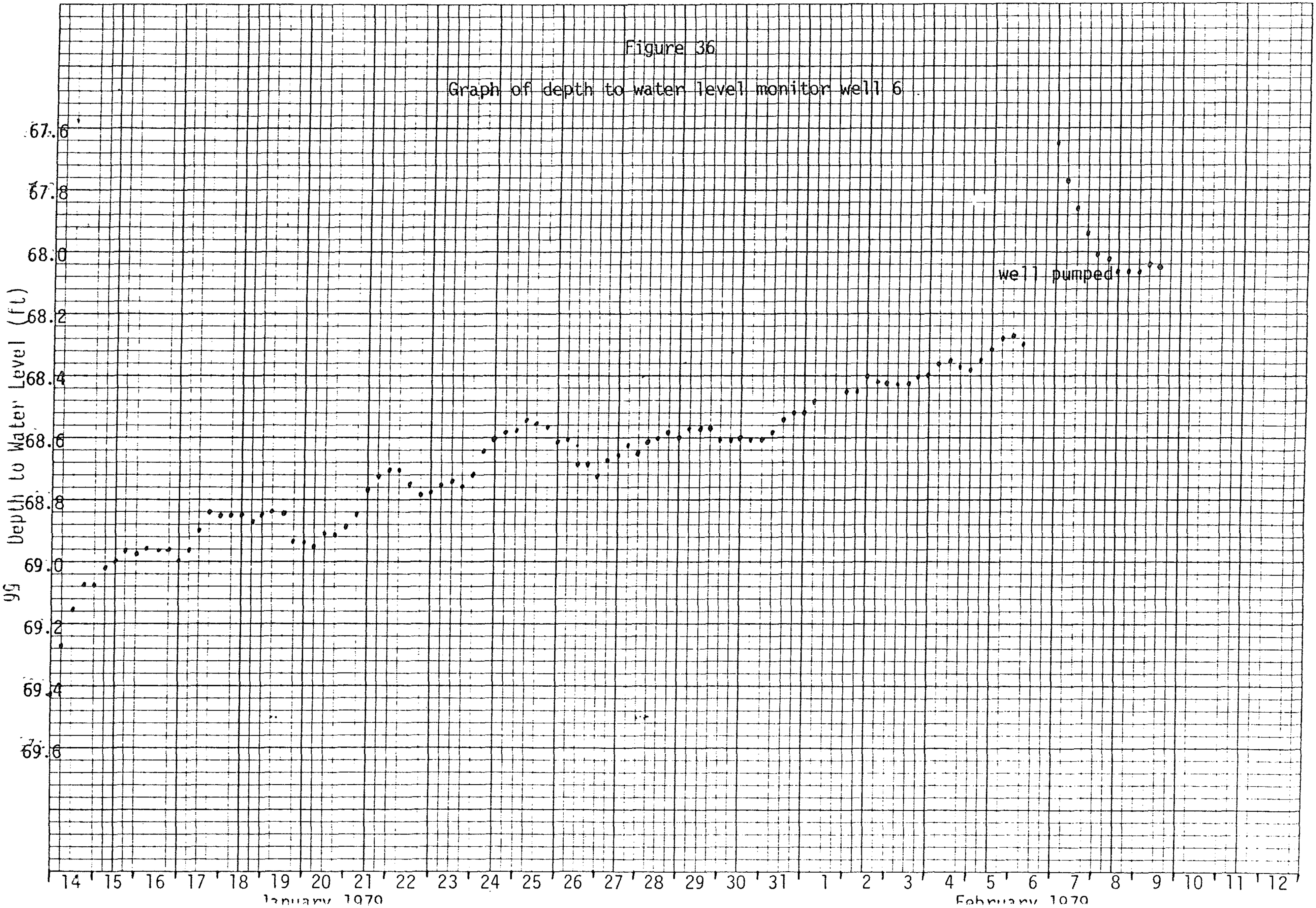
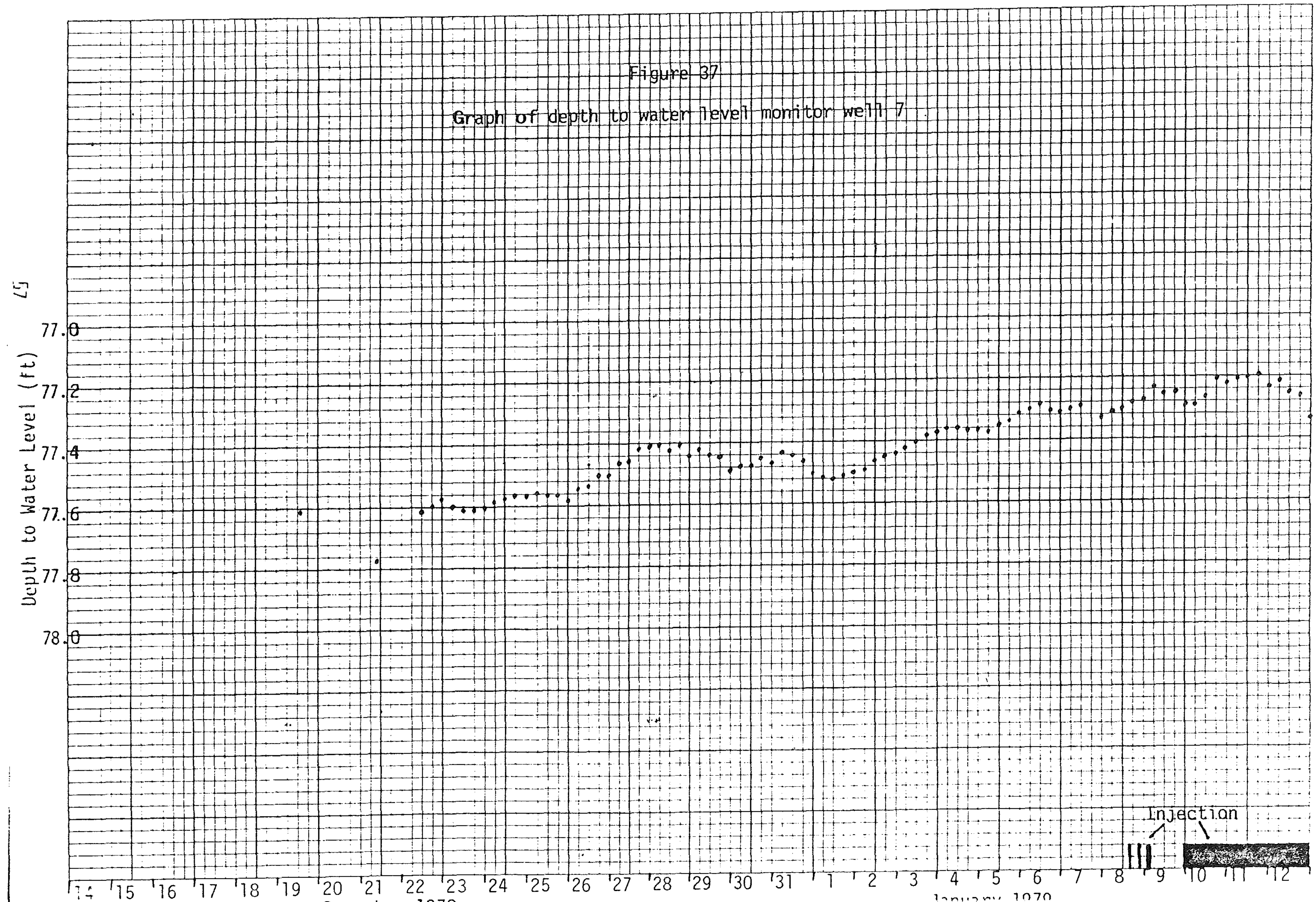


Figure 37

Graph of depth to water level monitor well 7



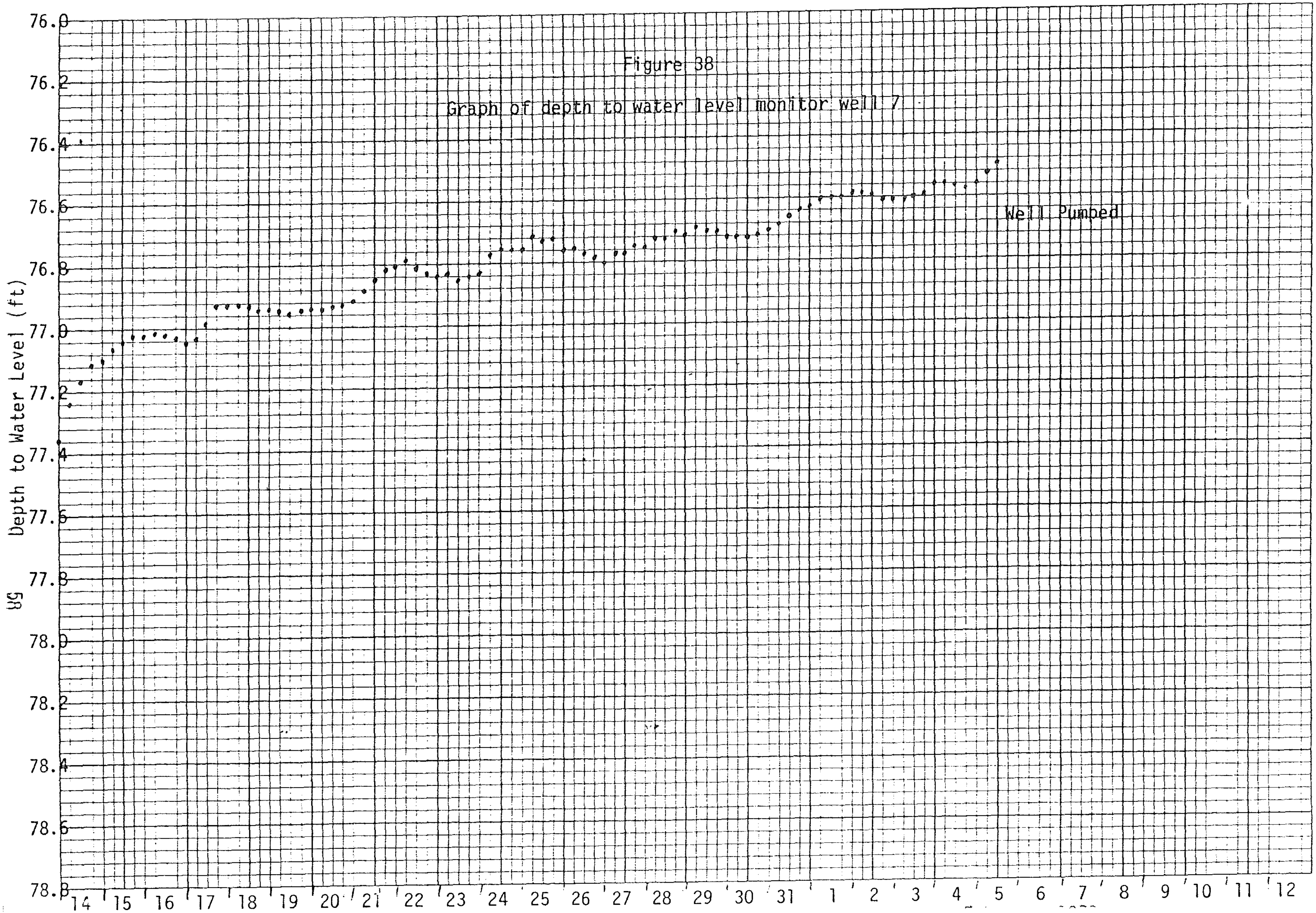


Figure 38
Graph of depth to water level monitor well 7
Well Pumped
Depth to Water Level (ft)
76.0
76.2
76.4
76.6
76.8
77.0
77.2
77.4
77.6
77.8
78.0
78.2
78.4
78.6
78.8
14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12