THE GEOTHERMAL RESERVOIR ENGINEERING OF HGP-A: A SUMMARY REPORT OF ACTIVITIES UP TO OCTOBER 31, 1976

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INTRODUCTION

There are five distinct, but related parts to the Hawaii Geothermal Project task on the geothermal reservoir:

1) Geophysical and drilling activities
2) Physical (laboratory) modelling
3) Performance prediction (empirical modelling)
4) Numerical (mathematical) modelling
5) Well testing and analysis

Geothermal reservoir engineering can be defined to include all phases of geothermal activity, beginning with the initial decision on where to locate the drill site, to well logging during the drilling program, to well measurement, and finally, to performance prediction of the geothermal field. Geothermal reservoir engineering interfaces with the initial geophysical/geological effort at the beginning and the actual utilization of the fluid at the end.

In a time perspective, the work can begin quite early, even before the geophysical tests, with mathematical and physical modelling programs to help predict the potential well sites and determine materials of construction. The activity continues through the entire operational life of the field, as periodic re-evaluation must be made of projected field life and optimal flow rates. Furthermore, well injection and stimulation efforts could be necessary.

The theory of the geothermal reservoir has been qualitatively summarized (Takahashi, Chen, Mashima, Seki, 1975) and mathematically expressed (Chen, Lau, 1975) in various earlier publications available through the Hawaii Geothermal Project. The following sections will emphasize material not previously covered in the above reports.

HISTORY OF GEOTHERMAL WELL DRILLING IN HAWAII

Six holes have been drilled on the island of Hawaii for the purpose of locating sources of geothermal energy. In summary, they are:

Well	Year	Location	Elev (ft)	Depth (ft)	Maximum Temp. (°C)
Thermal Test Well #1	1961	Puna Rift	1009	178	55
TTW #2	1961	Puna Rift	1035	556	102
TTW #3	1961	Puna Rift	563	690	93
TTW #4	1961	Puna Rift	250	290	43
Keller's Hole	1973	Kilauea Caldera	3615	4140	137
HGP-A	1975-6	Puna Rift (Pahoa)	615	6454	359

The initial four holes were drilled in 1961 by the Hawaii Thermal Power Company. Recent measurements have shown that these temperatures have not change significantly. It is interesting to note that TTW #2 shows virtually a continuous increase in temperature with depth, with a sharp gradient from 253 to 262 feet. However, the well had caved in at around 361 feet, when a temperature of 97° was measured at this point in 1975. TTW #3 was measured to the bottom of the well, where a peak temperature of 93°C was measured at around 540 feet. A sharp positive gradient was measured from 460 feet to 540 feet, and a rather sharp negative gradient (not as steep as the positive gradient) from 540 feet to the bottom (Epp and Halunen, 1976).

TTW #2 and #3 are both located along the Puna rift about 5 miles (8.5 km) apart, with TTW #2 close to site B (Opihikao anomaly) and TTW #3 just to the sea side of HGP-A (site A, Pahoa anomaly). (See Figure 1.) In short, with slightly warmer temperatures, TTW #2 has a peak of 102°C probably close to 600 feet below the surface or 400 feet above sea level, while TTW #3 has a peak temperature of 93°C at about 540 feet below the surface, or just at about sea level. The obvious conclusion is that warm fluid is not flowing from the higher elevation to the lower in a path along the Puna Rift.

In addition to the geothermal wells, several warm water wells are of interest. Well 9-9 (USGS #1 2782-01), Malamaki, has a maximum temperature of 55°C at around sea level (20 feet below sea level is the peak temperature point, although the warm region extends from sea level to the bottom, 42 feet below sea level). Well 9-6 (USGS # 3081-01), located somewhat north and seaward of HGP-A and TTW #3 has a temperature of 36.8°C. Epp and Halunen report that a significant temperature increase of 3°C occurred in well 9-6 from August 16, 1974 to September 3, 1976, before the November 1975 earthquake that was located south of the Puna region. The largest increase of almost 5°C occurred 10 feet below sea level. The Allison well (USGS # 2881-01) is at a temperature of 38.9°C. Finally, although other water wells to sea level have been drilled along the Puna Rift with virtually ambient temperatures, in general, water wells located in the Puna region show increasingly lower temperatures away from the rift. There is, however, a warm belt outside the rift region between Opihikao and Pohoiki, which suggests warm water movement from higher to lower levels into the sea between these two locations.

The well drilled by G.V. Keller is located more than twenty miles inland from HGP-A along the same principal rift zone. The well was drilled to a point 525 feet below sea level where a maximum temperature of 137°C was recorded. However, the gradient in the lower part of the well was 370°C/km, suggesting that acceptable geothermal energy conditions prevailed a short way down.

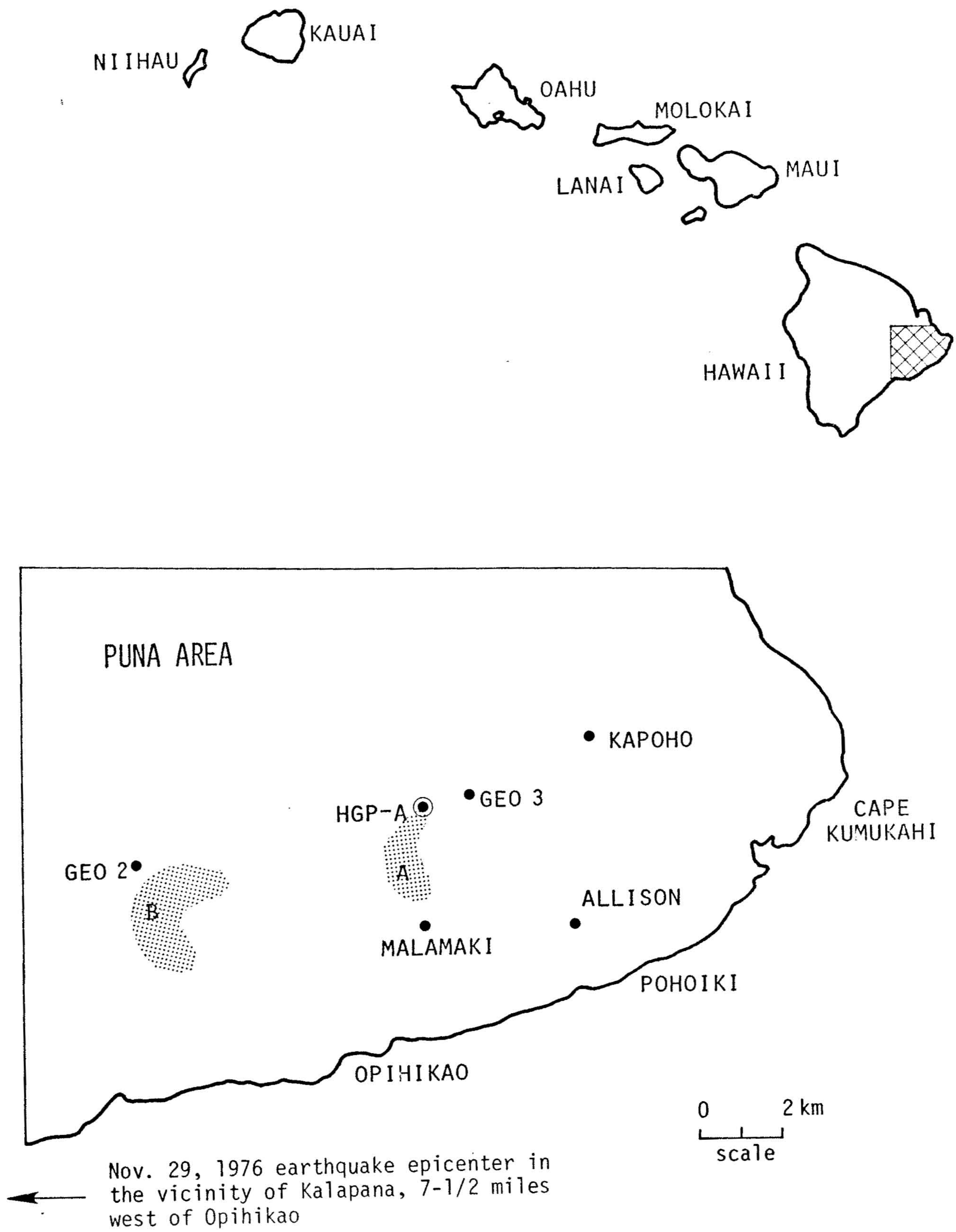


Figure 1 Location of HGP-A

The rocks penetrated were all tholeiitic basalt, with vesicularity ranging from a few percent to 40 percent. The water level was about 2000 feet above sea level. Permeabilities of less than 100 millidarcies were encountered at depths below 3000 feet from the surface (600 feet above sea level). Hydrothermal alteration in the form of calcite and zeolite was detected below the water table (Keller, 1974).

GEOPHYSICAL SUMMARY

The geophysical program was designed to select a drill site and develop an understanding of the thermal process of a basaltic volcano and its associated rift zones. Various geophysical surveys were utilized: IR, gravity, magnetic, electrical, well temperature, seismic, geochemical and hydrology. Data from a self potential survey by the USGS was also used. Testing and interpretation are continuing.

Several anomolous interesting areas were discovered, with two determined to be of particular significance. Figure 1 represents a series of maps pinpointing the location of these two areas, in particular, location A where Hawaii Geothermal Project Well A (HGP-A) is located.

Table 1, summarizes the major geophysical surveys. Area A was selected as the drill site primarily because of the earlier discussed hydrologic data, the proximity of wells with relatively high temperatures, high gravity data which suggested a dike complex below this area, low resistivity and the fact that land was available.

Geophysical evidence, as of May 1975, was mixed, with site B being favored by another group. Area B was shown by resistivity data to be larger in areal extent, by magnetic data to be above the Curie temperature and by seismic refraction to suggest a caprock formation at 700 meter depth. Furthermore, microearthquake data gave a high Poisson's ratio for the rock formation, indicating significant fracturing. Finally, thermal test well #2, prior to HGP-A, had the highest water temperature in the area, 102°C. However, this well site sits over one of the vent fissures of the 1955 eruption, so the high temperature was expected. TTW #2 is located right next to, but to the Kilauea Caldera side of site B. Site B certainly appears to be a site worth considering in future drilling plans.

PRE-DRILLING SPECULATIVE MODELS

Several models were advanced by HGP researchers. The three most prominent models will be discussed.

Model #1 suggested the presence of an intrusive zone under the Kilauea east rift with a width of 4 km on the western side, fanning out to a 6 km width on the

TABLE 1

SUMMARY OF GEOPHYSICAL/GEOCHEMICAL SURVEYS IN AREA A (before drilling)*

Type	Value	Meaning
self-potential	500-900 mV	high (good)
resistivity	less than 5 to 10 ohm-m	low (good)
ground noise level	9 db at 4 hz	above normal ambient (good)
magnetic	---	high (bad, below Curie temp.)
micro-earthquake	3 events/day	above normal (good)
gravity	22 milligals	high (indicates possibility of intrusives, which could be good, but also low permeability, which is bad)
temperature		
1) Archies Law	140°C	low (bad)
2) geothermometer (dissolved silica)	160-275°C	somewhat low (not good)
3) warm water in nearby wells	40^+ to 102°C	high temperature (good)
4) brackish water at water table	several hundred ppm chloride	relatively high salt content (good, indicates upwelling or convection caused by high temperature at depth)

*Data from HGP reports and personal communications with G. Macdonald and A. Furumoto of HIG.

eastern side, and extending from a depth of 0.9 km to 1.9 km. A relatively low water temperature of 140°C was predicted. Rainwater was seen to percolate downward through the permeable rock, rising in temperature with depth. Eventually, low permeability would prevent further percolation. It is at this point that the 140°C temperature was placed. The areal extent of the reservoir was determined to be in the range of one to two square kilometers.

Model #2 speculated that confined aquifers could exist at depth due to self-sealing. The heating would be provided by a magma chamber at shallow depth or some intrusion. This model was based on seawater recharge.

Model #3 has a vertical structure, with a series of dikes essentially parallel to the general topographic ridge. There is groundwater circulation within the dike system. The heat source consists of hot igneous bodies within the rift zone.

There are at least two different fluid circulation patterns: groundwater leaking through the dike structure, moving seaward, plus upwelling of seawater induced by the heat source.

GEOTHERMAL RESERVOIR ENGINEERING

Only a very brief treatment of the total geothermal reservoir engineering program will be given here, as detailed summaries can be found in HGP Technical Report #1 (Takahashi, Cheng, 1974), the July 1975 issue of the American Society of Civil Engineering Journal of the Power Division (Takahashi, Chen, Mashima, Seki, 1975) and the October 1975 issue of Geothermal Energy (Takahashi, Chen, 1975).

Figure 2 is the organizational plan for the Hawaii Geothermal Project task on Geothermal Reservoir Engineering. The emphasis in this report, as will be reported in the section after the next, will be on the left column, well measurement and analysis. However, for completeness, a quick summary will be provided on the three other related areas: physical modelling, computer prediction of well performance, and numerical modelling.

Physical Modelling of Geothermal Reservoir

A two year laboratory modelling investigation is coming to a phase one conclusion. Two models were built, unpressurized and pressurized, both 1 ft high x 1 ft deep x 4 ft wide. Glass beads were used as the permeable medium and tap water (save for self-sealing excursion where sodium borate at saturation was used) served as the fluid.

Modified Rayleigh numbers from 10 to 300 were investigated. Permeability was varied by changing the mesh size of the beads. The heat source varied from point (in 2-dimension) to exponential (2-D) to vertical dike (that is, vertical line in 2-D or vertical plane in 3-D). Temperature profiles were obtained using a bank of resistance temperature detectors wired to a 24-point recorder.

Analysis of the data is proceeding to correlate with the computer modelling program. It is expected that a better understanding of the physical process will result aiding in improved mathematical models.

The possibility of self-sealing was investigated, not to categorically define the mechanism, nor to prove or disprove the probable natural occurrence, but rather to explore significant parameters and suggest avenues for future study.

The long-term physical modelling program envisioned includes the following interacting modes: Ghyben-Herzberg lens dynamics, withdrawal and injection, and varying salinities.

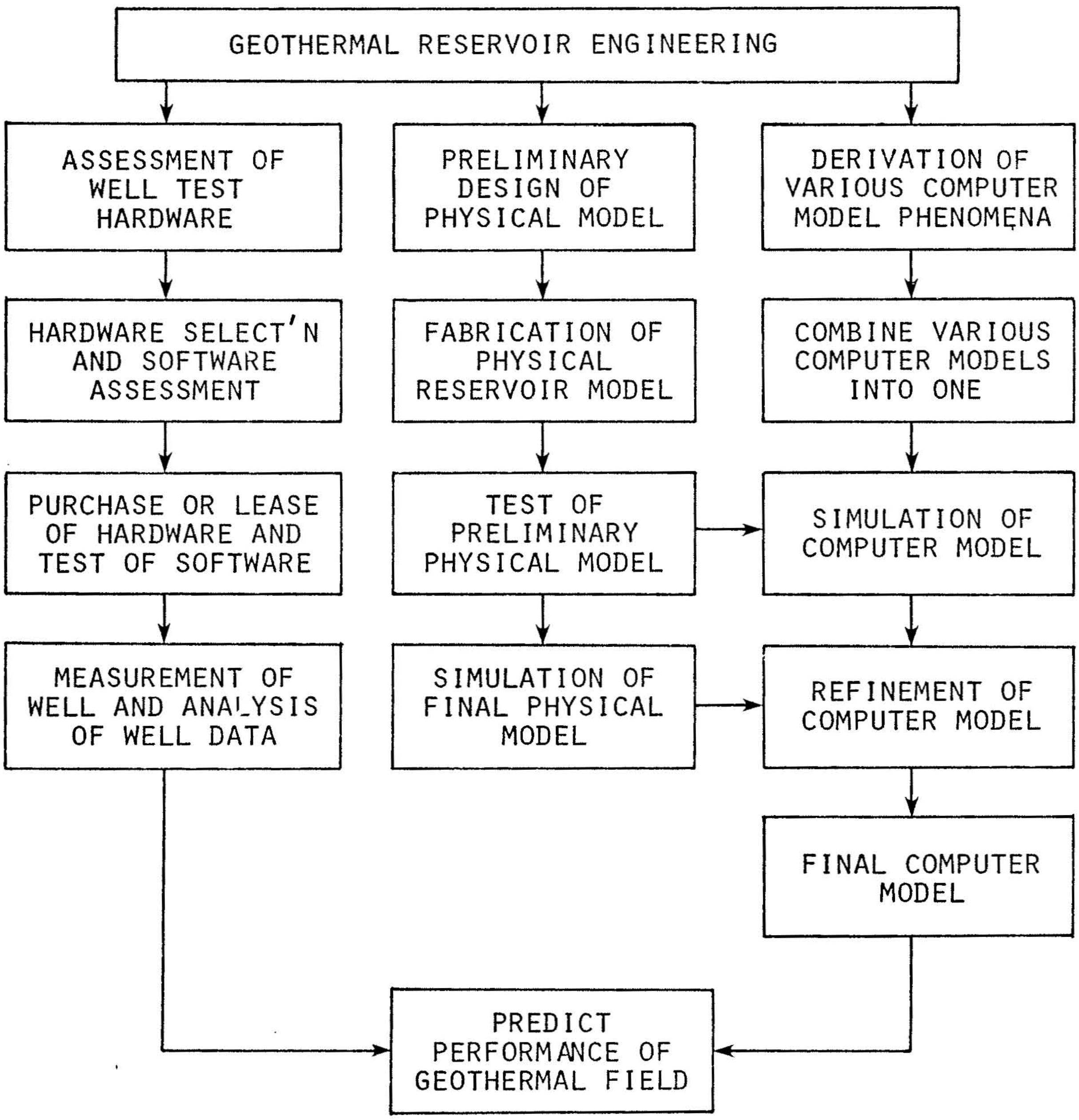


Figure 2. Organizational Plan for the Hawaii Geothermal Project Task on Geothermal Reservoir Engineering

Computer Model to Predict the Performance of a Geothermal Field Given Temperature, Pressure and Flow vs Time Data

The appropriate continuity equations were used to define reservoir properties. Given variations in average formation pressure and cumulative production data, a least squares technique utilizing the Box optimization routine and WASP (Water and Steam Properties code, formulated by NASA) subprogram was used to characterize the geothermal reservoir condition. Having inferentially deduced initial and present conditions, the computer model then suggested alternative means of optimal production for a 30-year reservoir lifetime.

Various parameter sensitivities were checked. New Zealand data was used to verify the model.

Theoretically, given pressure, temperature and flow data vs time, the computer model has the capability of determining initial conditions and predicting field performance of almost any geothermal reservoir: superheated, two-phase, compressed liquid. Unique formation conditions and high salinities have yet to be added to the model and are fruitful areas for future researach.

Numerical Modelling of Geothermal Reservoirs

P. Cheng and K.H. Lau have studied geothermal reservoir conditions through numerical modelling. Although a realistic simulation of the reservoir should take into account rock anisotropy, irregular geometry boundaries, the dynamics of the Ghyben-Herzberg lens and fluid input/output, mathematically, the problem in total is very complicated, involving the solution of a set of non-linear partial differential equations. The strategy adopted by the numerical simulation group has been to study simplified conditions to obtain a qualitative understanding of the physical processes involved. The ultimate model will attempt to predict the performance of a specific geothermal reservoir.

The work accomplished has been well documented (Hawaii Geothermal Project Report to ERDA, pp. 176-177). The following problems were investigated:

1) steady-state free convection in an unconfined rectangular geothermal reservoir
2) the effects of vertical heat sources on the upwelling of the water wells
3) free convection at high (up to 2000) Rayleigh number in confined geothermal reservoirs
4) effects of steady withdrawal and reinjection of fluids in confined geothermal island aquifers
5) finite element analysis of free convection in unconfined geothermal reservoirs
6) analytical studies on heat and mass transfer in liquid-dominated reservoirs.

THE DRILLING PROGRAM

The drill site was dedicated on November 22, 1975, and drilling commenced on December 10. Water Resources International of Honolulu was the drilling contractor, with Kingston, Reynolds, Thom and Allardice of Auckland, New Zealand, providing technical assistance.

HGP-A is located approximately 200 feet north of the Pohoiki Bay Road, 0.23 miles south of the first vents of the 1955 eruption (the well site itself was covered by lava from this eruption) and 25 miles east of Kilauea Volcano. The well-head is located at an elevation of approximately 600 feet above sea level.

The drilling log is summarized in Figure 3. Tungsten carbide insert bits proved to give the best performance. Drilling was completed on April 27, 1976. A depth of 6455 feet was reached.

The casing/liner arrangement is given in Figure 4. Table 2 lists the location of the slotted liners. Typically, the slots were 2" x 1/2", 32 slots per linear foot, and 8.8 ft^2 of open area per 39.51 feet (average length) liner. The liner, with an internal diameter of 7", was placed in an 8-1/2" diameter bore hole.

Mud temperatures during drilling are shown in Figure 5. The mud weighed between 8.8 and 9.4 lb/gal, consisting chiefly of bentonite. Credible analysis of the results is difficult because of coring (mud is allowed to heat up) and the installation of a cooling tower when drilling had reached a depth of 4500 feet. At depth, there was some mud loss at 5968 feet and again at 6330 feet.

Ten cores were taken at the following depths below the rotary kelly bushing (about 15 feet above the surface): 456'-458', 1057'-1068', 1412'-1423', 2230'-2240', 2876'-2886', 3666'-3676', 4447'-4457', 5400'-5410', 6029'-6039', 6445'-6455'. A gross summary of the core analysis is given in Figure 6 (Palmiter, 1976). The high permeability regions are around 2000' and 4000'. Sandy material (hyaloclastite) was observed between 3658 and 3724 feet. All cores below 3280 feet showed some degree of hydrothermal alteration, with calcite and zeolite comprising as much as 15% of the rock between 2300 feet and the bottom (Macdonald, 1976). Secondary chlorite and pyrite are also present.

MEASUREMENT

Temperature and Pressure Measurements

Upon initial completion of the well, Gearhart-Owen electronic equipment was used to obtain: standard E, resistivity, gamma ray, two arm caliper, temperature and cement bond logs. Unfortunately, the capability of this type of equipment is limited by the temperature tolerance of the cable insulation. The limit is 150°C. As a result, the only reliable measurements were obtained down to a depth of 3478 feet (1060 meters).

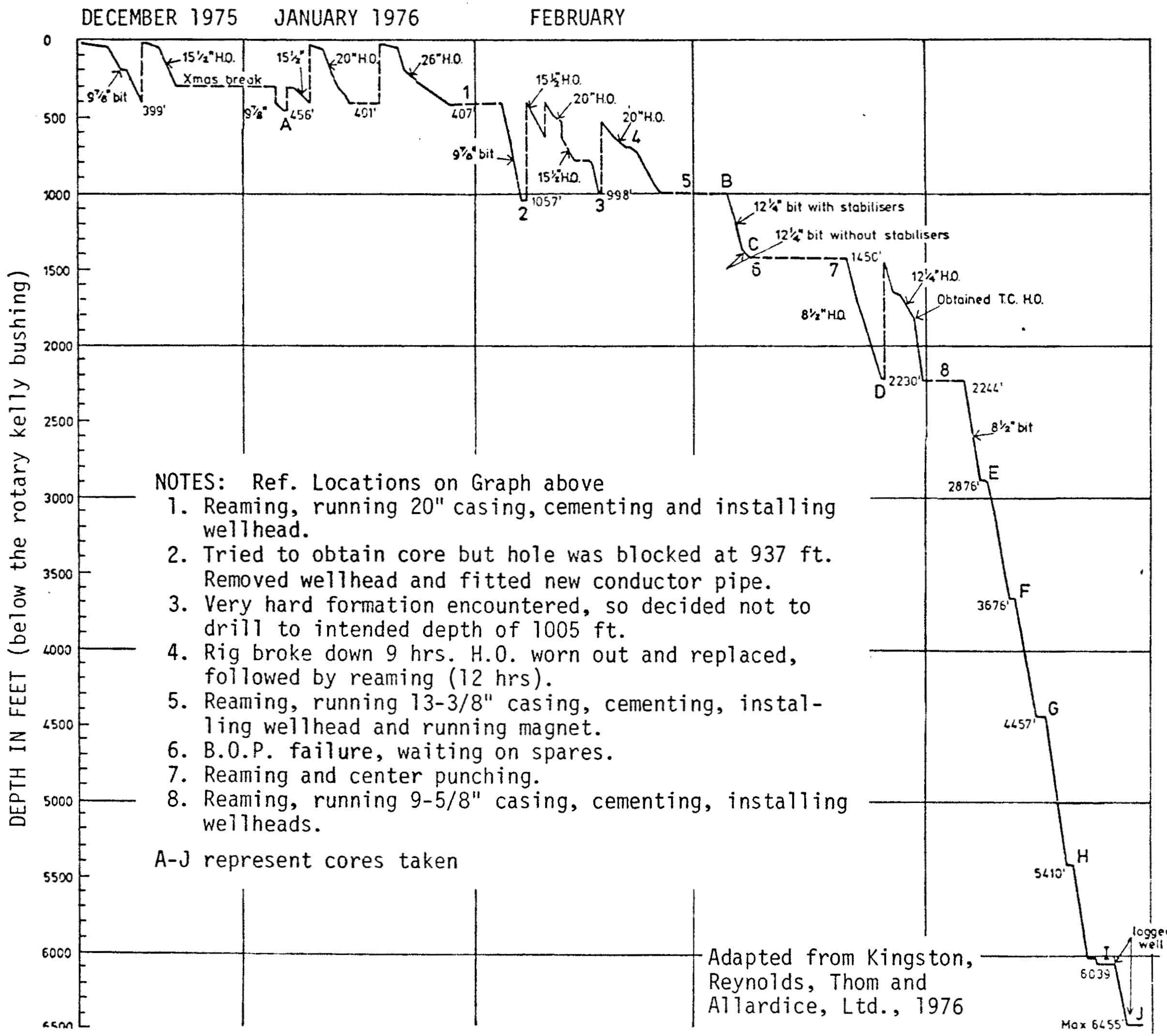


Figure 3. Drilling and Operations Summary

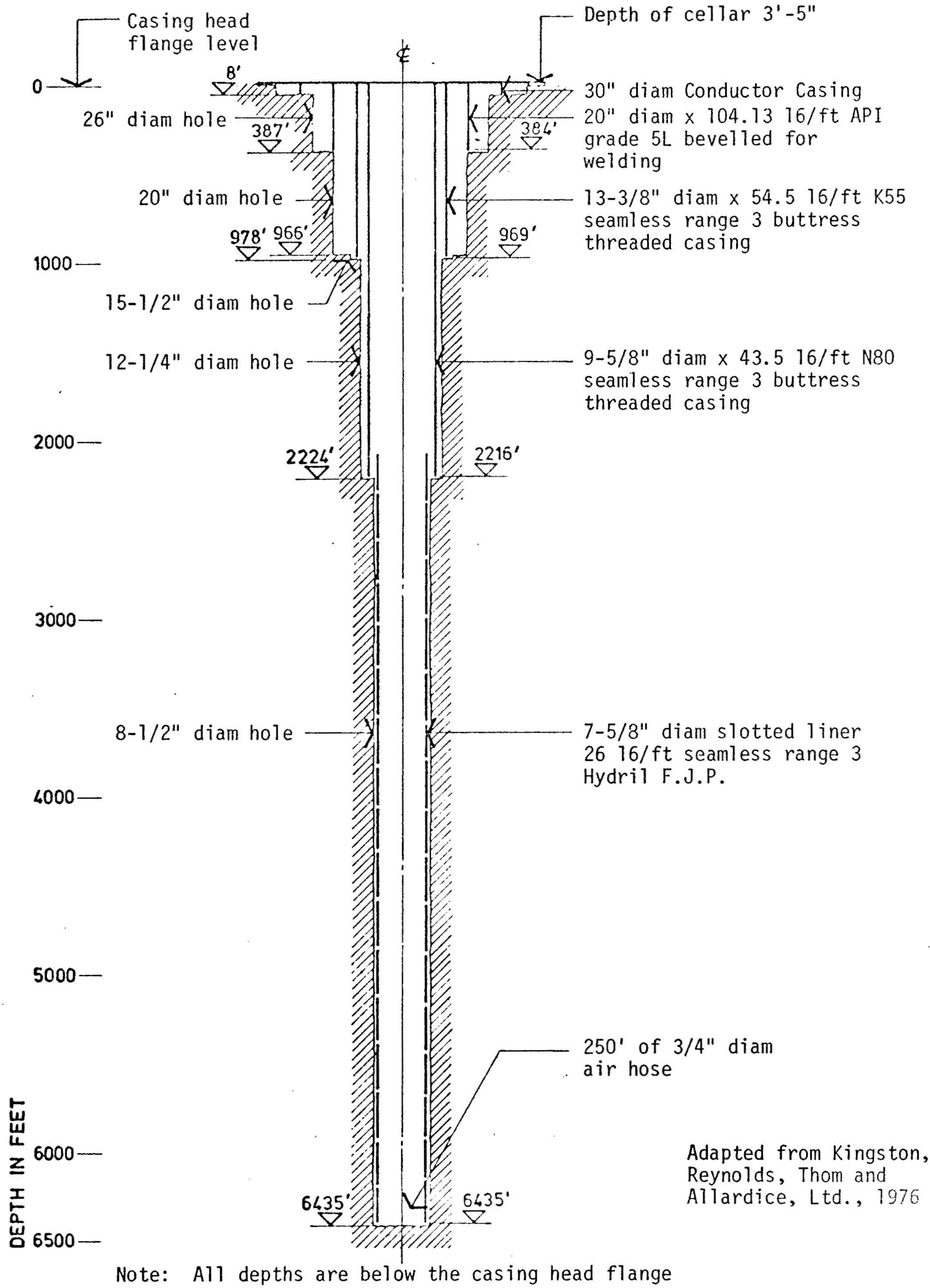


Figure 4. Present Subsurface Well Status

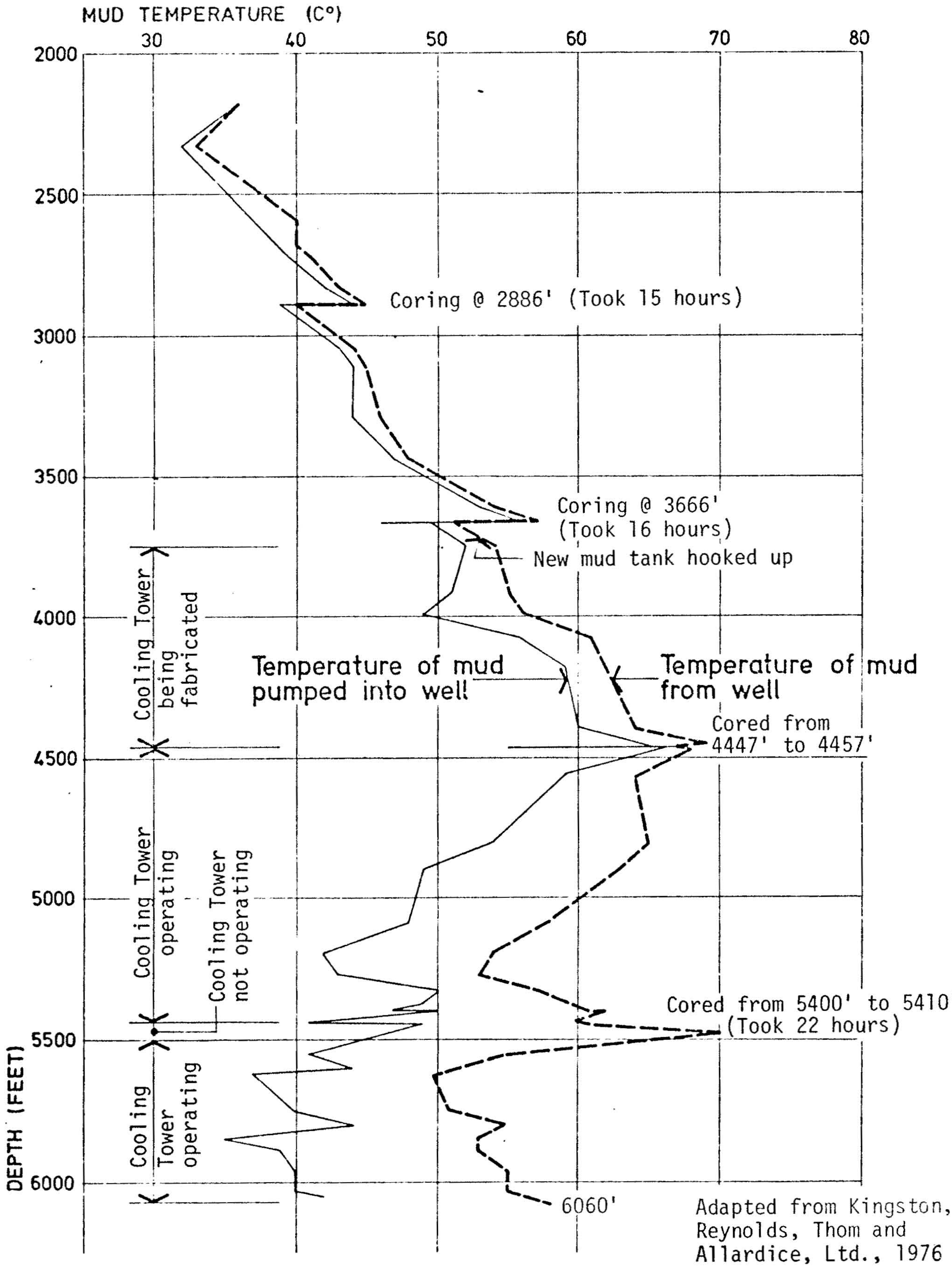


Figure 5. Mud Temperatures

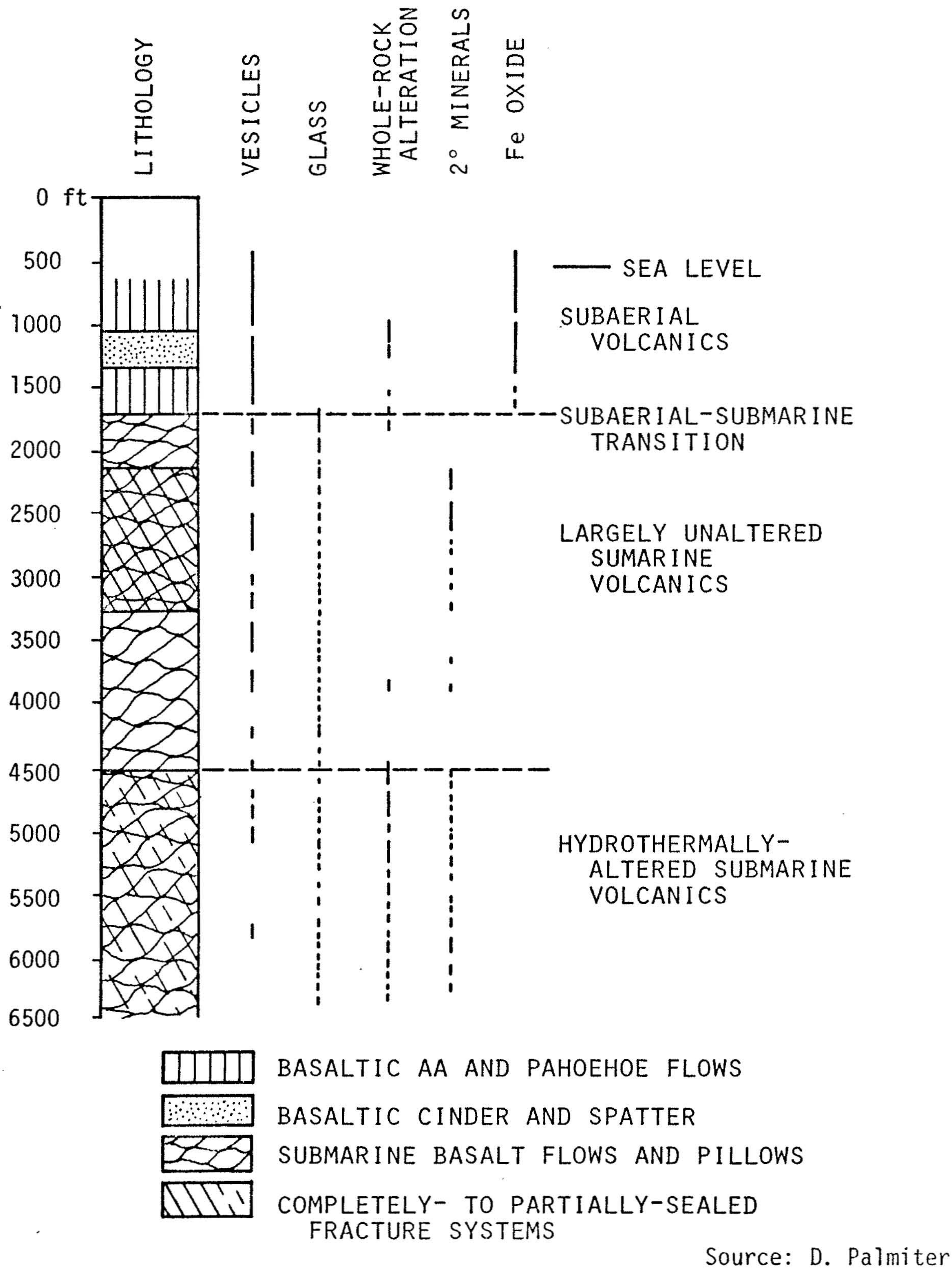


Figure 6. HGP-A Lithologic Log from Cores and Cuttings

TABLE 2

HGP-A SLOTTED/PLAIN LINER LOCATIONS

2146.70'

109		87		65	x	43		21	
108		86	x	64		42	x	20	x
107		85		63		41		19	
106	x	84		62	x	40	x	18	x
105		83		61		39		17	
104		82		60	x	38	x	16	x
103		81	x	59		37		15	
102		80		58	x	36	x	14	
101	x	79		57		35		13	x
100		78		56	x	34	x	12	
99		77	x	55		33		11	
98		76		54	x	32	x	10	x
97		75		53		31		9	
96	x	74		52	x	30	x	8	
95		73	x	51		29		7	x
94		72		50	x	28	x	6	
93		71		49		27		5	
92		70		48	x	26	x	4	x
91	x	69	x	47		25		3	
90		68		46	x	24	x	2	
89		67		45		23		1	x
88		66		44	x	22	x		6455'

NOTE: (1) x = Slotted liner

(2) Joints have been numbered starting from the bottom of the hole

(3) Average length of liner = 39.51'

Kuster mechanical subsurface temperature and pressure recorders were then used to measure downhole conditions. Figure 7 is the pressure recording assembly. The length is 66 inches and diameter is 1-1/4 inches. This type of equipment is said to be capable of operating at temperatures as high as 370°C. However, the clockwork mechanism was occasionally found to break down at temperatures over 300°C. Nevertheless, save for this inconvenience, reliable temperatures were obtained.

Figure 8 is a schematic diagram of the entire operation. The assembly is hooked on to a 0.082" stainless steel wire and placed in the lubricator, which is a device which allows operation of the measurement equipment during flashing. The lubricator is made out of aluminum and is rated at 4,000 psi.

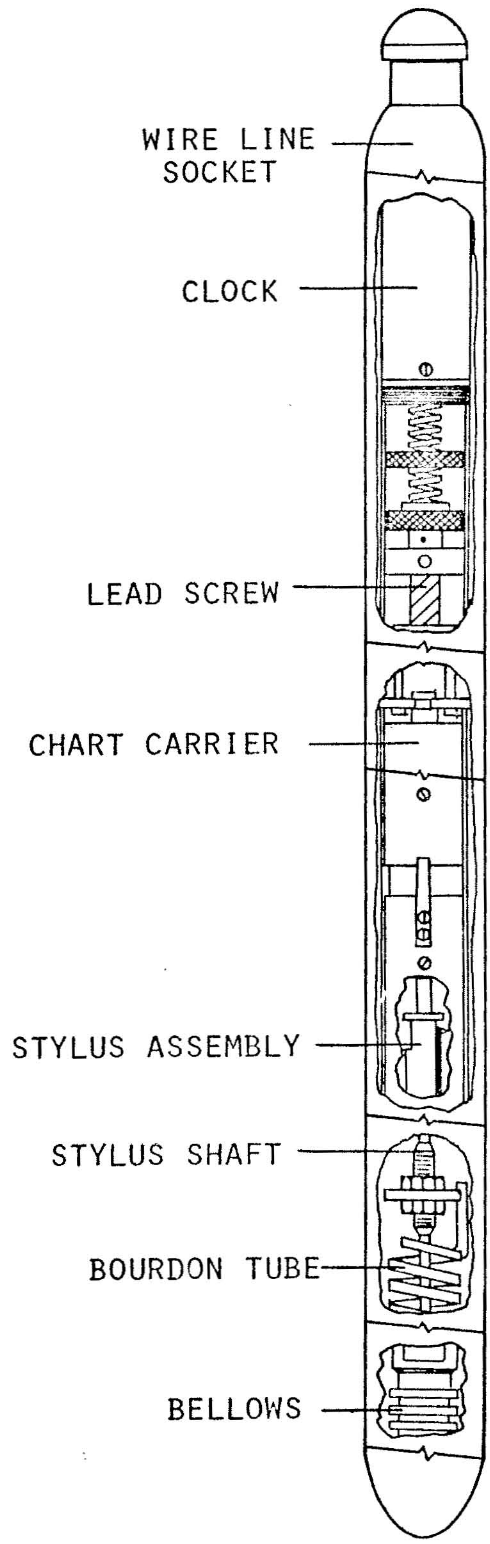


Figure 7. Kuster Pressure Recorder

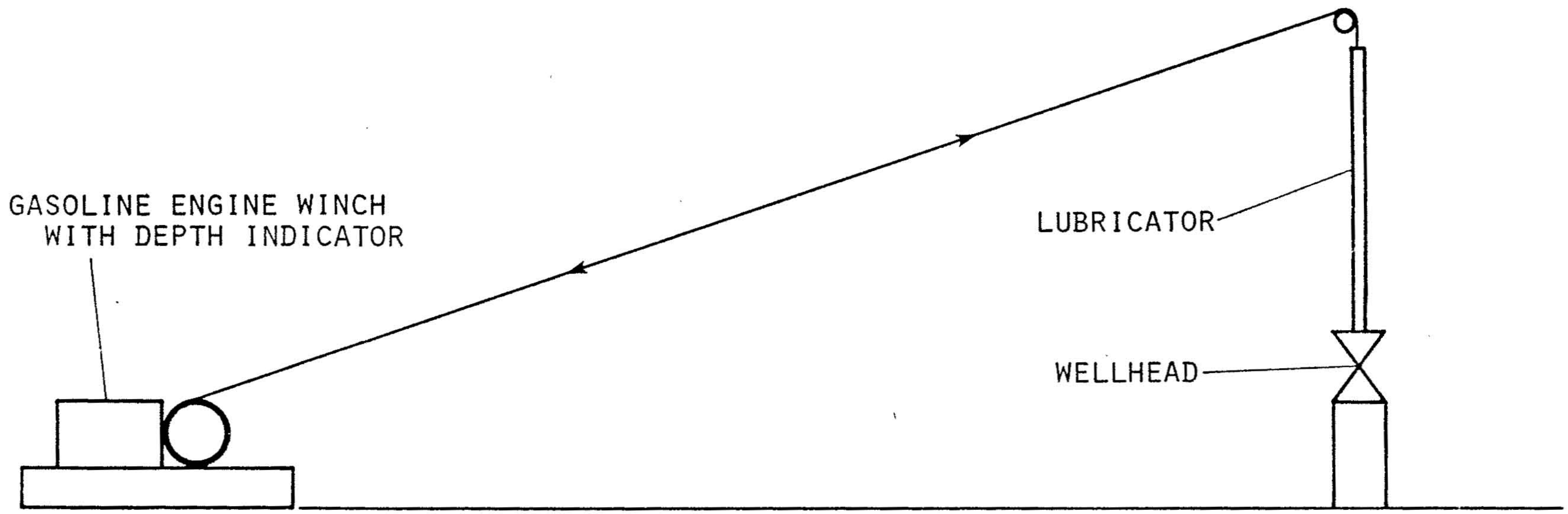


Figure 8. Kuster Measurement Equipment

The wireline is raised and lowered using a winch run by a gasoline engine. A depth indicator is part of the entire assembly. The wire, as purchased for the project, is 10,000 feet in length.

Six clocks -- three two-hour and three six-hour ... three temperature gauges -- 30-275°C, 99-285°C and 200-404°C ... and three pressure gauges -- 0-205 kg/cm^2, 0-185 kg/cm^2, and 0-100 kg/cm^2 ... were ordered to cover ranges likely to be encountered. Pump down tests showed that a 0-300 kg/cm^2 pressure gauge would be another useful pressure gauge.

The zero point was taken to be 7 AM, April 28, 1976, when mud circulation was terminated after completion of drilling. It should be noted that all measurements up to and including May 20, 1976, were taken with mud in the borehole. In Figure 9 the maximum depths at which temperatures were measured give an indication of the rate at which mud caking occurred. Table 3 shows the daily mud loss record. The initial depth of 5950 feet on July 28 was not due to mud caking. The downhole

TABLE 3

MUD LOSS FROM INITIAL COMPLETION OF HOLE

Date	Mud Loss Down Well* in feet/day
April 30	300
May 1	286
2	184
3	186
4	174
5	170
6	146
7	107
8	84
9	67
10	61
11	55
12	49
13	49
14	39
15	37
16	38
17	30
18	30

*Mud was added each morning to bring well to approximately the same level.

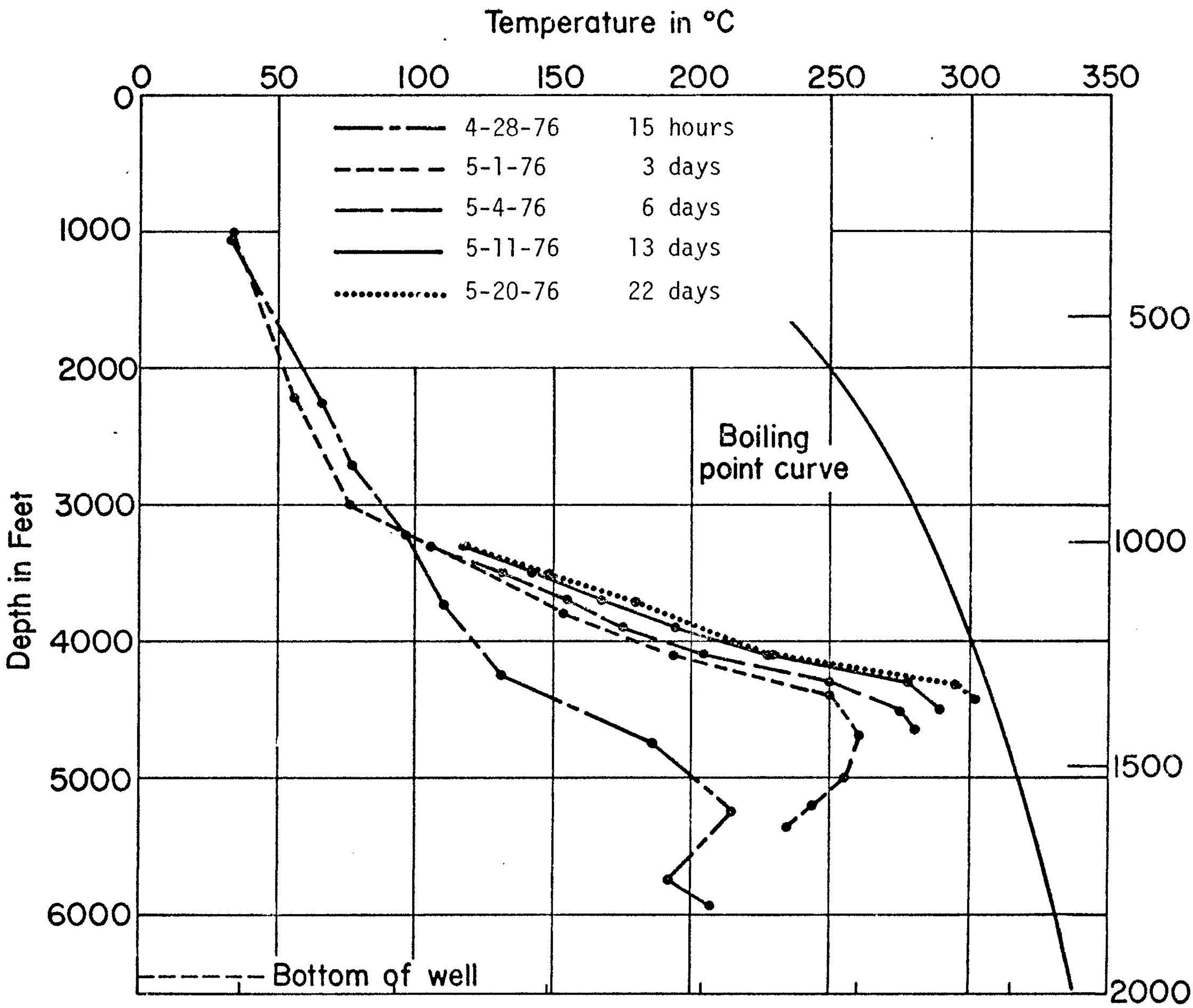


Figure 9. Temperature-Depth Plot for HGP-A (after liner installed)

instruments during this initial measurement phase were lowered using a 3/4" cable, which only had a length of 5950 feet. It was feared that the 0.082" stainless steel wire was not strong enough to pull the assembly up in the event that a cave-in or obstruction of some sort existed, as the liner had not been installed yet.

The liner was installed on June 4-5, the borehole was washed and 8:30 PM, June 5 was taken to be the new zero time. A temperature-depth log was made 12-1/2 hours after washing, shown in Figure 10.

Pump Down Test

A pump down test was run on June 6 and 7. A summary is given in Table 4.

TABLE 4

SUMMARY OF PUMP DOWN TEST

Date	GPM	Time of Flow (minutes)	Volume (gal)	Back Pressure (psig)
June 6	340	46	15,640	700+
June 6	108	105	11,340	500+
June 6	108	60	6,480	500+
June 6	200	55	11,000	600+
June 6	300	70	21,000	700+
June 6	530	10	5,300	750+
June 6	630	7	4,410	800+
June 6	300	8	2,400	700+
June 6	200	5	1,000	600+
June 6	100	6	600	500+
June 7	300	3	900	---
June 7	100	180	18,000	300
		TOTAL	98,070 gal	

Theoretically, the rise in pressure between 0 and 300 gpm can be used as an indication of permeability. According to New Zealand specialists, a rise of (KRTA, 1975):

20 psi or less = high permeability
up to 75 psi = moderate permeability
over 150 psi = very poor permeability (non-producing well)

However, it is reported that erroneous results can be obtained if drilling mud is blocking flow paths.

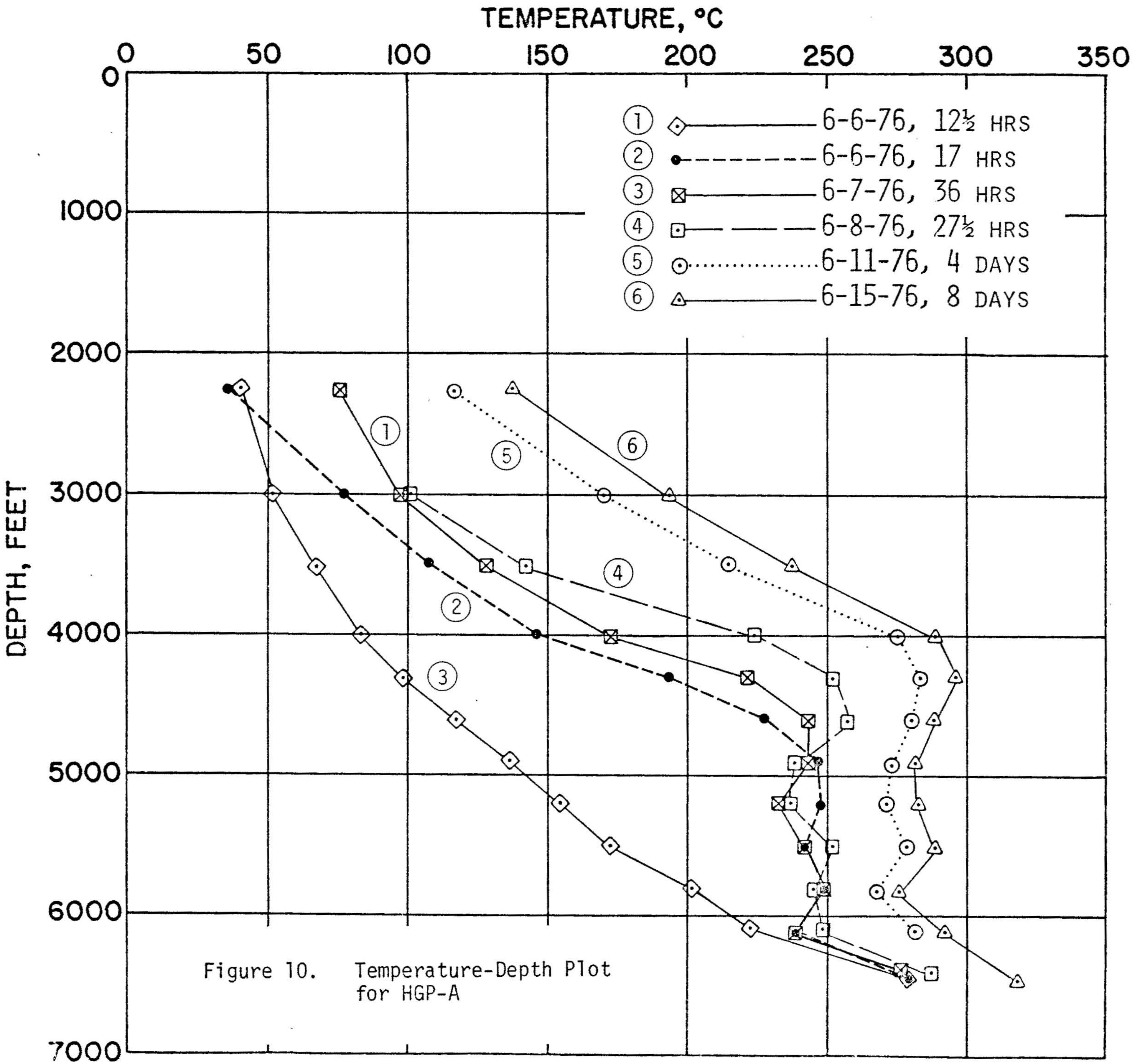


Figure 10. Temperature-Depth Plot for HGP-A

If back pressures of over 150 psi indicate the presence of a non-producing well, it seems discouraging that at 300 gpm the back pressure was in excess of 700 psi. However, three qualifying factors could be of import. First, mud caking could have damaged the well. Secondly, there was a decrease of more than 200 psi in back pressure of the 100 gpm flows on June 6 and June 7. There is speculation that either the extremely high (530 and 630 gpm) pumping rates caused some hydrofracturing of the mud cake or formation, or the overnight layover caused thermal fracturing. The latter might be the more important cause because 300, 200 and 100 gpm flow rates were run immediately after the high flow rates, resulting in essentially the same back pressures as before. Finally, the flash test a month and a half later showed that 100,000 to 200,000 lb/hr flows could be achieved.

The temperature profile following the pump down test is shown in Figure 10. Recovery was quite rapid.

Noise Control

During the 50 minute flash on July 19, noise measurements were made at the following locations:

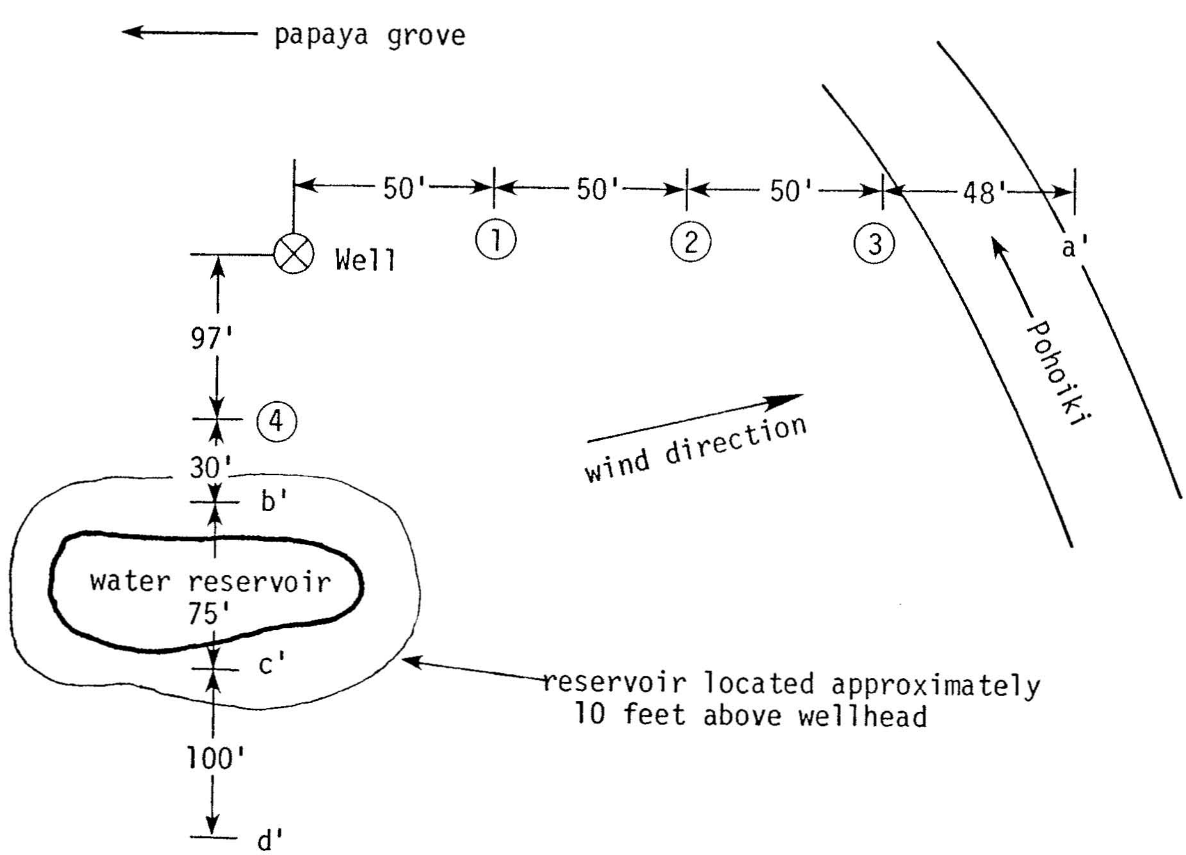


Table 5 summarizes the results.

TABLE 5

NOISE MEASUREMENTS

July 19, 1976

Vertical Discharge (discharged at 12:42 pm)

position	sound level (dBC)	time
1	94	12:42
2	100	12:42
3	105	12:43
4	113	12:44
1	125	12:44
2	125	12:45
3	122	12:45
a'	122	12:46
4	124	12:47
1	124	12:49
2	122	12:49
3	120	12:50
4	122	12:51
1	125	12:52
2	117	12:52
3	117	12:43
4	119	12:54
b'	112	12:58 (113, 1:03)
c'	107	12:59
d'	91	1:02
1	119	1:05
2	114	1:06
3	113	1:06
4	116	1:04

Horizontal Discharge (93 dBC, 2" discharge @ (1))

position	dBC	time
1	113	1:25
2	111	1:25
3	112	1:26
4	116	1:27
b'	108	1:28

Vertical Discharge

1	117	1:56
2	112	1:56
3	112	1:57
4	113	1:52

Flash Test

Air lifting was used to artificially induce the well to discharge. A complete log of fluid conditions during this phase can be found in the data for June 30 to July 2. Two 100 psi, 175 cfm air compressors were used to accomplish this task.

In air lifting, air is injected into the water column causing it to expand and the fluid level to rise eventually reaching the surface. The compressor back pressure and flowrate necessary to stimulate flashing depend on the depth of the water column from the surface and the actual underground temperature conditions. In short, as fluid is discharged at the surface, the water column is raised. Eventually, a portion of the column at depth will reach the boiling point temperature and flash. The water column density then is even further lowered allowing more water to flash into steam, and the process continues so that flow now proceeds without the aid of the air compressor.

On July 19 the well was flashed for 50 minutes, on July 21 for 30 seconds and on July 22 for 4 hours. Surface measurements of lip and well pressure and wellhead temperature were taken. Figure 11 is a plot of lip and wellhead temperature vs time and Figure 12 lip and wellhead pressure vs time.

The enthalpy was estimated to be 600 Btu/lb. Using the Russel James formula (James, 1970),

$$G = \frac{11{,}400\ P_c^{0.96}}{h_o^{1.102}}$$

where G = flowrate in lb/(ft^2-sec)

P_c = lip pressure, psia

h_o = stagnation enthalpy, Btu/lb

for a 6" pipe at a lip pressure of 23 psig, the flowrate is 227,880 lb/hr. The equivalent electrical production rate is about 5 megawatts.

If 1000 Btu/lb is used as the stagnation enthalpy, a flowrate of 129,842 lb/hr is calculated. However, the potential electrical production is now 7 Mw, because of higher steam quality (80% vs 38%).

Immediately after flashing, temperature and pressure measurements were obtained as shown in Figure 13.

Figure 14 is the temperature vs depth plot for HGP-A immediately after flashing, one week, two weeks and three weeks later. There was rapid temperature recovery.

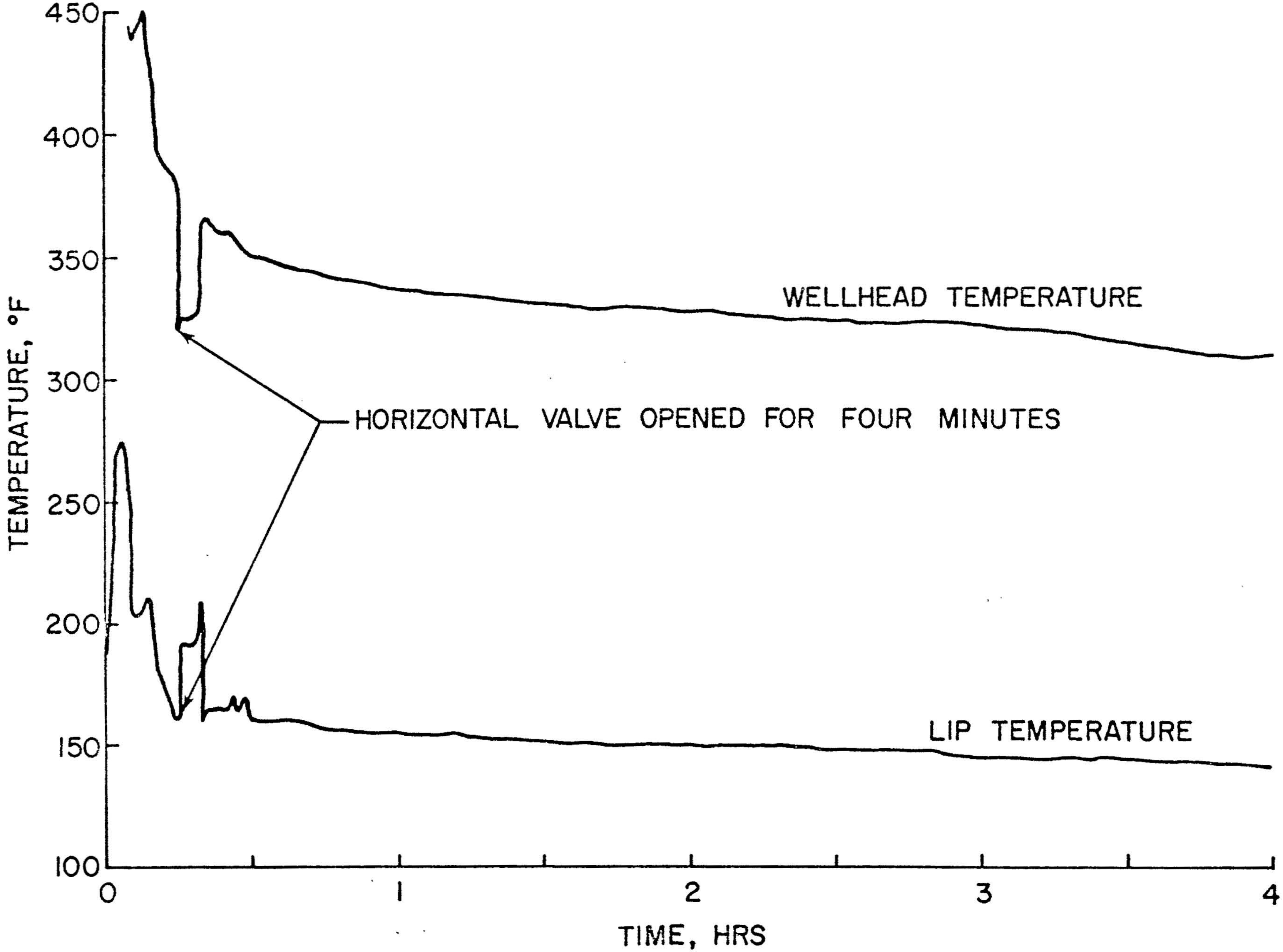


Figure 11. HGP-A Flow Test, July 22, 1976
Variation in Wellhead and Lip Pressure with Time

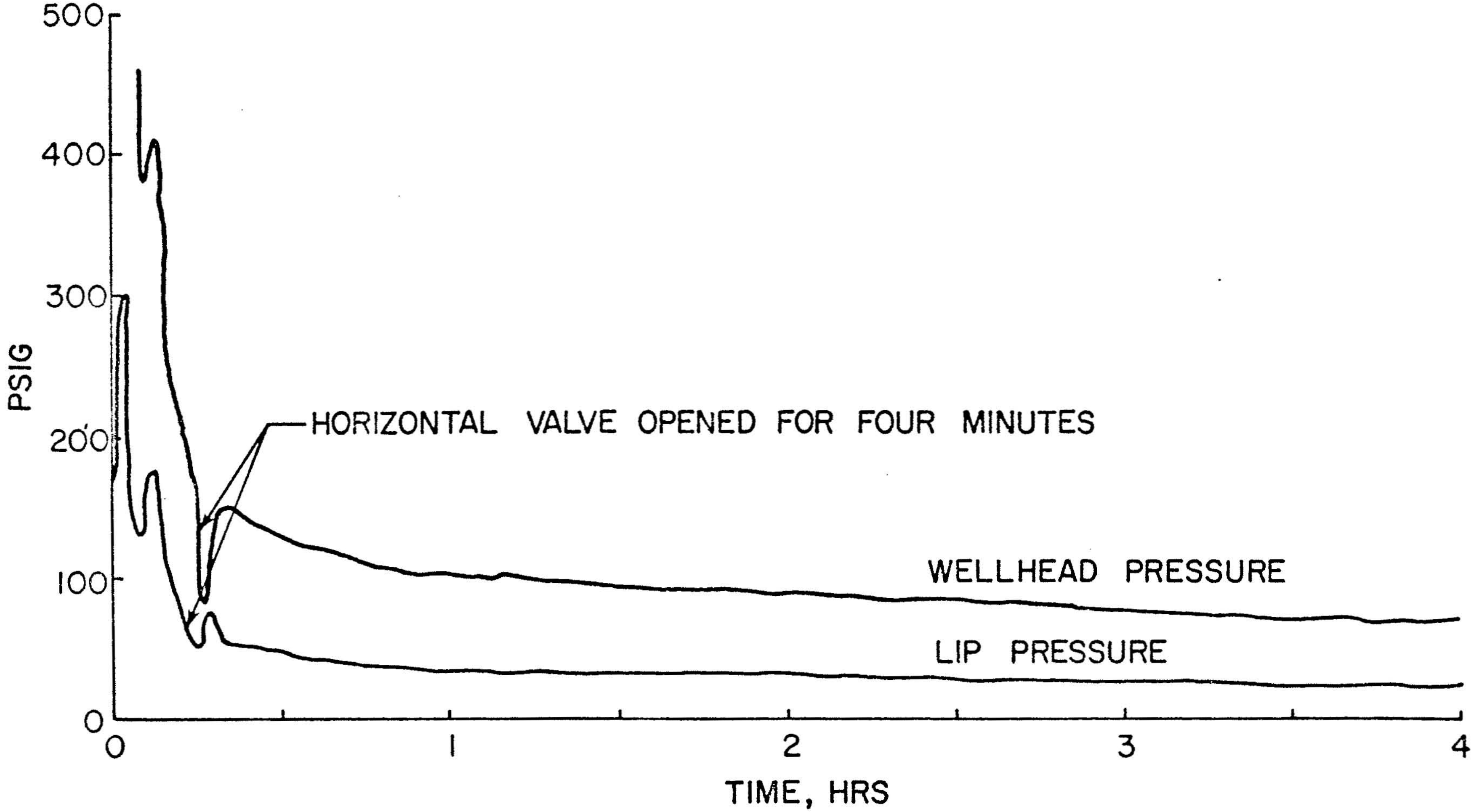


Figure 12. HGP-A Flow Test, July 22, 1976
Variation in Wellhead and Lip Temperature with Time

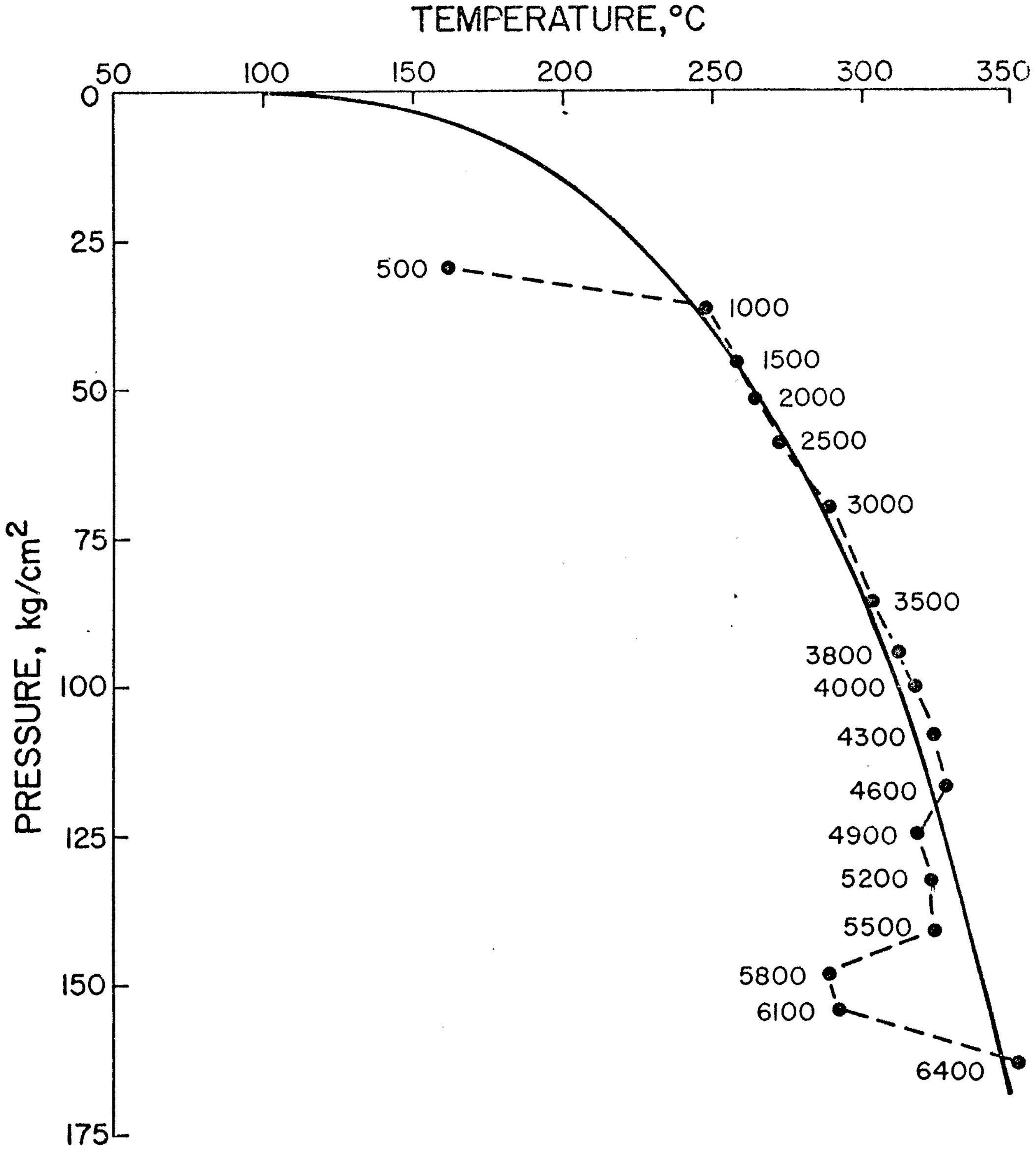


Figure 13. Temperature vs Pressure for HGP-A, July 22, 1976
After Four-Hour Discharge

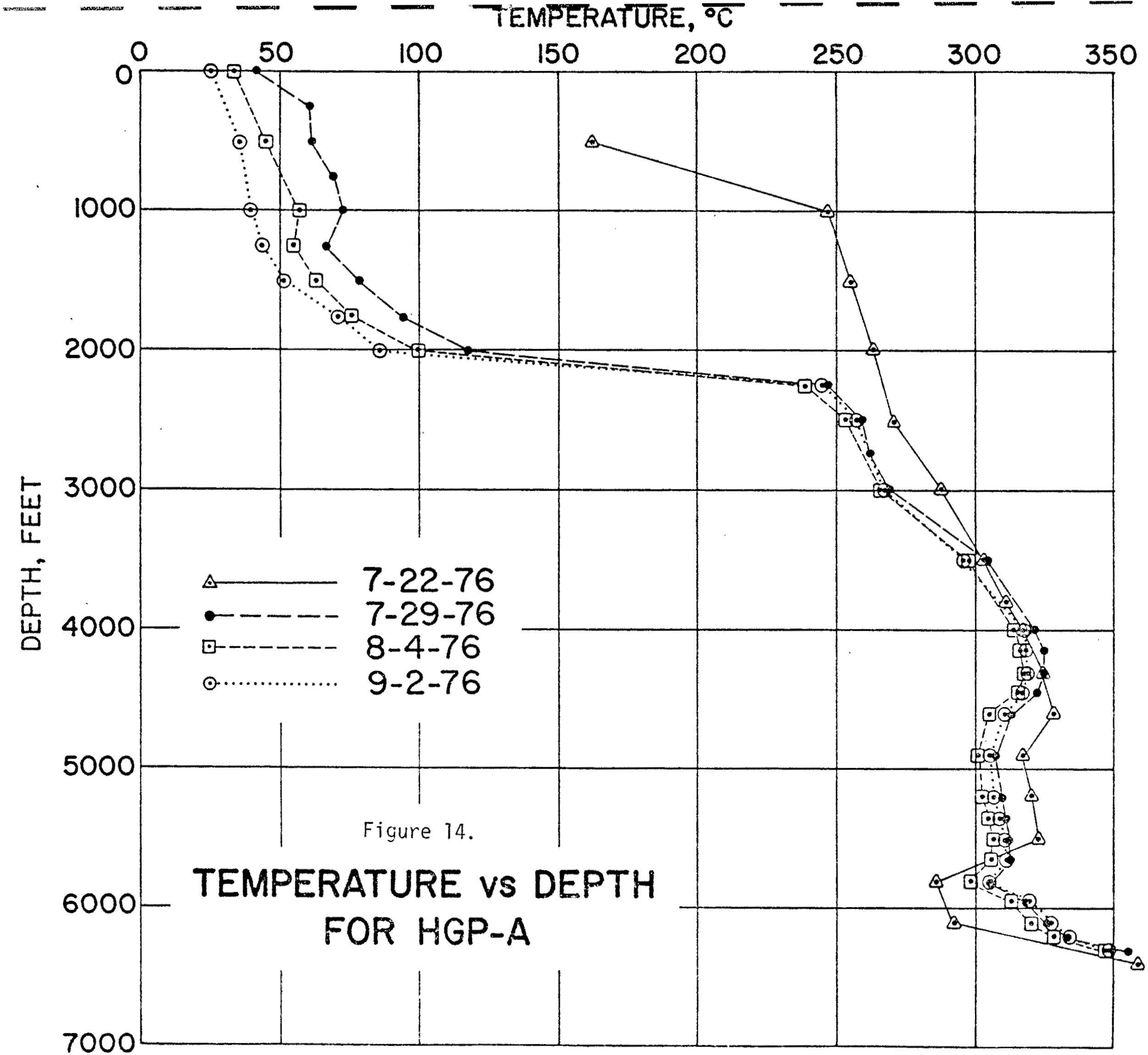


Figure 14.

TEMPERATURE vs DEPTH FOR HGP-A

Water Quality Measurements of HGP-A Well Waters

(Kroopnick, Lau, Thomas, Buddemeier, and Siegel, 1976)

Surface water samples have been collected since the well first flowed on June 24 (Table 6a). The water has a low chloride ion concentration but very high silica value. The concentration of silica and possibly other water quality parameters is caused by high temperature exchange with the host rocks. The geochemistry of the rock-water interactions will be discussed in more detail after the analyses of the cores is completed.

Downhole samplings have been conducted on three separate occasions to characterize the water quality variation with depth before well flash and to ascertain the depth zones of active recharge (Table 6b). The samples were collected using a Klyen sample bottle which is designed to collect downhole water at temperatures lower than actually encountered in this well. Despite attempts to change the gaskets the sampler still occasionally leaks, as noted in Table 6b. Figure 15 is a diagram of the sampler. The downhole data show that the low pH ($\sim$2) is consistent with high values of sulfides (up to 370 mg/l). Silica values as high as 630 mg/l were encountered. Dissolved mercury is exceedingly low (<1 μg/l) except at the 100 ft level. The majority of the mercury present is in the particulate fraction. Rock samples cored from the bottom of the cased part of the well (2270 ft) also had a very high mercury content of 244 μg/Kg compared to about 70 μg/Kg for the rest of the cored samples (Table 6c).

The above data, a single tritium water age, pre-flash well head evidence of the water level, and related general geology known for the area, support the following conclusions:

1) There are likely dikes or dike-like impermeable subsurface formations located between the ocean and the HGP-A well. The occurrence of dikes would account for the low salinity, chloride and electrical conductance measured in the well water.

2) The HGP-A well water is drawn in part from dike impounded high-level ground water which is recharged by recently infiltrated rain water. The annual rainfall for this area is on the order of 125 inches and furnishes a sizeable source of fresh water for groundwater recharge.

3) The HGP-A well water would derive its salinity and other water quality parameters from other sources than from the percolating rain water alone. The geothermal source that heats up the HGP-A well water evidently can help create these sources; the possibility of contact with unknown saline water sources cannot be excluded at present.

Upon arrival at sampling station the suspension wire is vigorously shaken with consequent oscillation of inertia mechanism. As striker fractures break-off tube the non-return valve is opened under bore pressure with piston depressed into wider diameter portion of valve chamber. As sample vessel fills and exterior and interior pressures equalize valve spring pressure closes bottle.

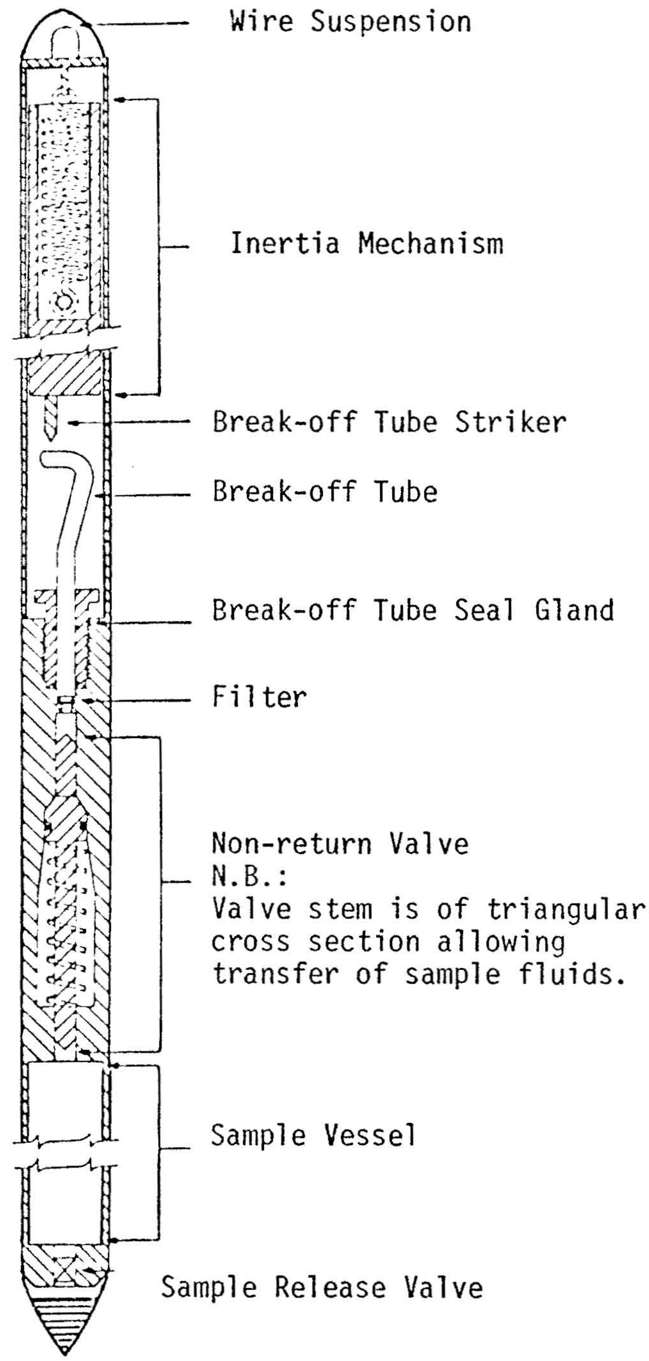


Figure 15. Klyen Deep Well Subsurface Sampler

TABLE 6a

MAJOR ION CONCENTRATIONS (mg/1) OF SURFACE WATER SAMPLES

	#	pH	Cl	SO_4	CO_3	Na	Mg	Ca	K	SiO_2	Hg (μg)	^{18}O(‰) SMOW	$S^=$	F	T
Seawater 1‰			553.0	77.5	4.1	307.0	37.0	11.8	11.1	3	0.06				
Water used in drilling	I-1		6.3	16.1	0.6	15.8	1.8	2.1	2.7	35.6	3.5	-			
First H_2O flow 06-24-76 I-2 I-5 I-9	ave.		552.0	176.0	1.0	407.0	1.2	5.0	52.0	-	0-6 (I-5)	-			
After steam 07-03-76	II-1	6.5	610.0	160.0	45	350	-	-	-	151	0	-		0.8	7 T.U.±2
Before flash 07-22-76;11:15	G1-A		757									-3.7_{steam}			
Just before production 07-22-76;13:40	G1-B											-2.0_{H_2O}	300		
1 hr into test 07-22-76;15:30 condensate	G1-C		94.5			50.9		1.3	7			-6.5_{steam}	110		
After production test 07-23-76;09:20	G1-D	6.6	166	72	133					220		-3.9_{H_2O}	626		

Sample II-1 of 07-03-76: Nitrate = 0.04; total solids = 2322; suspended solids = 289; volatile solids = 34; turbidity (NTU) = 85.

TABLE 6b

HGP-A DOWN HOLE SAMPLING
August-October 1976

Depth (ft)	Date	pH	Cl (ppm)	Conductance (μmho-cm)	Si (ppm)	$S^=$ (ppm)	Total Hg† (μg/l)
Surface	08-04-76	5.1	880	3050	-	-	-
	08-19-76	5.2	1000	3250	370	-	-
1,000	08-19-76	5.6	830	2700	210	190	44.4
	10-12-76	4.9	725	1980	220	250	26.3
2,270	08-17-76*	5.3*	950*	3200*	300*	-	2.4
	10-12-76	1.4	730	3450	620	-	3.6
	10-30-76	2.3	685	3650	630	210	-
3,000	08-18-76	2.3	710	4450	530	-	-
4,300	08-19-76*	5.3*	900*	2950*	270	300*	3.5
	10-29-76	2.7	685	2700	630	210	-
5,500	10-12-76*	1.9*	735*	3050*	650*	-	7.5*
5,800	08-19-76	2.5	800	4400	340	-	3.2
	08-19-76	3.5	780	2550	430	-	-
	10-29-76	3.4	850	2600	630	210	-
6,300	08-19-76	3.0	660	2800	190	-	1.6
	10-30-76	3.5	440	1650	630	370	-

†∿85% as particulate except at 3000 and 4300 feet where particulate: soluble ratio is ∿1:1.

*Due to the extremely high down hole temperature we suspect that the "Klyen" sample bottle occasionally leaks.

TABLE 6c

MERCURY CONTENT OF HGP-A CORE SAMPLES

Depth (feet)	Mercury (μg/kg)
456	46
1057	98
1412	100
2230	68
2231	125
2876	244
2877	56
3666	70
4447	62
5396	80
6029	28
6446	88

PRELIMINARY RESERVOIR ANALYSIS OF HGP-A

As of October 31, 1976, flash discharge occurred four times -- for periods of 4 minutes, 50 minutes, 30 seconds, and 4 hours. There is general agreement that years of well-documented data from several wells within the same geothermal field are necessary to understand performance.

It is understandable, then, that the analysis for HGP-A can, at this time, only be preliminary and superficial. However, the following analysis is offered to stimulate discussion. Readers are urged to contact the authors of this report to share their ideas so that better understanding can be achieved.

Wellhead and Formation Pressure Analysis

With respect to water level in HGP-A, before flashing, the average temperature of the fluid in the reservoir was about 150°C -- after flashing, the average temperature rose to about 250°C -- the volumetric expansion of the same mass of water from 150°C to 250°C represents an increase of about 15%. The water level previous to flashing was approximately 150 feet below the wellhead. The volumetric expansion percent necessary to expand the fluid in the 6450 feet deep borehole from 100 feet below the wellhead to the wellhead amounts to 2.3%. It therefore appears that simple heating of the borehole water resulted in raising the water level to the surface ... heating alone accounts for seven times the volume necessary to lift the water level 100 feet.

There was some belief that artesian action was responsible for raising the water level from sea level, or 600 feet below the wellhead, to the 150 feet mark, but that this same action was not the cause of a subsequent (after flashing) lifting of an additional 150 feet plus 77 psig pressure at the wellhead. (77 psig, incidentally, represents 177 feet of water.) It remains open to speculation, though, that flashing could have caused thermal cracking of the underground system, thus allowing a new artesian source to impact the borehole.

There was initially a rapid increase in wellhead and lip pressure during the four hour flash. Figure 16 is the approximate boiling point curve for the final data taken on June 30, 1976, three weeks before the four hour flash test. (Quasi-equilibrium had been reached.) The process of flashing both:

1) raised the fluid temperature curve -- the result of flowing is a lifting of the fluid in the borehole ... the incoming fluid enters the well in regions of high permeability -- in the 3800'-4800' region the average reservoir temperature is 320°C, and even at the very bottom of the casing, 2250', the reservoir temperature appears to be 250°C (the presumption here is that the casing is intact, i.e., no leakage of cold water into the wellbore) and
2) lowered the boiling point curve -- the fluid density was reduced through the combined effect of higher fluid temperatures and two-phase conditions (a steam quality of only 10% at 250°C increases the total steam-liquid volume by about a factor of five).

Therefore, the initial high pressure was caused by flashing in the wellbore, probably initially at around 4000 feet, plus emptying of the well.

The wellhead and lip pressures fell during the four hour flash test. There was no consensus as to why, but one explanation is that the relatively low permeability (as was indicated during the water pumping test) restricted flow of fluid into the wellbore. The result would then be reduced flow at the wellhead with the resultant pressure drop.

There is a competing analysis (and process) which states that as the fluid mass flow rate decreases, there should be a reduced pressure drop along the wellbore, and therefore, the result should be increased pressure at the wellhead. An attempt at explaining this apparent contradiction follows:

1) The controlling mechanism is the pressure drop across the low permeability rock formation (chimney region) immediately adjacent to the bore. The pressure drop along the wellbore is relatively small compared to the former. Thus, regardless of flow rate, the low permeability rock (which could be caused by caked mud) controls the flow, and therefore, pressure.
2) As the flowrate dropped, although the bore system experienced a reduced pressure drop, the cause of the lowered flowrate was the chimney impermeability. The fluid in the rock adjacent to the wellbore was depleted with

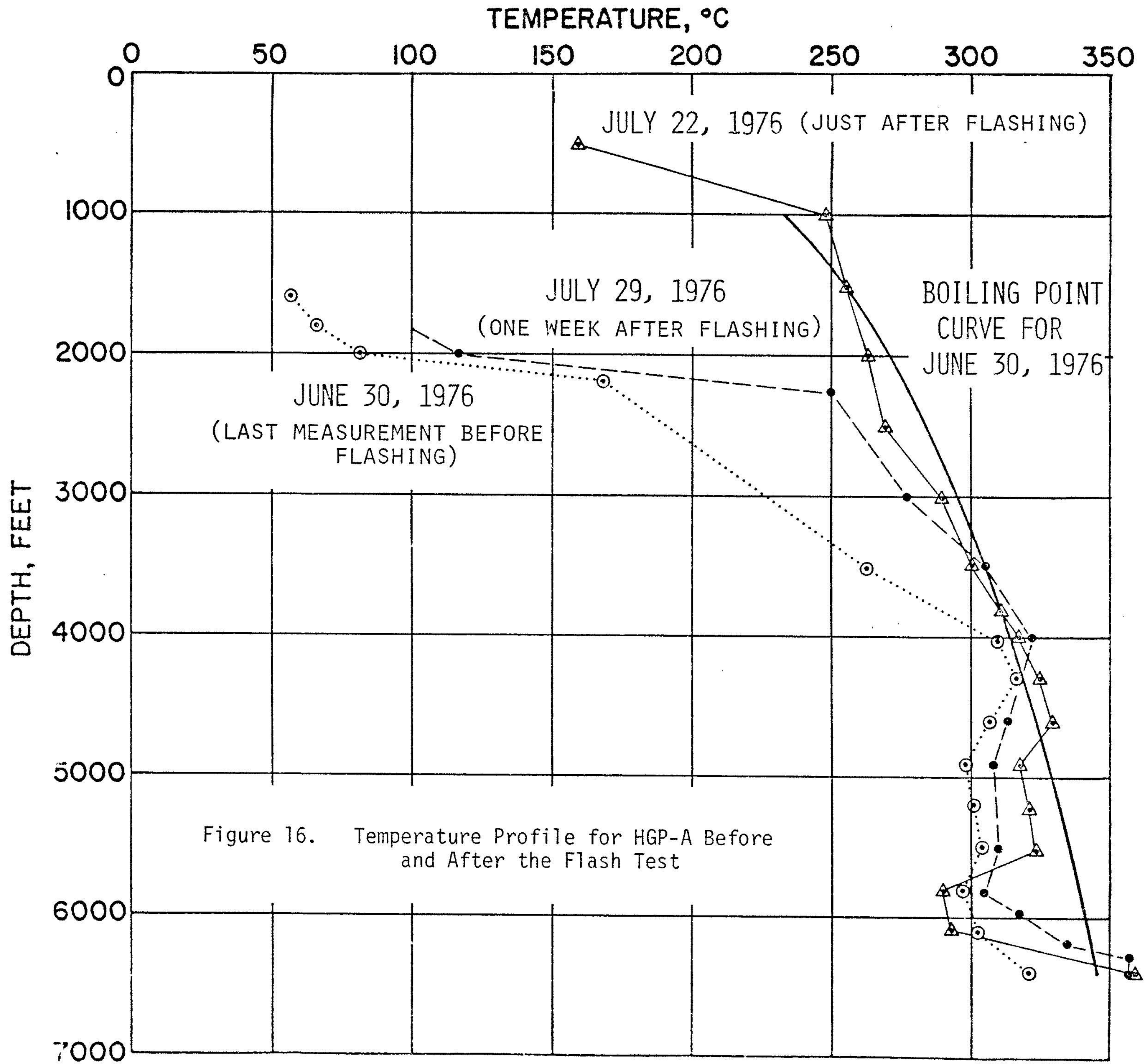


Figure 16. Temperature Profile for HGP-A Before and After the Flash Test

time and fluid had to travel longer distances at increased overall system pressure drop to enter the wellbore.

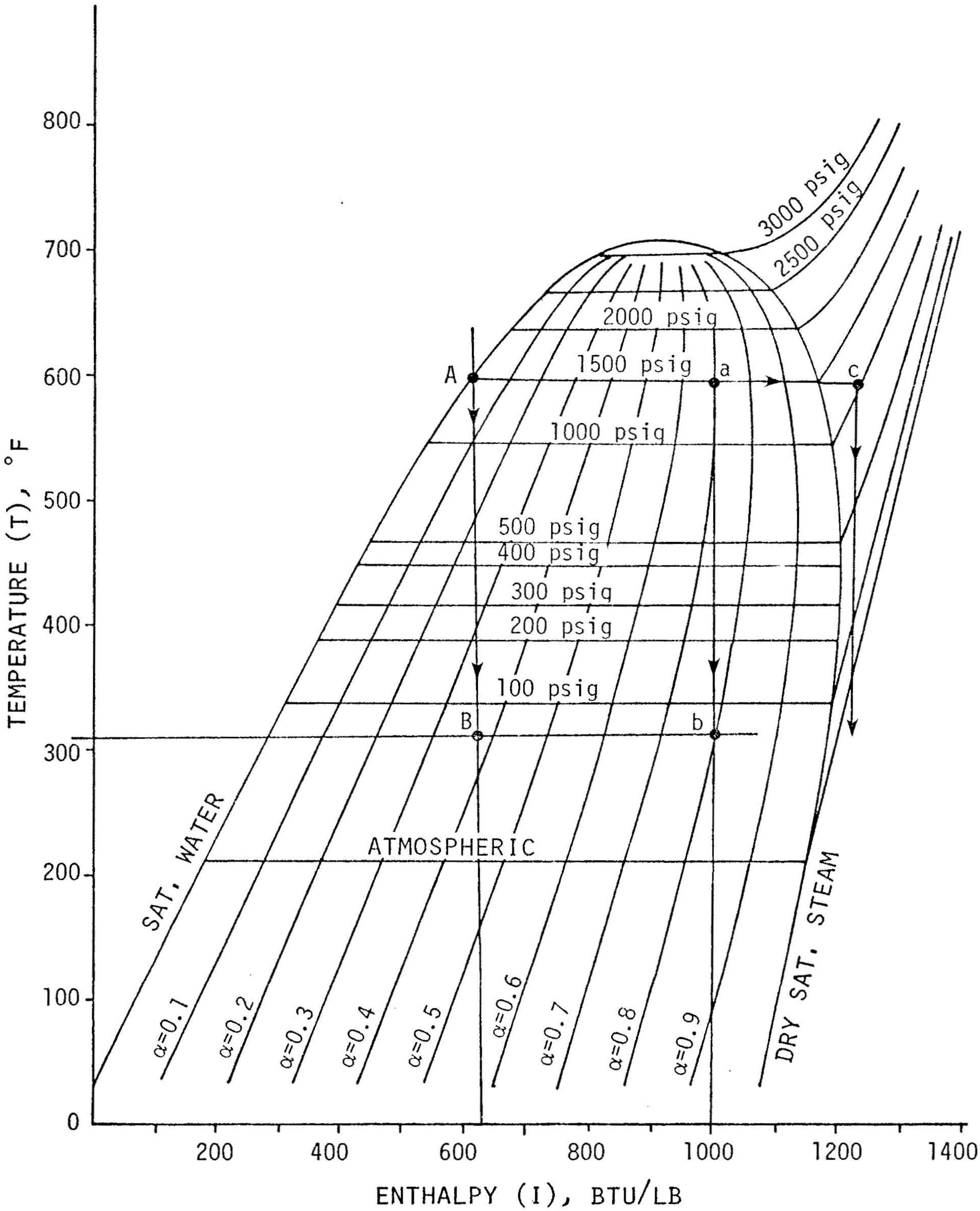
The key question is, "When will the total system reach reasonable equilibrium?" The calculated flowrate using R. James' lip pressure method was 227,880 lb/hr if the fluid enthalpy was 600 Btu/lb, or 129,842 lb/hr if a 1000 Btu/lb enthalpy prevailed. If the fluid flashed in the wellbore, the 600 Btu/lb enthalpy shou[illegible]e correct. If the fluid flashed in the reservoir, the 1000 Btu/lb enthalpy co[illegible] be correct. The latter case is appearing to be the most favored speculation at this time, as there was no "rainfall" effect of the plume, indicating that the enthalpy must have been around 1000 Btu/lb. In any case, the matter of what the enthalpy is or where flashing is occurring can be checked:

1) enthalpy -- calorimeter at surface
2) flash depth (location -- downhole pressure vs depth measurement during flashing.

Temperature Analysis

There is general agreement that not long (perhaps a couple of hours) after initiation of flow, the region close to the well approximately reaches equilibrium. The fluid flow through the wellbore can then be assumed to be isenthalpic (constant enthalpy, that is, no heat loss or gain through the well casing/liner). Four possible explanations can be offered on why the wellhead temperature was so low relative to the bottomhole temperature.

1) Figure 17 is a typical enthalpy/temperature chart (Armstead, 1976). In either case, 600 or 1000 Btu/lb, the initial conditions can be shown to result in the final wellhead conditions. If flashing is in the wellbore, and if it can be assumed that the producing region is between 3800 and 4800 feet, the average temperature is 320°C. The enthalpy is thus 628.8 Btu/lb (see A in Figure 17). (Point A need not necessarily be on the saturation line, as compressed liquid conditions could prevail.) As flashing eventually occurs somewhere in the wellbore, the steam quality increases from zero to about 38% at the wellhead. The resultant pressure is 63 psig as shown by point B. If the 1000 Btu/lb enthalpy is correct, then point a is one possible starting point. However, for this point, the steam quality is about 70% initially, and in the process of flowing up the well, increases to 80% at the wellhead, point b. The flashing did not occur in the wellbore but in the underground formation. The issue of contention is, why was the wellhead temperature so low relative to producing region temperatures, especially since New Zealand experiences a temperature drop only in the order of 70°F (39°C) while HGP-A had a 301°F (167°C) drop (Figure 18, from Dench, 1973). The drop in New Zealand was about



Source: Adapted from Armstead, Geothermal Energy Magazine, Aug. 1976

Figure 17. Enthalpy/Temperature Chart (I/T)

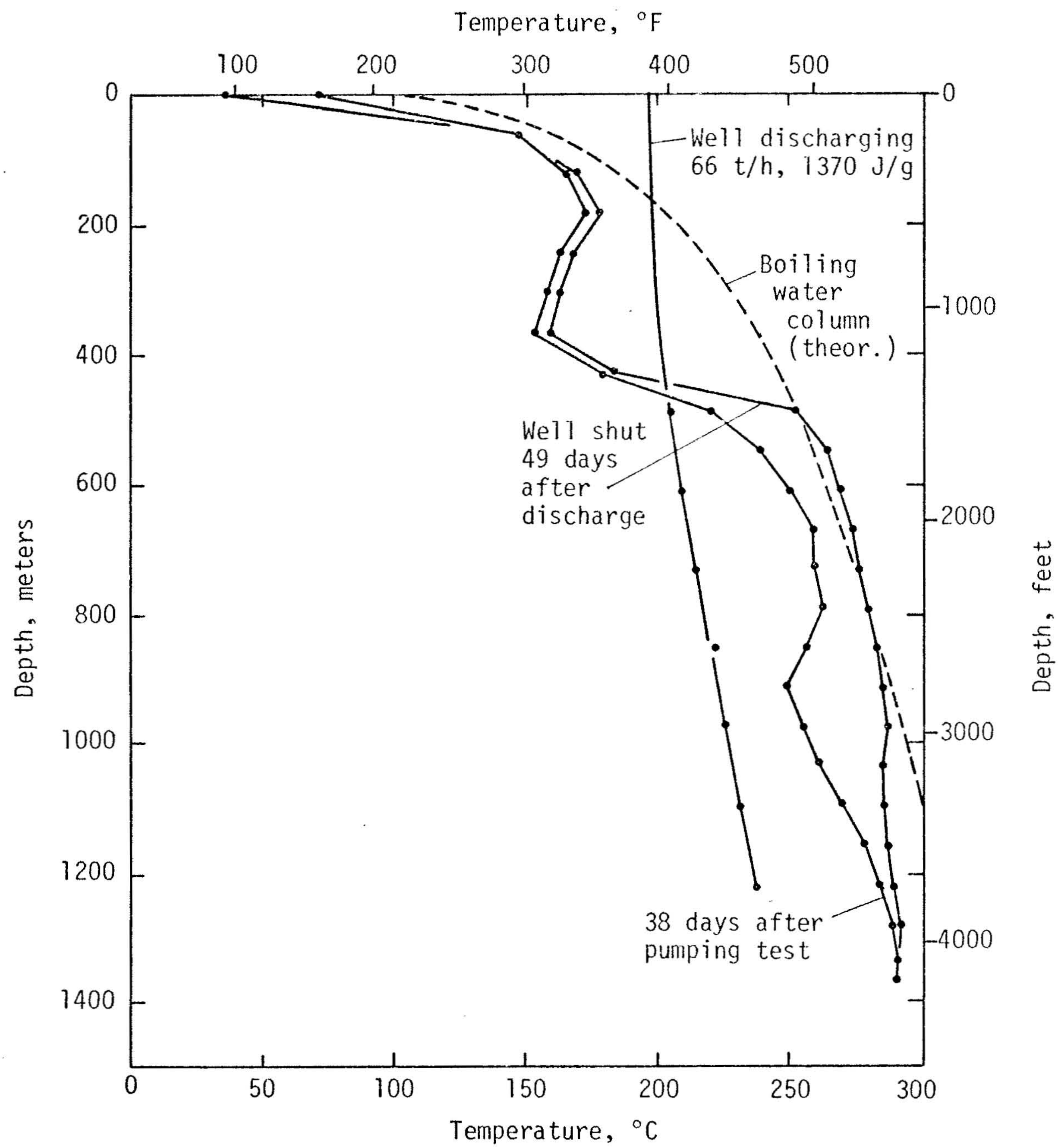


Figure 18. Downhole Temperatures at Various Well Conditions (Adapted from Dench, 1973)

1.94×10^{-2} °F/ft while HGP-A had a figure of 6.2×10^{-2} °F/ft. A partial explanation is that when the fluid flashes in the reservoir there will be an initial temperature drop. For New Zealand, the drop at 3600 feet was about 100°F. If there is an equivalent temperature drop for Hawaii, the flashing temperature at 4800 feet can be expected to be below 508°F, not 608°F, or the temperature drop in the wellbore will be close to 4.19×10^{-2} °F/ft, which is still twice as large as New Zealand's. However, as indicated in Figure 17, if the steam quality at point b is already 70%, this means that 70% of the water had changed phase before entering the wellbore and the fluid temperature no doubt should be somewhat lower than 508°F. In other words, as explained earlier, the low permeability rock had a significant pressure drop effect allowing for the phase change to occur within the formation, resulting in a temperature drop of at least 100°F at 4800 feet. Downhole temperature with depth measurements during flashing should prove or disprove this theory.

2) A second hypothesis is that there is contamination of cooling water, either through a break in the casing or below the casing. There is very little doubt that during flashing the fluid in the casing above the producing region is virtually all in two-phases. Therefore, the hydrostatic head outside the wellbore is higher than the pressure within the casing. If there is a break in the casing, cold water would flow in. What size hole would cause this temperature depression? Calculations were made using expected and encountered wellhead conditions in combination with the orifice equation. For the particular situation of encountered well conditions, a 60 psi pressure differential (effective hydrostatic head outside casing minus wellbore pressure at point of cold water entry), a 3/4" diameter hole could supply the required amount of contamination. If Δp was 6 psi, a 1-1/2" diameter hole is necessary. As the perforation bullet had a 5/8" diameter, two bullet holes through the casing and concrete would provide sufficient area for reducing the wellhead temperature, if low permeability rock condition was not the cause. (It could very well be a combination of both.) The diameter size is dependent on $(\text{mass flow rate})^{1/2}$ $(\text{pressure drop})^{-1/4}$. It is then of some concern that cooling water might be infiltrating the wellbore during flashing, as only a relatively tiny break or hole could provide the area through which leak could occur. (It should be noted that this possible leak cannot be detected if only liquid is flowing through the wellbore as the pressure drop across the casing would be quite small.) The second hypothesis can be checked by measuring both temperature and pressure vs depth during two-phase discharge. Theoretically, there should be two somewhat linear slopes on the T vs d plot, with

the intersection being the point of cold fluid entry. The pressure-depth curve would also, but to a much more limited extent, show this intersection.

3) A third possibility is that a portion of the 9-5/8" diameter pipe in the region between 978 and 2100 feet is resting in a lava tube cavity where an enormous river of cold water is flowing. An order of magnitude heat conduction calculation was made for the following system:

cold water temperature = 70°F
hot fluid temperature = 482°F
diameter of lava tube = 10 ft
thermal conductivity of pipe = 25 Btu/[hr-ft^2(°F/ft)]

The maximum possible cooling effect for the above is less than 3%. This third theory can then be discarded. A similar type of calculation was made for a one centimeter layer of basalt around the wellbore through a bore length of 1000 feet. Again, the maximum heat loss was quite low.

4) A significant obstruction in the casing/liner could retard flow sufficiently such that anomolously low wellhead temperature can result. The possibility of a crimp in the casing was checked by lowering a weighted balsa object down the well. There was no crimp in the casing. However, this theory cannot be completely discarded as it is possible, though highly unlikely, that the liner could be crushed to an extent whereby downhole instruments could be lowered, but flow could be retarded.

In summary, both low formation permeability and leakage of cold water could be the cause of low wellhead temperatures. The likelihood of external cooling through conduction heat exchange or a crimp in the casing/liner appears remote enough to discard as a viable speculation.

There is a sharp temperature gradient between 2000 and 2300 feet that seems to indicate that this is a very low permeability region such that vertical convection is prevented from occurring. In the loose definition of the word, caprock conditions are being experienced here. The geologic report is that below 1200 feet to 4000 feet secondary zeolite and calcite alteration is moderately abundant. Caprock formation? Also, Dr. Gordon Macdonald, of the Hawaii Institute of Geophysics, reported that the 0-2000' region of the wellbore was relatively permeable. Flushing of cooler water could be the reason for a sharp drop in temperature above 2000 feet.

Analysis of Reservoir Characteristics

A summary of heating and cooling of the underground system is presented in Figure 19 and Table 7. Figure 19 is a plot showing the approximate equilibrium states after initial completion, pumping and flashing. Relative to the initial completion plot, the temperature of the latter two showed significant temperature

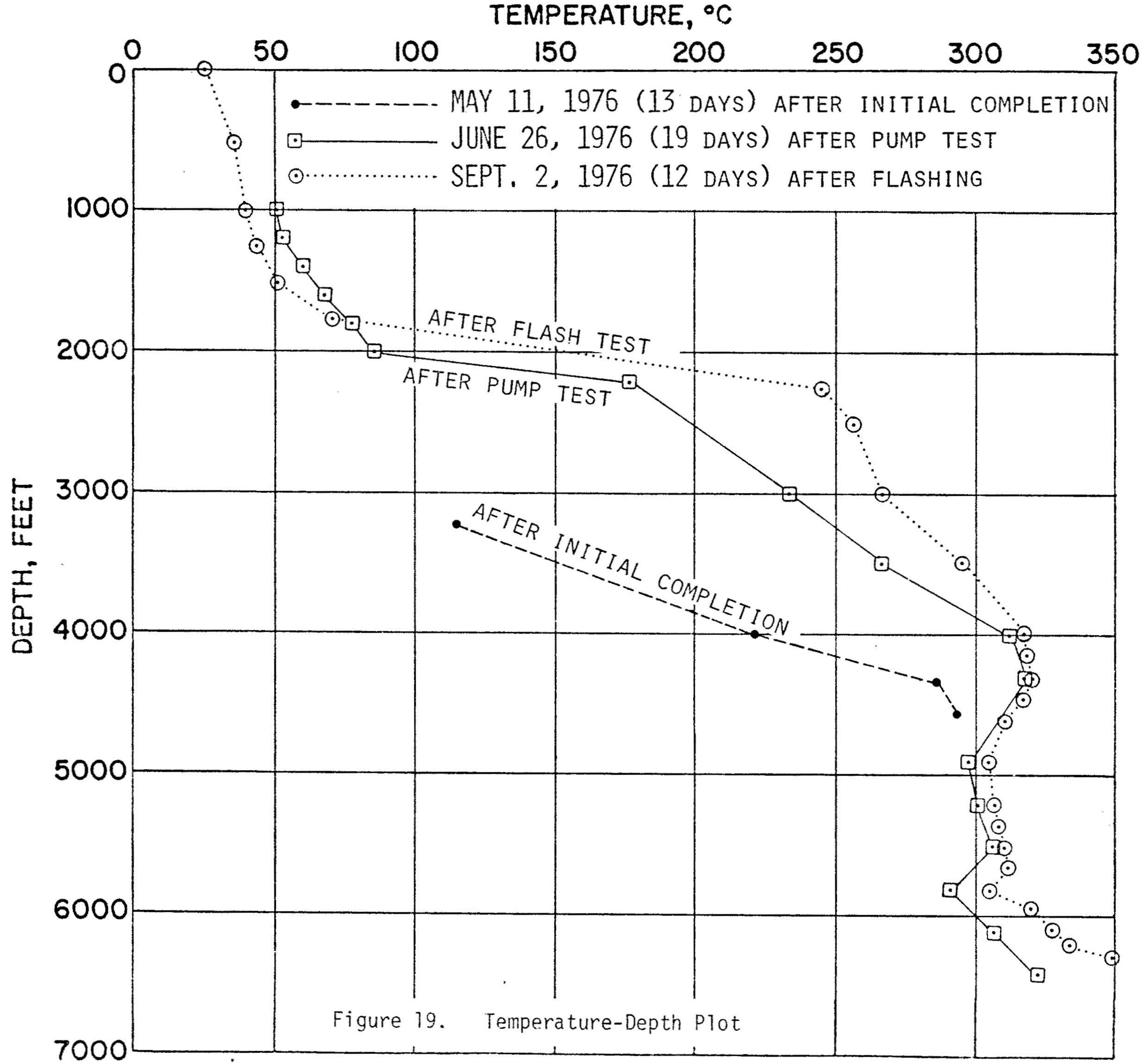


Figure 19. Temperature-Depth Plot

TABLE 7

REGIONS OF COOLING AND HEATING

Depth	After Initial Completion	After Pump Down Test	After Flashing
2300		heating	heating
		heating	
2500			
3000			
3500			
		heating	heating
		heating	heating
4000		heating	heating
		heating	heating
		heating	heating
	heating	heating	
	heating	heating	
4500	heating	heating	
	heating	heating	
	heating	heating	
	heating	heating	
	heating	cooling	cooling
5000	heating	cooling	
	heating		
		heating	
		heating	
		heating	heating
5500		heating	heating
		heating	heating
		heating	heating
	cooling	cooling	cooling
	heating		
6000+		heating	heating

increases in the 2100 to 3500 feet region. It could be argued that the increase was due to insufficient equilibration time. However, Figure 9 shows that very little change was occurring from the 6-day to the 13-day interval.

Therefore, "something" happened between the initial completion and pump test period to cause increased heating in the upper regions of the liner. Thus in

Table 7, the 2300 foot region is indicated as heating up. There also is heating in three other regions, 4300 ± 300 feet or so, 5500 ± 200 feet or so and greater than 6000 feet. There are two regions where a cooling effect is noticed -- at 4900 and 5800 feet.

It appears from the above discussion that the major producing areas are regions around 4300 and 5500 feet, with the 4300 feet portion possibly dominating. Dan Palmiter, of HIG, analyzed ten core samples by hand specimen techniques and concluded that the 3300'-4500' zone was highly fractured and would have high permeability. Finally, the mud loss record indicates that the region above (closer to the surface) 4400' experienced higher losses and therefore would be permeable. The 4600'-5600' section had very little mud loss and therefore would be expected to be impermeable.

Figure 10 shows that recovery was initially most rapid at 4600 feet, then sometime later at 4300 feet. On the other hand, Figure 11 shows that a significant temperature increase was experienced from before to after flashing at the very bottom of the well. Could this latter area also be a producing region?

Another possible producing region is at 5800 feet. Figure 14 shows that soon after flashing, there was a significant temperature drop at 5800 feet, perhaps caused by conversion of water to steam. (Refer to earlier isenthalpic discussion.)

In summary, then, it appears that there are several possible producing regions:

2300 ± 100 ft (250°C)*
$4300 \pm 300^{+}$ ft (320°C)
$5500 \pm 200^{-}$ ft (310°C)
5800 ± 50 ft (300°C)

*Casing extends down to 2250 ft

The pump down test indicated that permeability (whether natural formation or mud cake skin) is very poor. If the 4-hour discharge enthalpy was 1000 Btu/lb, then flashing is already occurring external to the wellbore. It is conceivable that within the formation, fluid conditions can proceed from point a to point c (see Figure 17). As the superheated fluid moves up the wellbore, superheated steam conditions could be experienced at the wellhead. When this special steam condition might occur is debatable. Perhaps only a couple of hours after the next flash as the pump down water is used up ... or perhaps much longer if there is sufficient permeability to allow fluid to flow through the system ... or perhaps never if permeability is high enough to utilize the formation heat before superheated conditions are reached.

There was some consensus that a combination of geophysical surveys, long-term testing data and analysis and additional holes would be necessary to determine the areal extent and temperature distribution of the reservoir. However, in the extreme optimistic case, the computer model developed by Art Seki, given average formation pressure with time (monthly acceptable, yearly for more than four years better), can theoretically inferentially determine the total amount of energy in the geothermal reservoir.

There was some surprise as to why the water in HGP-A was nearly fresh water when saline water had been expected. One speculation was that we got fresh water because we pumped in fresh water. Other possibilities range from artesian replenishment from high elevation rainfall to dike prevention of seawater encroachment. A minerals and isotope concentration analysis should clear up most doubts. Long term flow tests will no doubt aid in resolution.

One final conern was whether the discharge of the liquid effluent 50' from the wellhead and the subsequent percolation of the liquid into the ground, possibly around the wellbore, could affect the performance of HGP-A. If there is a caprock-like formation at 2000-2300 feet, there should be no effect. Furthermore, at 200,000 lb/hr, the volume discharged in twenty years of continuous flow will about equal the volume of fluid in a cylindrical reservoir 500 feet in radius 6450 feet deep at 10% porosity. The rainfall rate is about 1/4 of the geothermal flow rate. In short, it would appear that for the relatively short experimental period (less than five years) dumping of effluent on the ground should only minimally impact the producing capability of HGP-A.

Discussion on Skin Damage and Mud

There appears to be some evidence that mud cake is causing some skin damage. After very high (630 gpm) water pumping rates, there was some lowering of the back pressure. However, instead of the mud cake being cracked, the result could very well have been the rock formation being hydrofractured.

If the skin damage can be calculated, then this resistance layer can be mathematically removed from the analysis and the resultant natural permeability can be determined. Then, the ultimate maximum flow rate can be calculated.

Unfortunately, it is not as easy to physically remove skin damage. Various washing solutions can be tested and used, the hole can be re-drilled to a larger diameter, hydrofracturing might help and mere flowing of the well could loosen the skin.

To measure the mud output from the well during flashing as a function of time both immediate field and laboratory tests can be run. Among the field tests that can be used are cone settling to measure mud level and instrument turbidity. Both tests give only gross indications, and for the low mud concentrations expected will probably not be of much use. The laboratory measurement technique involves taking samples at regular intervals and individually filtering and oven drying to obtain mud weight. Thus, mud concentrations over time can be determined.

The sample location should also be considered. Ideally, one would want to sample the fluid in the pipeline. For example, the liquid discharge from the 2" cyclone separator would suffice. However, on the assumption that the mud will not immediately settle, since there will be some turbulence, the area around the silencer weir might be acceptable.

FUTURE ACTIVITIES

Table 8 is a summary of present and future activities. The actual tests will vary depending on flow and fluid characteristics.

The wellhead assembly with twin cyclone separators is diagrammed in Figure 20. The 2" twin cyclone sampler will be used to obtain gas and fluid samples. The large twin cyclone separators serve two purposes: as a silencer and a device to separate the liquid portion from the steam.

With respect to noise control, one deficiency of this type of silencer is that high steam quality geothermal fluids are not effectively muffled. The injection of cold water at the pipe outlet should aid to some extent. However, if the steam quality is very high, say more than 50%, enormous quantities of water will be necessary to reduce the noise level. If the fluid remains two-phased, the eventual operational silencer-separator system will involve the positioning of what amounts to a full scale cyclone separator system, somewhat similar in principle to the 2" version, between the wellhead and stack.

Figure 20 also shows a calorimeter. The purpose of the calorimeter will be to measure the enthalpy of the fluid. Currently, flow rates are being obtained by the James lip pressure method. This method requires knowledge of the fluid enthalpy.

Eventually, given the fluid enthalpy and steam fraction, using the calorimeter, and the liquid flow rate, by measuring the water height in the weir following the separator/silencer stack assembly, an accurate determination can be made of fluid flow and enthalpy.

Various downhole temperature and pressure measurements will be made during and after discharge. Pressure build-up and drawdown analyses can then be undertaken to evaluate reservoir characteristics.

TABLE 8

WELL TEST AND ANALYSIS PROGRAM SCHEDULE

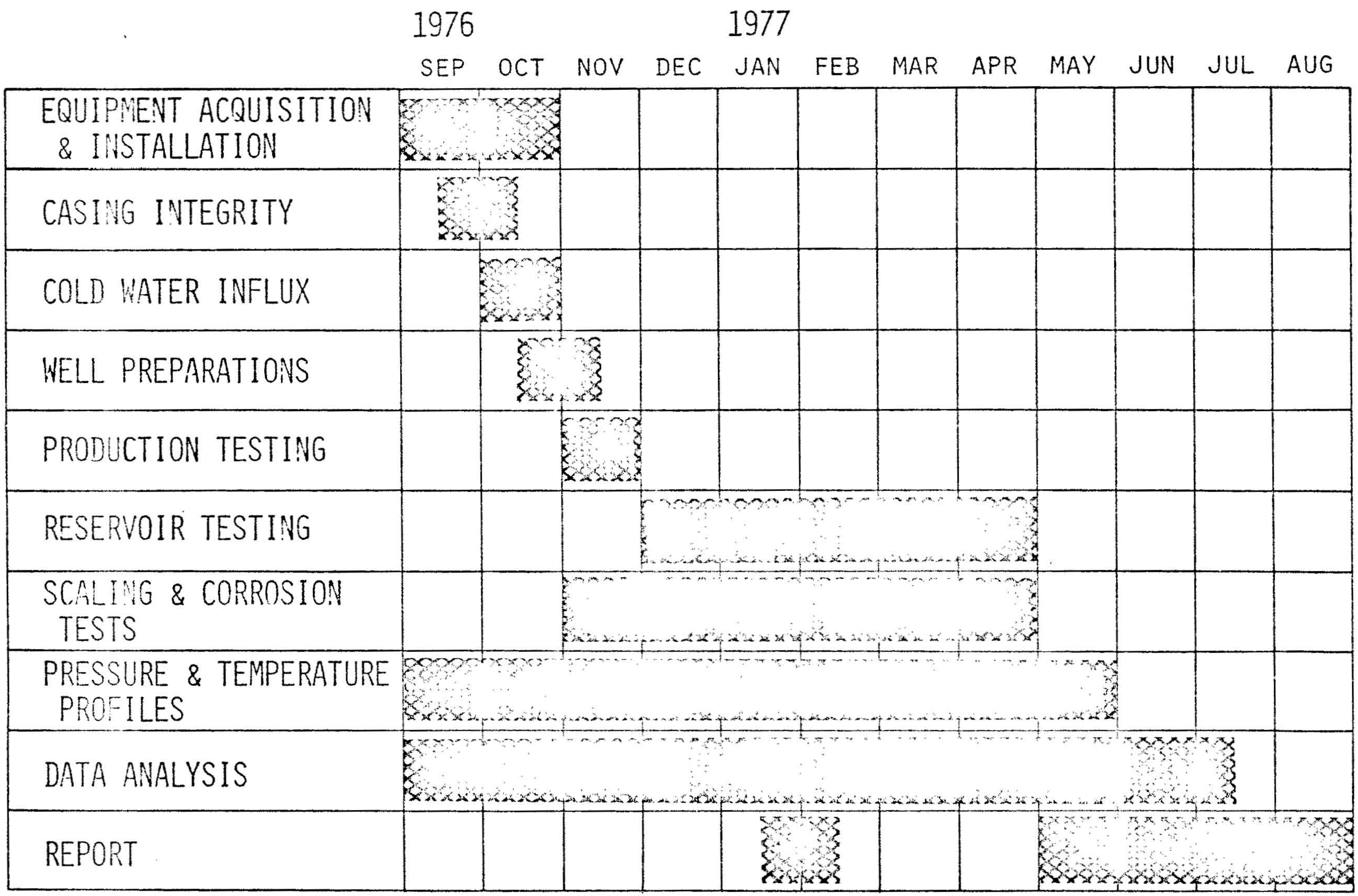
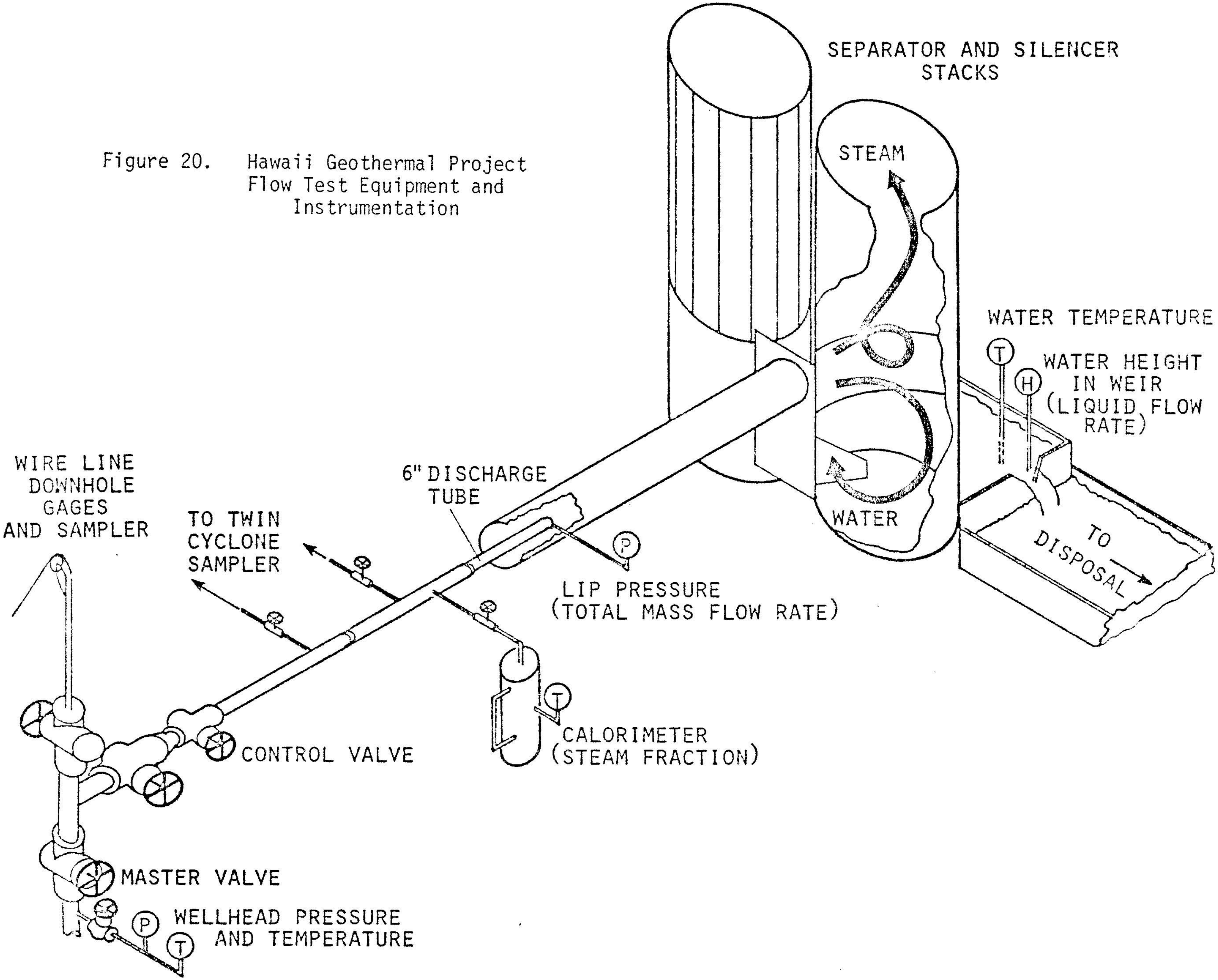


Figure 20. Hawaii Geothermal Project Flow Test Equipment and Instrumentation



FINAL NOTES

A complete listing of all measurement data as of October 31, 1976, is available.

We thank the National Science Foundation and the Energy Research and Development Administration for supporting this research project. We also would like to acknowledge the excellent work on graphics and physical production of this report by the Center for Engineering Research.

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