

HAWAII GEOTHERMAL PROJECT

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WELL TEST AND RESERVOIR ENGINEERING

PROGRESS REPORT FOR JANUARY 1977

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During January the modifications to the wellhead were completed and another series of discharge tests were started. Pressure buildup and draw-down data from the November and December discharge tests were analyzed, and tentative conclusions reached on the state of the Pahoehoe Geothermal Field.

I. Wellhead Modifications and January Discharge Test

Because of numerous complaints about the noise from residents in the Puna area and because of the need for additional safety conditions, several modifications were made to the wellhead equipment to improve its operation and to alleviate the high noise levels produced. A specially-built muffler was installed in place of the 24-inch horizontal discharge line. The muffler, of standard design, is 6 feet long and made up of two annular regions, the inner one filled with cinders for absorption of noise while the outer region is empty. To reduce the noise generated by the low-frequency vibration of the separator stacks, circular stiffeners were welded at two heights on each vertical stack.

The stilling basin for measuring the height of water flowing over the weir was moved to a more convenient location for personnel monitoring. To facilitate the insertion and removal of the temperature and pressure probes during discharge tests, a six-foot spool was added above the vertical valve. A steel platform with stairway (which meets OSHA requirements) and a pulley and winch for manipulating the recovery tube have been installed in place of the temporary wooden platform, which was deteriorating.

During the time that the wellhead equipment was being modified, the water column level in the well was monitored with the results presented in Figure 1. On January 24, 1977, the 36th day after shut-in, the water level was at ground level. This curve is similar to that following the November discharge test. Two temperature profiles were taken during this buildup period and are shown in Figure 2. The temperatures in the wellbore have essentially returned to their pre-flash values measured on December 8, 1976.

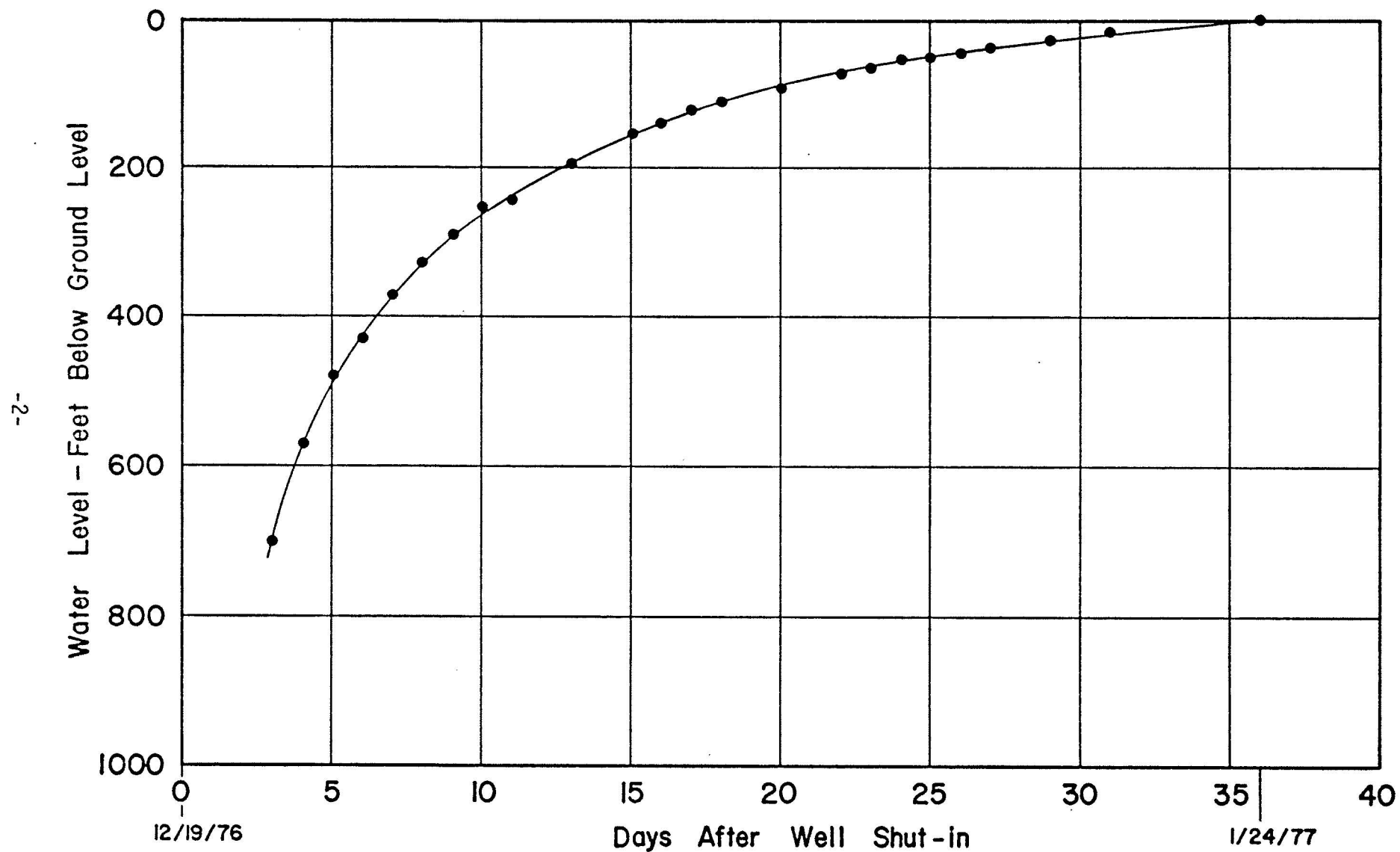


FIG. 1. WATER LEVEL RECOVERY AFTER WELL SHUT-IN

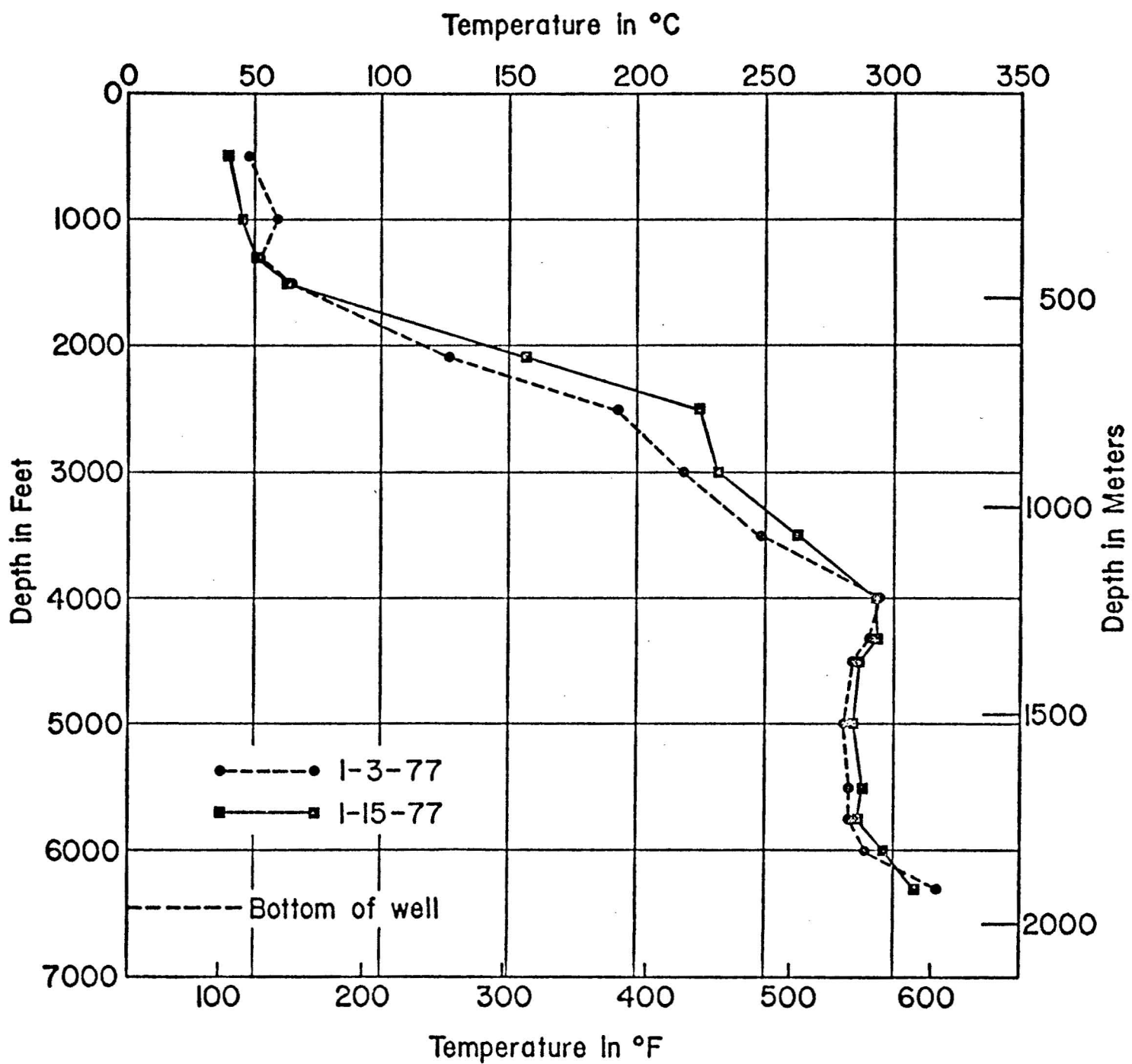


FIG. 2. TEMPERATURE PROFILES AFTER DECEMBER DISCHARGE TEST

Equipment modifications were completed on January 25, 1977, and discharge tests began on January 26 following a warm-up period during which the well was allowed to flow through a 2-inch bleed line. Initially, the well was allowed to surge for one-hour periods in an attempt to remedy suspected skin damage. During the three surges rock chips and drilling mud were ejected with the well fluid.

Following this period of surging, the well was allowed to discharge with the control valve wide open. A comparison of the characteristics of the flows during the early stages in the three discharge tests is shown in Table 1. There has been a steady increase in flow rate and wellhead pressure with each successive test.

Temperature and pressure profiles taken 48 hours after initiation of wide open flow are presented in Figures 3 and 4. Within the accuracy of the instruments, these measurements indicate that the fluid in the wellbore is at saturation conditions throughout the wellbore so that the flow is a mixture of liquid and vapor. The slight change in slope of the pressure curve at 2090 ft. is due most likely to the change in the cross-sectional area of flow at the junction of the slotted liner and the casing.

Sound level measurements taken around the site show that the noise level has been attenuated by roughly 7 dB--typically a reduction from 100 dBa to 93 dBa inside the fenced area (50' x 80') and from 87 to 80 dBa at the nearest public highway 120' away. In addition, the low frequencies associated with uncomfortable sensations of the chest and abdominal area (15 to 45 Hz) have been reduced. It appears that while some of the noise sources have been reduced, one important source, that of the circular stack's air column, has not and that this "organ pipe" remains as a primary source of sound.

A series of tests to determine well output parameters under throttled flow conditions was initiated by placing orifice plates of various sizes in the 8-inch portion of the discharge line. A 6-inch diameter orifice plate produced, as expected, a rather insignificant change in the flow conditions. Four-inch and 3-inch diameter plates did result in some change as shown in the data in Table 2. There is a substantial increase in wellhead pressure as the flow is throttled. A more complete table of data for a greater range of throttling will be obtained in February and will provide preliminary design information required for selecting a wellhead turbine-generator.

TABLE 1

## COMPARISON OF DISCHARGE TESTS AT 7 HOURS AND 25 HOURS AFTER INITIATION OF FLOW

	<u>AFTER 7 HOURS</u>			<u>AFTER 25 HOURS</u>		
	NOVEMBER	DECEMBER	JANUARY	NOVEMBER	DECEMBER	JANUARY
WELLHEAD PRESSURE (PSIG)	55	66	72	47	53	59
WELLHEAD TEMPERATURE (°C)	150	157	160	146	150	151
5" LIP PRESSURE (PSIG)	11.1	10	17	7.9	10.1	12.5
WEIR HEIGHT (INCHES)	3-1/2	4-3/4	4-5/8	3-1/2	4	4-1/8
WEIR TEMPERATURE (°F)	203	207	208	203	205	205
MASS FLOW RATE (KLB/HR)	97.3	120.0	139.7	87.9	103.4	114.3
WATER FLOW RATE (KLB/HR)	24	52	48	24	34	36
STEAM FLOW RATE (KLB/HR)	73.2	68.3	91.7	63.8	70.0	78.0
STEAM QUALITY (%)	75	57	65	73	68	68
ENTHALPY (BTU/LB)	912	725	805	888	833	845
THERMAL POWER (MW)	26.0	25.5	33.0	22.9	25.2	28.3

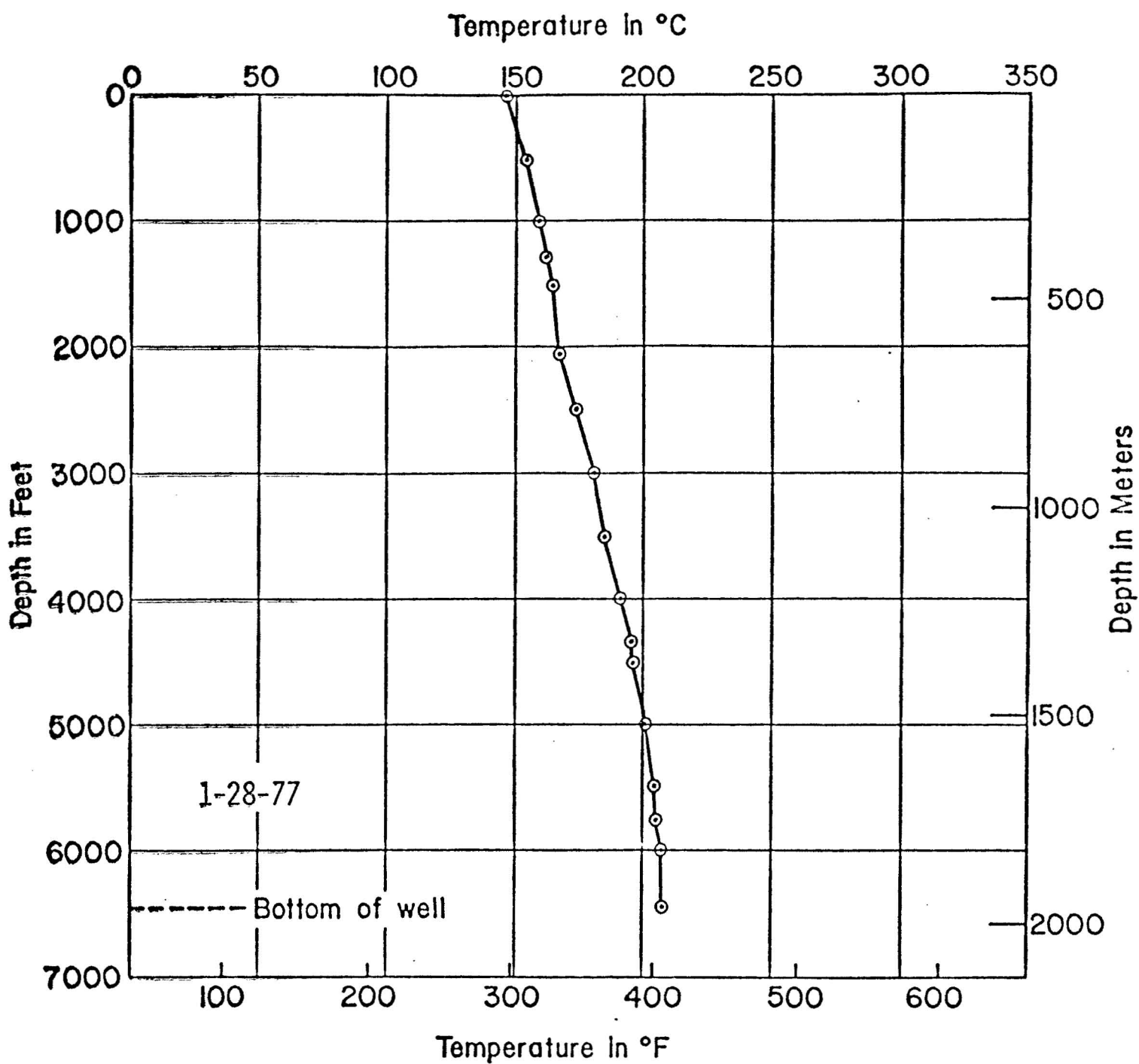


FIG. 3. HGP-A TEMPERATURE PROFILE DURING DISCHARGE TEST

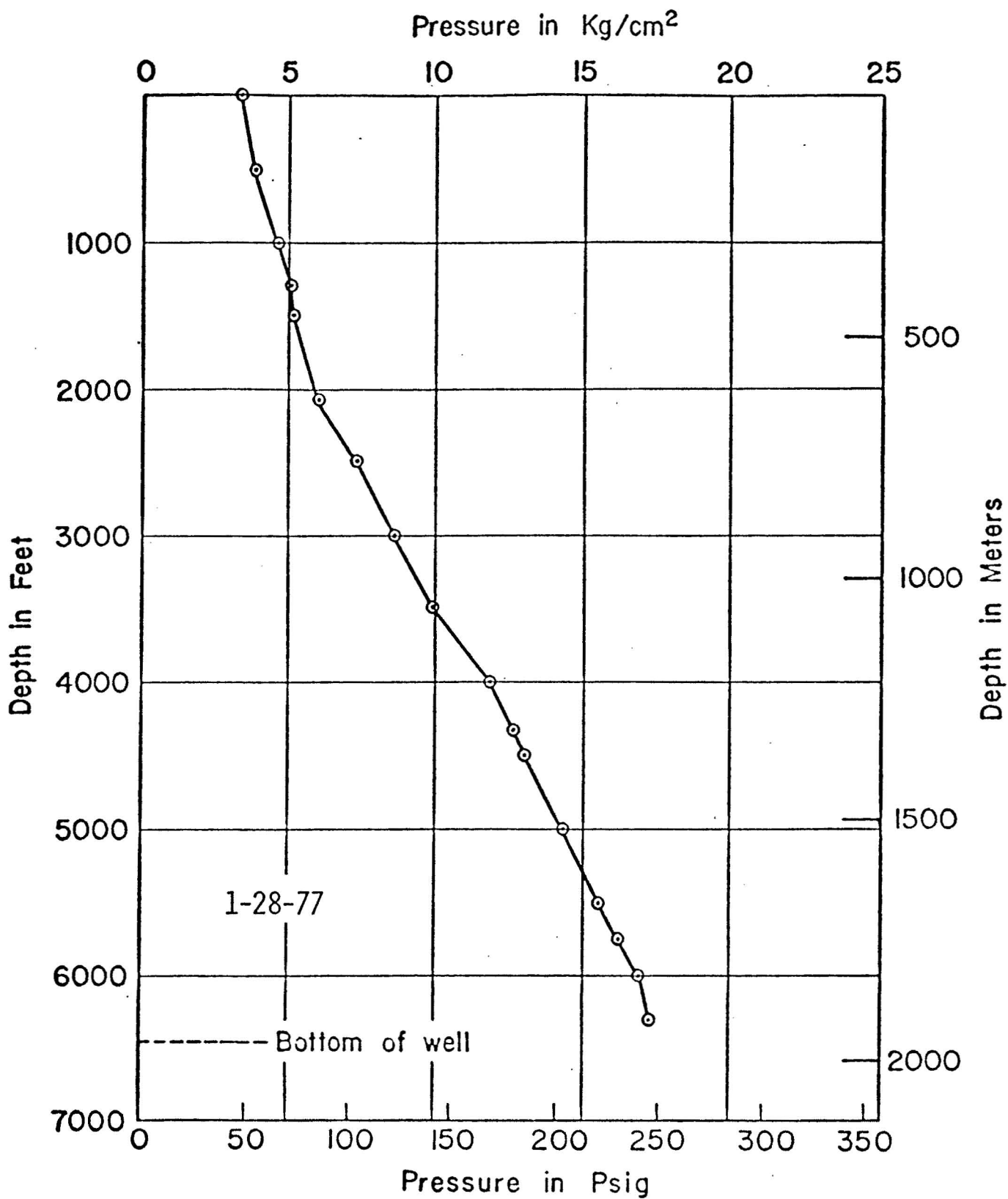


FIG. 4. HGP-A PRESSURE PROFILE DURING DISCHARGE TEST

TABLE 2

PRELIMINARY THROTTLED FLOW DATA

<u>ORIFICE SIZE (INCHES)</u>	<u>TOTAL MASS FLOW RATE (KLB/HR)</u>	<u>STEAM FLOW RATE (KLB/HR)</u>	<u>STEAM QUALITY (%)</u>	<u>WELLHEAD PRESSURE (PSIG)</u>	<u>WELLHEAD TEMP. (°C)</u>	<u>POSSIBLE ELECTRICAL POWER OUTPUT (MWE)</u>
8	101	70	69	51	146	3.5
6	99	70	71	54	149	3.6
4	93	66	72	100	170	3.9
3	89	62	69	165	189	4.0

## II. Pressure Drawdown and Buildup Tests

While data sufficient to assess a producible geothermal field can be obtained only from a number of properly-spaced wells, some information can be obtained from a single geothermal well by utilizing the theory developed for oil and gas fields. A summary of the basic theory and references are given in HGP Engineering Technical Memorandum No. 2, Geothermal Reservoir and Well Test Analysis: A Literature Survey, 1974, by B. H. Chen.

During the two-week discharge test in November, data were collected which permit a pressure drawdown analysis, and after the one-week discharge test in December, data were collected for a pressure buildup test. Results from the analyses of these two tests are given below.

### A. Pressure Drawdown Test

Wellhead pressure vs. time plotted on log-log scales for type-curve matching and on semi-log scales for a pressure drawdown analysis are shown in Figures 5 and 6, respectively. The initial pressure was obtained from Figure 7. While these data can be used in a pressure drawdown analysis to obtain information about the geothermal reservoir, some skepticism must be directed towards this analysis because of the following reasons:

1. The analysis is based on a constant production rate during the discharge, and this condition was not held during the November test. In order to apply the theory, a normalized pressure was obtained by dividing the pressure by the concomitant production rate.
2. There was some overpressure at the wellhead prior to the start of the test. Consequently, opening the valve took some effort and about 2 to 3 minutes were needed to open the valve completely. Thus there is an uncertainty of that amount in the determination of zero time.
3. The theory is for bottomhole pressure whereas the data in Figures 5 and 6 are for wellhead pressure. Thus the assumption must be made that wellhead pressure is proportional to downhole pressure and the proportionality factor remains constant throughout the test.

With these restrictions and assumptions, several pieces of information can be obtained. To normalize the pressure with respect to production the pressure relation can be written as

$$\frac{P_i - P_{wf}}{q} = \frac{162.6\mu B}{kh} \left( \log_{10} t + \log_{10} \frac{k}{\phi\mu C_t r_w^2} - 3.23 + 0.87s \right) \quad (1)$$

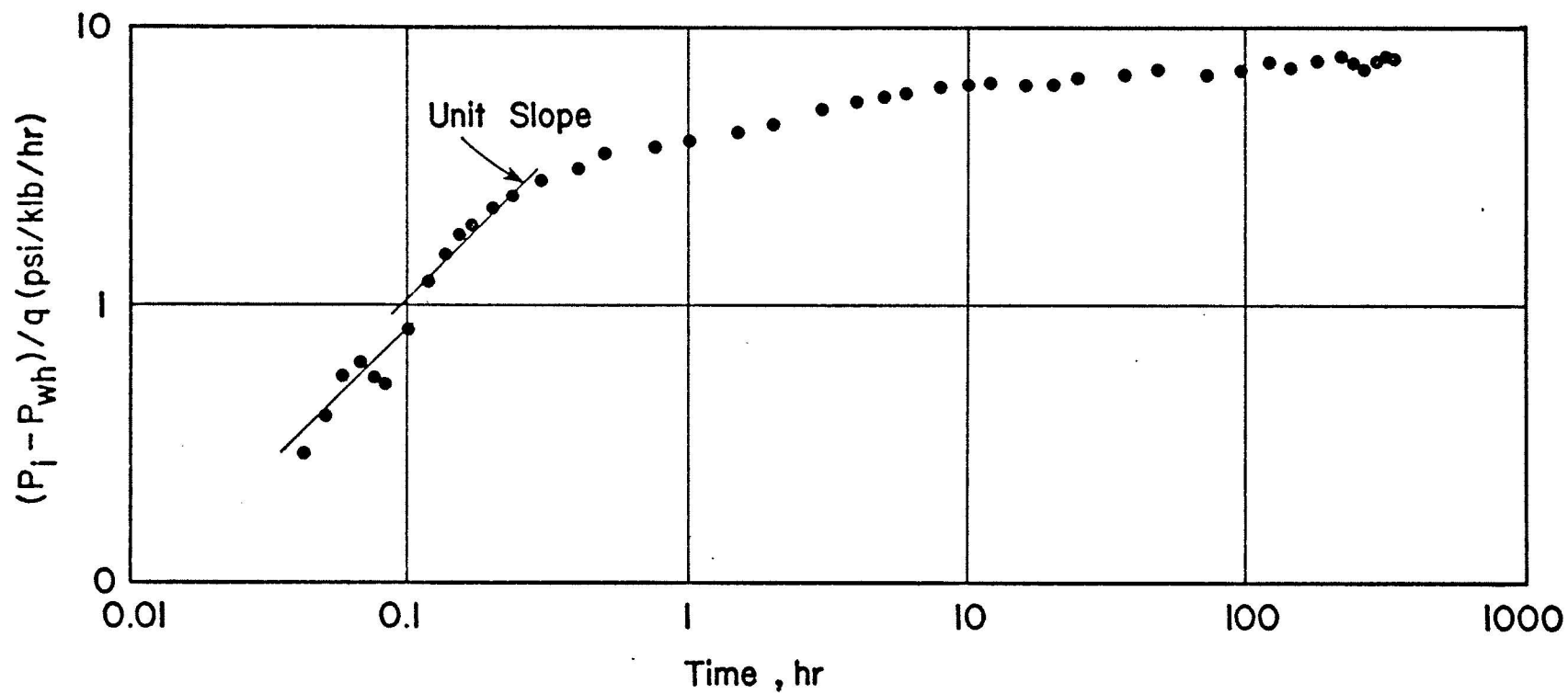


FIG. 5. LOG-LOG PLOT OF NOVEMBER DISCHARGE TEST DATA

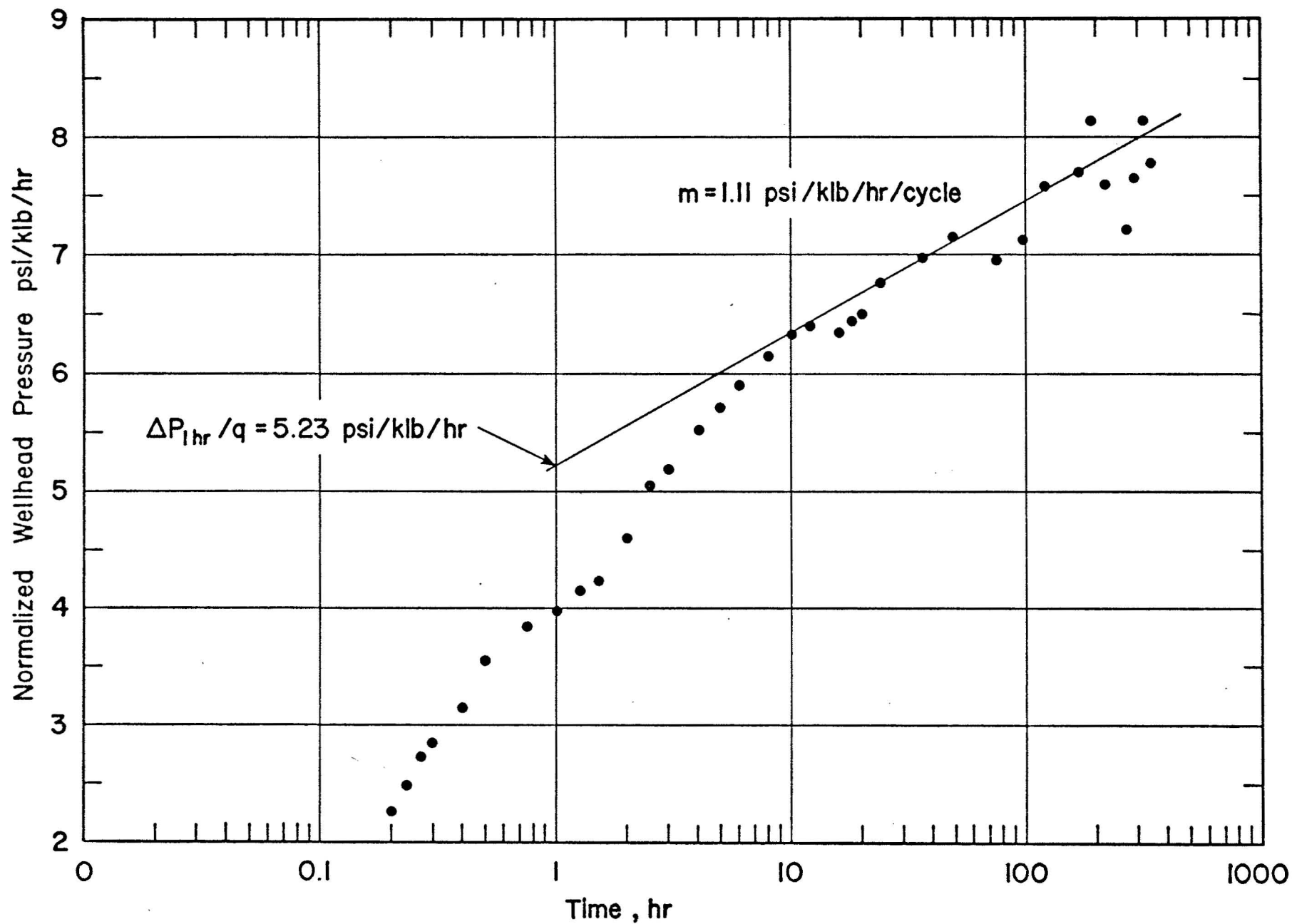


FIG. 6. SEMI-LOG PLOT OF NOVEMBER DISCHARGE TEST DATA

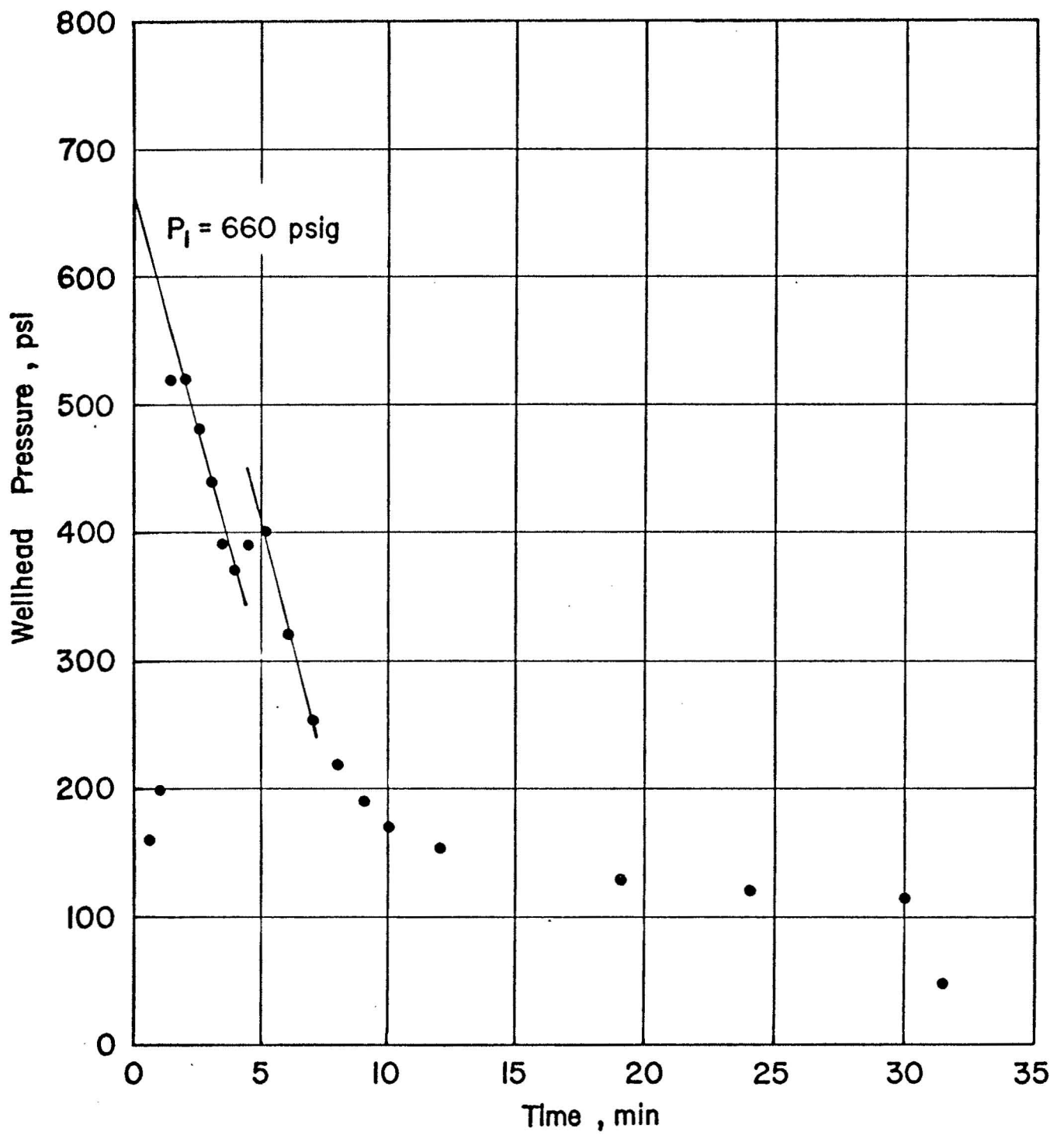


FIG. 7. LINEAR PLOT OF INITIAL DATA FOR NOVEMBER DISCHARGE TEST

where  $P_i$  = initial pressure, psi  
 $p_{wf}$  = flowing pressure, psi  
 $q$  = production rate, std bbl/day  
 $\mu$  = viscosity, cp  
 $B$  = formation volume factor, res vol/std vol  
 $k$  = permeability, md  
 $h$  = formation thickness, feet  
 $t$  = time, hr  
 $\phi$  = fractional porosity  
 $C_t$  = total system effective isothermal compressibility,  $\text{psi}^{-1}$   
 $r_w$  = well radius, ft  
 $s$  = skin effect factor

The left side of equation (1) is a linear function of  $\log_{10} t$  so that a plot of  $\frac{P_i - p_{wf}}{q}$  vs.  $\log_{10} t$  will yield a straight line with a slope,  $m$ , psi/bbl/day/cycle, where

$$|m| = \frac{162.6\mu B}{kh} \quad (2)$$

and this equation can be used to calculate the permeability-thickness,  $kh$ .

Equation (1) can also be used to calculate the skin effect factor,  $s$ . Letting  $p_{1hr}$  be the value of  $p_{wf}$  for  $t=1$  hour on the correct semi-log straight line, equation (1) can be rearranged to yield

$$s = 1.15 \left( \frac{\frac{P_i - p_{1hr}}{q}}{|m|} - \log_{10} \frac{k}{\phi \mu C_t r_w^2} + 3.23 \right) \quad (3)$$

By using (3), the pressure drop due to the skin effect can be calculated from

$$\frac{\Delta p_{skin}}{q} = 0.87 |m| s \quad (4)$$

and the flow efficiency

$$FE = \frac{\frac{p_i - p_{wf} - \Delta p_{skin}}{q}}{\frac{p_i - p_{wf}}{q}} \quad (5)$$

With the assumptions made previously, a log-log type-curve plot of  $\frac{p_i - p_{wf}}{q}$  vs.  $t$  for the November test is shown in Figure 5. The two unit-slope lines shown verify the existence of wellbore storage effects. From the end of the second straight line, it appears that the semi-log straight line or the radial flow period started at about 10 hours after the test was begun.

Figure 6 is a semi-log graph of  $\frac{p_i - p_{wf}}{q}$  vs.  $\log_{10} t$ . An analysis of the plotted data shows that the permeability thickness

$$kh = \frac{(162.6) (24 \text{ hr/day}) (0.09 \text{ cp}) (1.5 \text{ res bbl/std bbl})}{(350 \text{ lb/bbl}) (1.11 \times 10^{-3} \text{ psi/lb/hr/cycle})}$$

$$kh = 1356 \text{ md-ft}$$

and if the thickness of the producing layer is assumed to be  $h = 1000 \text{ ft.}$ , then the permeability

$$k = 1.4 \text{ md.}$$

The skin effect factor

$$s = 1.15 \left[ \frac{5.23 \times 10^{-3}}{1.11 \times 10^{-3}} - \log_{10} \frac{1.4}{(0.03)(0.09)(8 \times 10^{-6}) \left( \frac{8.755}{24} \right)^2} + 3.23 \right] = -0.86$$

The small negative skin effect factor suggests that skin damage is not present. Therefore, the flow efficiency of the well is approximately 1, or the well is discharging as much as it is able to produce.

The minimum drainage area for the duration of the November flow test can be estimated to be

$$A = \frac{0.000264 (1.4)(3.36)}{(0.03)(0.09)(8 \times 10^{-6})(0.05)} = 1.15 \times 10^8 \text{ ft}^2$$

Thus the minimum volume reached during this discharge test was

$$Ah = 0.8 \text{ cu mile}$$

## B. Pressure Buildup Analysis

As with the pressure drawdown test, the pressure buildup test employs the standard methods used in petroleum and gas field analysis. The end of the December discharge test permitted a pressure buildup test. Bottom-hole pressures were taken by two Kuster KPG pressure elements and recorders in tandem to ensure that pressure data were acquired since considerable difficulty had been experienced with equipment malfunction because of the very high temperature.

Figure 8 is a log-log type-curve plot of  $(P_{ws} - P_{wf})$  vs.  $t$ . It shows two distinct wellbore storage effects as in the pressure drawdown test; the top of the second wellbore storage effect is indicated by the arrow A. The rule of thumb used is that the onset of the radial flow period on the conventional semi-log straight line is  $1\frac{1}{2}$  log cycle beyond A, which is indicated by the arrow B. This time is approximately 70 hours after well shut-in. Figure 9 is a semi-log graph of  $(P_{ws} - P_{wf})$  vs.  $\log_{10} \frac{t + \Delta t}{\Delta t}$ .

From the curves the permeability-thickness

$$kh = \frac{162.6 (87.700)(24)(0.09)(1.5)}{(350)(150)} = 880 \text{ md-ft}$$

Again if the height of the producing layer is assumed to be  $h = 1000$  ft, then  $k = 0.88$  md-ft.

The skin effect factor

$$s = 1.15 \left[ \frac{1900 - 467}{130} - \log_{10} \frac{.88}{(0.03)(0.09)(8 \times 10^{-6}) \left( \frac{8.755}{24} \right)^2} + 3.23 \right]$$
$$= 4.30$$

The pressure drop across the skin

$$\Delta p_s = (0.87)(150)(4.30) = 561 \text{ psi}$$

and the flow efficiency

$$FE = \frac{2300 - 467 - 561}{2300 - 467} = 0.65$$

This indicates the well is producing about 65% of the capability without damage.

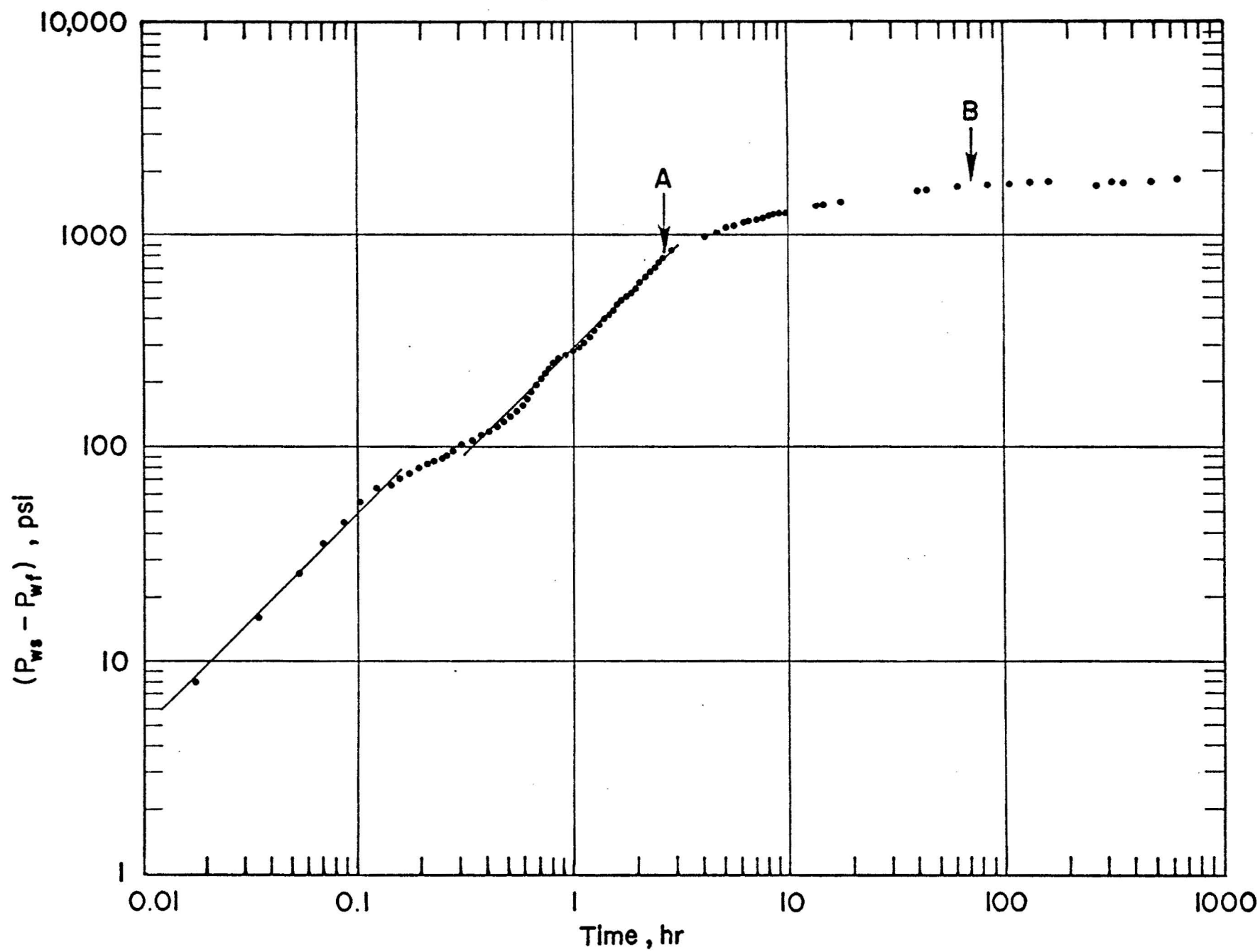


FIG. 8. LOG-LOG PLOT OF DECEMBER PRESSURE BUILDUP TEST DATA

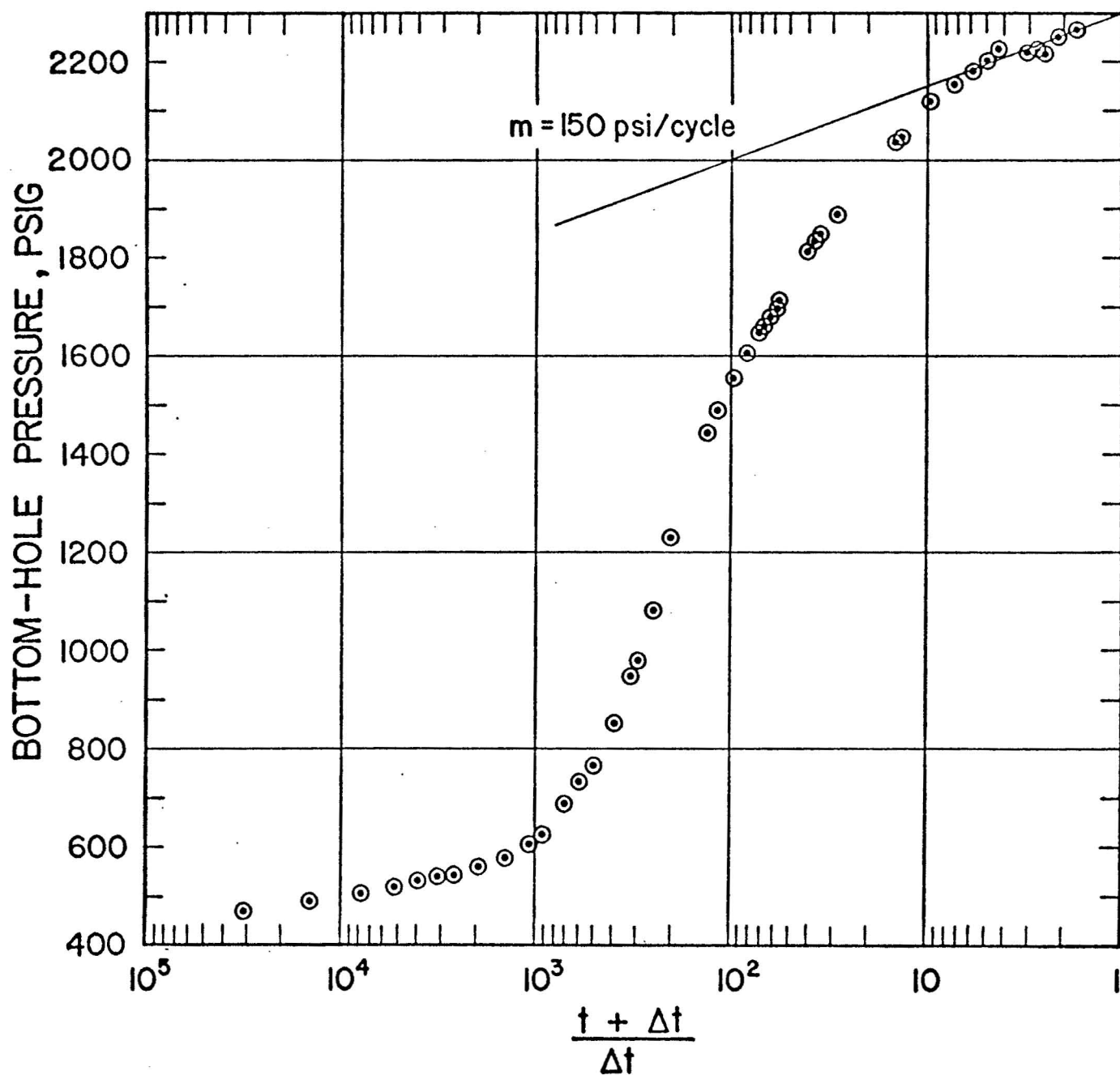


FIG. 9. SEMI-LOG PLOT OF DECEMBER PRESSURE  
BUILDUP TEST DATA

### C. Discussion

Table 3 summarizes the preceding analyses of the pressure drawdown and buildup tests. The permeability thickness figures from both analyses are similar, but the skin effects and flow efficiencies are widely divergent. The assumptions for a pressure drawdown analysis include the production of fluid at a constant rate, which is difficult to satisfy in practice. In order to apply the theory, the pressure data were normalized by dividing by the production rate, which can be questioned for its validity. On the other hand, the pressure buildup analysis has no similar, difficult assumption to satisfy in practice. Thus more reliable conclusions can be drawn from the pressure buildup test and analysis.

In a very preliminary way the pressure buildup test indicates that the reservoir is tight (low permeability of perhaps less than 1 millidarcy) and that the well suffers from significant skin damage, resulting in a discharge rate of only 65% of what it is capable. This latter tentative conclusion is supported by the data in Table 1, which shows that the flow rates have increased with each succeeding test. This may have been a result of the initial surges in each test, which either removed the baked-in mud and thus reduced the skin damage, or possibly induced stress-caused microfractures.

TABLE 3  
COMPARISON OF PRESSURE BUILDUP AND DRAWDOWN TESTS

	<u>BUILDUP</u>	<u>CONSTANT PRODUCTION DRAWDOWN</u>
PERMEABILITY THICKNESS, KH, MD-FT	880	1356
APPARENT SKIN FACTOR, S	4.30	-0.86
PRESSURE DROP ACROSS SKIN, PSI	561	---
FLOW EFFICIENCY	0.65	~1

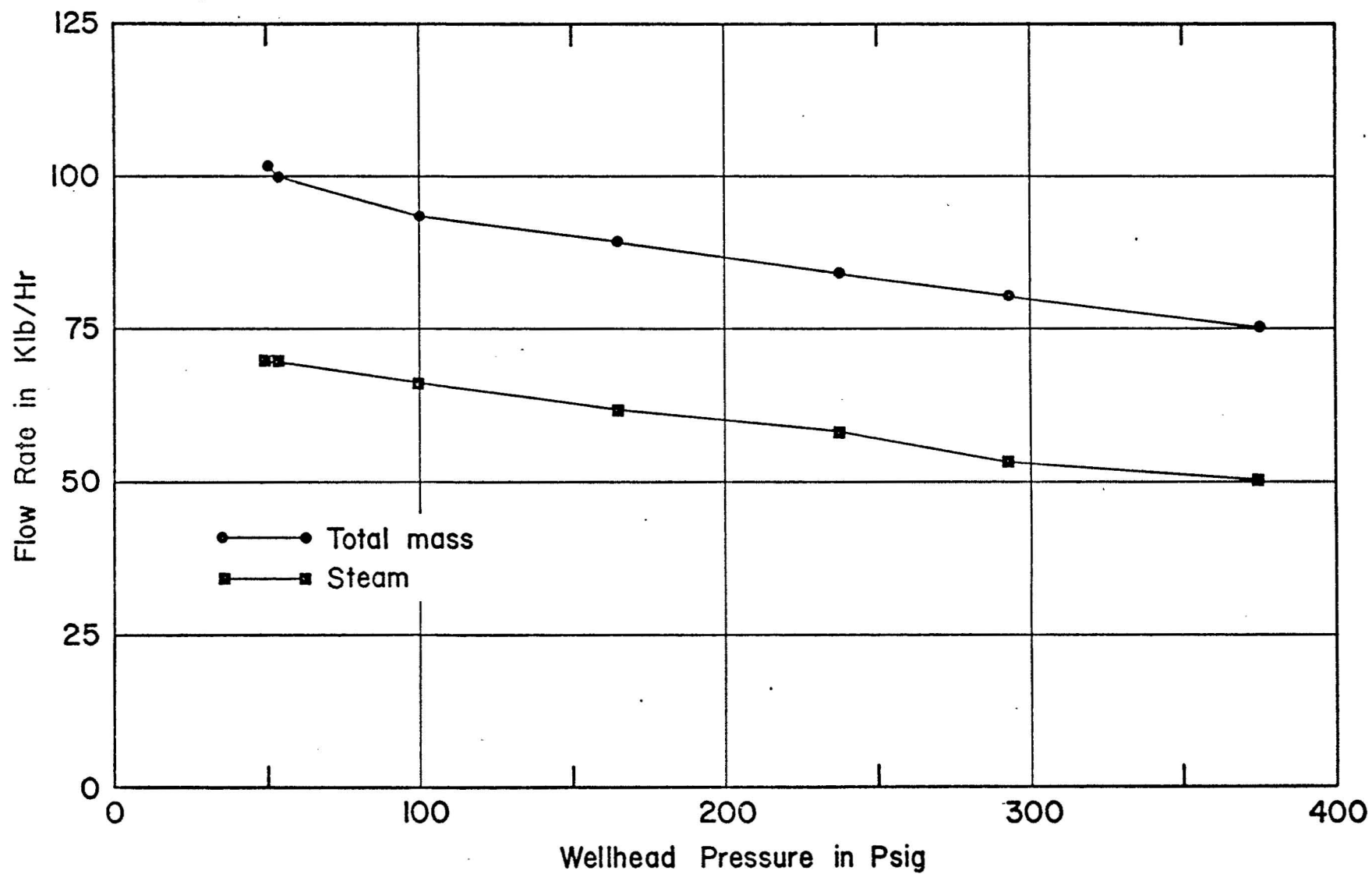
PRELIMINARY THROTTLED FLOW DATA

<u>ORIFICE SIZE (INCHES)</u>	<u>TOTAL MASS FLOW RATE (KLB/HR)</u>	<u>STEAM FLOW RATE (KLB/HR)</u>	<u>STEAM QUALITY (%)</u>	<u>WELLHEAD PRESSURE (PSIG)</u>	<u>WELLHEAD TEMP. (°C)</u>	<u>POSSIBLE ELECTRICAL POWER OUTPUT (MWE)</u>
8	101	70	69	51	146	3.5
6	99	70	71	54	149	3.6
4	93	66	72	100	170	3.9
3	89	62	69	165	189	4.0
2-1/2	84	58	69	237	205	4.0
2	81	54	66	293	215	3.9
1-3/4	76	50	67	375	226	3.8

2/11/77

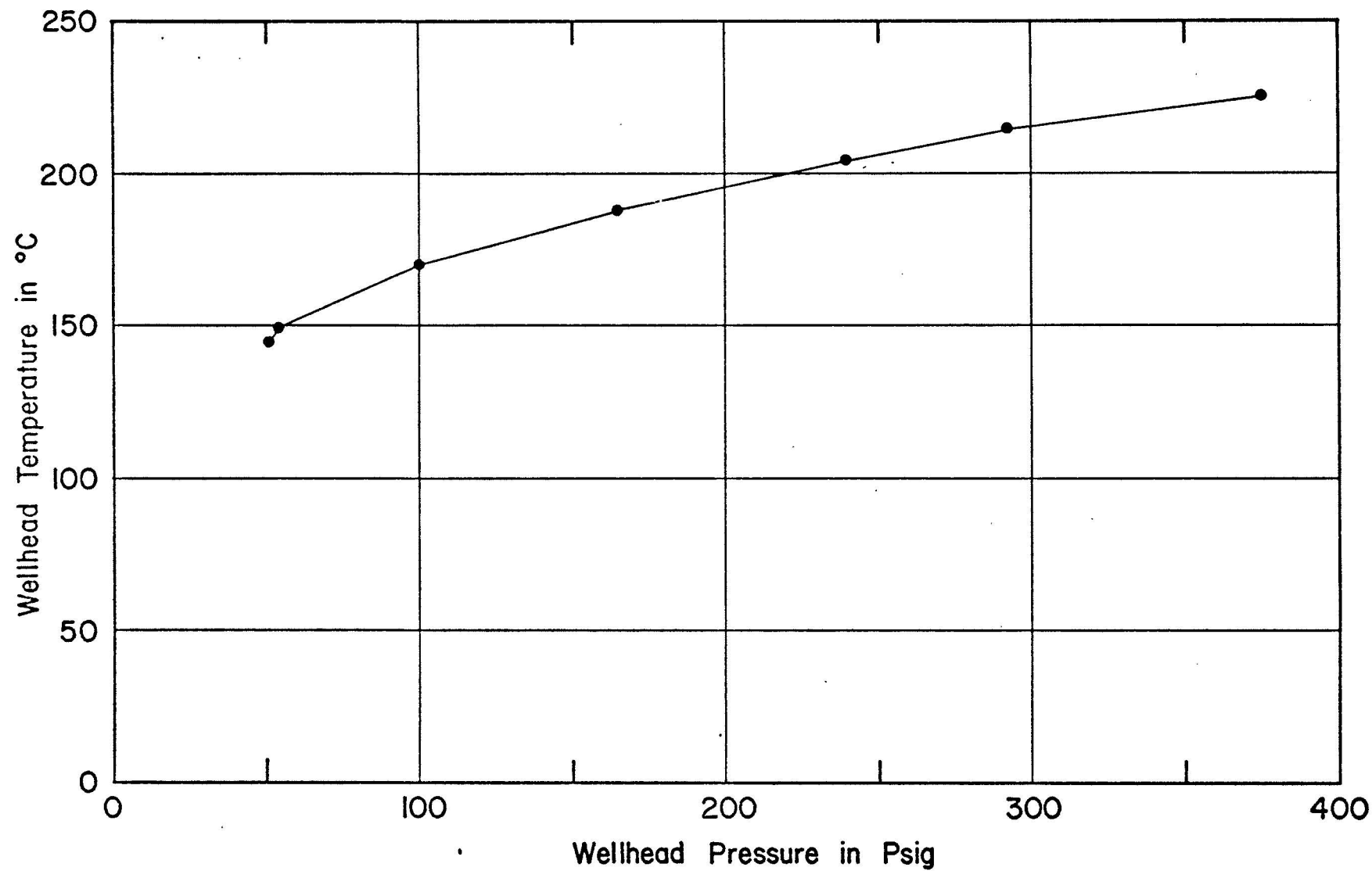
# FLOW RATES DURING THROTTLED FLOW TEST

1/26/77 - 2/10/77



# WELLHEAD TEMPERATURE DURING THROTTLED FLOW TEST

1/26/77 - 2/10/77



# POSSIBLE ELECTRICAL POWER OUTPUT DURING THROTTLED FLOW TEST

1/26/77 - 2/10/77

