FLOW TESTING OF THE NEWBERRY 2 RESEARCH DRILLHOLE, NEWBERRY VOLCANO, OREGON

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ABSTRACT

A 20 hour flow test of the Newberry 2 research drillhole at Newberry Volcano produced about 33,000 kilograms of fluid. The flow rate declined from about 0.8 kilograms per second to less than 0.3 kilograms per second during the course of the test. The mass ratio of liquid water to vapor was about 3:2 at the separator and stayed fairly constant throughout the test. The vapor phase was about half steam and half CO_2 by weight.

The average enthalpy of the steam/water mixture at the separator was about 1,200 kilojoules per kilogram. Because of the low flow rate and the large temperature gradient into the surrounding rocks, heat loss from the wellbore was high; a simple conductive model gives overall losses of about 1,200 kilojoules per kilogram of H_2O produced. The actual heat loss may have been even higher due to convective effects, and it is likely that the fluid entering the bottom of the wellbore was largely or entirely steam and CO_2.

INTRODUCTION

Newberry Volcano is in central Oregon, approximately 60 km east of the axis of the Cascade Range (Fig. 1). It is one of the largest volcanoes of the Cascades, covering an area of more than 1,200 km^2 and rising about 1,100 m above the surrounding terrain. The 6- to 8-km-wide caldera at the summit is the result of several episodes of mid to late Quaternary caldera collapse (MacLeod and Sammel, 1982). Numerous Holocene silicic domes, breccias, and flows are present within the caldera. Those less than 6,700 years old are all chemically similar (MacLeod and Sammel, 1982), suggesting the continuous presence of a shallow magma chamber. Such a magma chamber may have been identified by recent high-resolution seismic studies carried out by the U.S. Geological Survey (Stauber and others, 1985).

The Newberry 2 drillhole was preceded by Newberry 1, a small-diameter wireline corehole drilled in 1977 on the northeast flank of the volcano. Newberry 1 was drilled to a depth of 386 m and encountered a maximum temperature of only 9°C at 154 m (Sammel, 1981; MacLeod and Sammel, 1982). The location of the second test hole was based primarily on environmental and access criteria (Sammel, 1981); however, it was located near the toe of the youngest (1,350 years B.P.) obsidian flow in the caldera (Fig. 1 - N 2). At the total depth of 932 m, Newberry 2 encountered temperatures near 265°C, the highest yet reported in a geothermal drillhole in the Pacific Northwest.

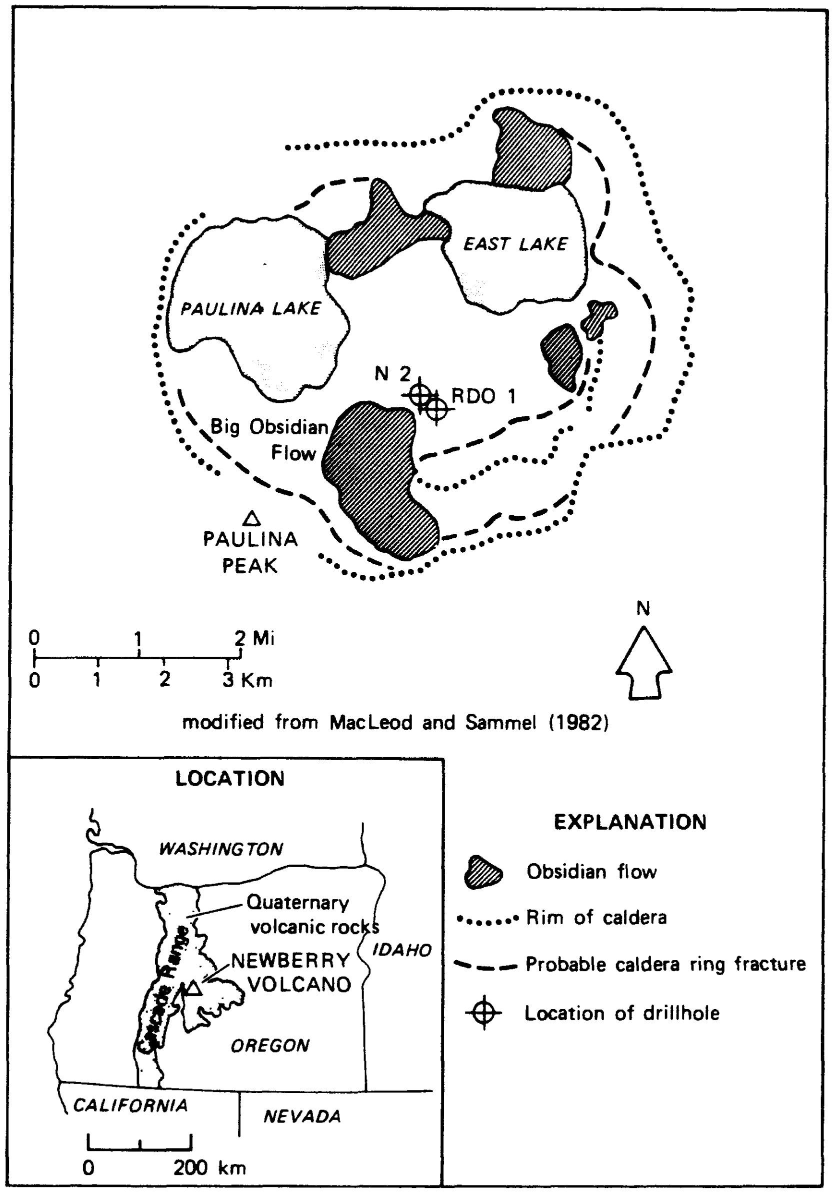

Fig. 1 Location of Newberry Volcano and drillhole Newberry 2.

Purpose and scope

The purpose of this paper is to present data and interpretations from a 20-hour flow test of the U.S. Geological Survey's Newberry 2 research drillhole at Newberry Volcano, Oregon. Although Newberry 2 was completed and abandoned in 1981, much of this information has not previously been published. It is of interest in light of current efforts to assess the geothermal potential of the Cascade Range in general and the Newberry Volcano area in particular.

Previous investigations

Several published reports discuss results from the Newberry 2 drillhole from various perspectives. Sammel (1981) presented the temperature profile and a generalized lithologic log, and discussed preliminary results from the flow test. MacLeod and Sammel (1982) discussed the geology and heat flow of the volcano and the possible nature of a magmatic heat source. Sammel (1983) analyzed the temperature profile from Newberry 2 in greater detail, and used the data in creating a conceptual model of fluid circulation within the hydrothermal system. He suggested that thermal fluids move up the ring fracture zone and migrate laterally at relatively shallow depths (Sammel, 1983; Sammel and Craig, 1983). A well drilled in 1983 by Sandia National Laboratory, to the southeast of Newberry 2 and nearer the ring fracture zone (Fig. 1 - RDO 1), had a temperature profile similar to that in Newberry 2 but reached higher temperatures at similar depths, tending to support Sammel's hypothesis. The Sandia well reached a depth of 457 m and was then abandoned due to casing problems (Black and others, 1984). Keith and others (1984) analyzed hydrothermal alteration in the drill core from Newberry 2 and drew conclusions regarding the age and evolution of the hydrothermal system. They also studied fluid inclusions in quartz samples from below 750 m depth.

Among the several reports there is lack of agreement regarding the nature of the fluids sampled in the course of the flow test. Sammel (1981) originally suggested that the dilute fluid samples consisted largely of condensed steam, presumably from the formation. MacLeod and Sammel (1982) later concluded that the samples consisted of drilling fluid combined with dry gas from the formation. Muffler and others (1982) also stated that the fluids recovered appeared to be mostly drilling fluid. However, Sammel (1983) regarded the source of the sampled fluids as an open question, and Keith and others (1984) considered the samples likely to be a mixture of formation fluid and drilling fluid. Most recently, W. W. Carothers and others (written commun., 1986) have shown that the average isotopic composition of the sampled fluids ($\delta^{18}O$ = -11.6 o/oo and δD = -105 o/oo) is close to that of steam in equilibrium with formation water at about 265°C ($\delta^{18}O$ = -10.2 o/oo and δD = -109 o/oo) and quite different from that of the drilling fluid ($\delta^{18}O$ = -15.7 o/oo and δD = -116 o/oo; reported by Keith and others, 1984).

Acknowledgements

We would like to thank Everett Miller of Jex & Miller Drilling, Orem, Utah, and Rick Davis of Portable Separators, Inc.,[1] Bakersfield, California, for their help in reconstructing the history of the flow test. T.E.C. Keith, M.L. Sorey, and C.J. Janik provided formal technical review of the manuscript. Manuel Nathenson reviewed the final manuscript informally and provided valuable advice at an earlier stage. We would also like to thank Don Michels of Don Michels Associates, Whittier, California, for his critical appraisal. Finally, we would like to note the efforts of Rebecca Munn, who typed the manuscript, and David Jones, who drafted the figures.

DRILLING HISTORY AND STATIC MEASUREMENTS

The Newberry 2 drillhole was spudded on the caldera floor in 1978, 400 m east of the toe of the Big Obsidian Flow (Fig. 1) at an elevation of 1,935 m. During the drilling season of 1978 the drillhole was completed to a depth of 310 m, using the mud rotary method to allow for later reduction in diameter (Sammel, 1981). During the summer drilling seasons of 1979 and 1981 wire line coring was used to complete the hole to a depth of 932 meters. Core recovery between 310 and 932 m was generally more than 90 percent (Keith and others, 1984).

The temperature profiles obtained over the same depth intervals during each of the three seasons of drilling were nearly identical (Sammel, 1981). The temperature profile shown in Figure 2 is considered representative of pre-drilling

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[1] Use of brand, trade, or firm names is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

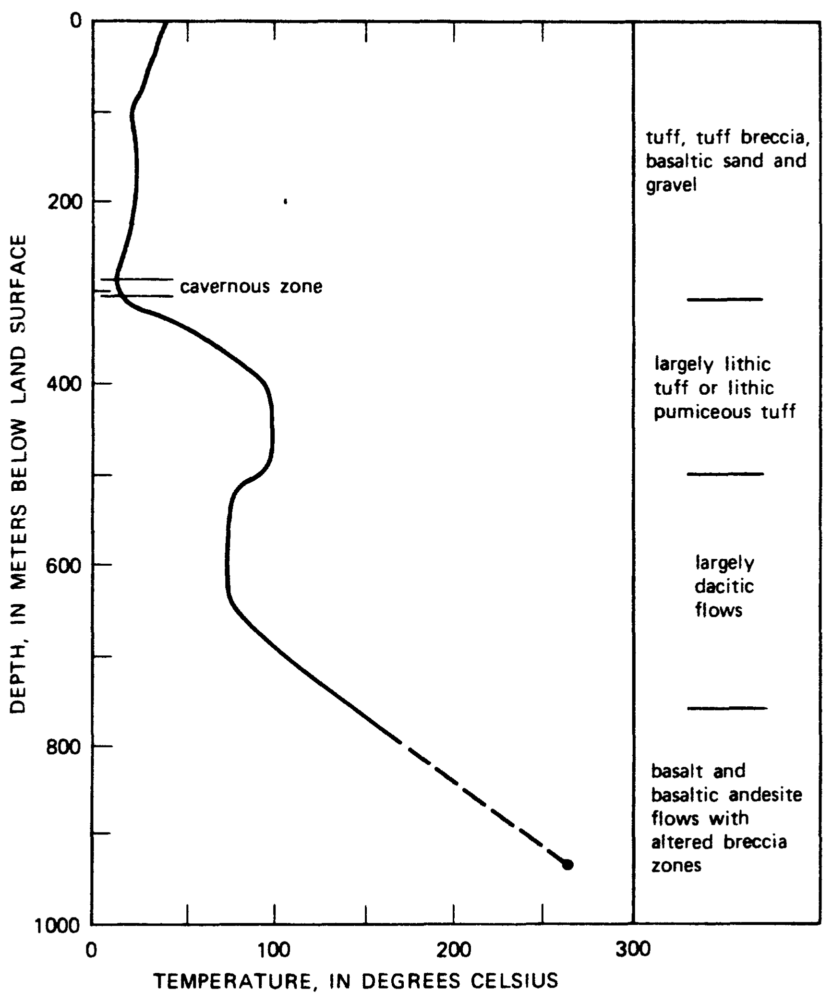

Fig. 2 Temperature profile and generalized lithologic log from the Newberry 2 drillhole.

formation temperatures, though no continuous temperature log was made below about 810 m. The temperature profile from 810 to 932 m is based only on bottom-hole measurements made with maximum-reading thermometers prior to daily drilling. The bottom-hole temperature of 265°C was measured more than 48 hours after drilling was halted. A generalized lithologic log is also included in Figure 2. Detailed core logs show no evidence of cross-cutting relations in the core, and all of the units penetrated are apparently horizontal or subhorizontal (Keith and others, 1984).

A pressurized gas-bearing interval was encountered in the bottom 2 m of Newberry 2 on September 18, 1981. Gas began surfacing in the annulus between the casing and the drill rods, and the blowout preventors were activated. On September 19 gas was discharged to the atmosphere for approximately 8 hours in an attempt to reduce bottom-hole pressures. The wellhead pressure stayed fairly constant at about 43 bars[1/] during this period. After the flow was shut off, the weight of carbonox-based mud pumped into the well was increased to 1.32 kg/l in order to stabilize the hole. At this point a decision was made to attempt to log the hole. The drill rods were pulled 91 m (300 feet) off the bottom of the hole before operations were suspended for two days for logistical reasons. Attempts to pull more rods after this period were unsuccessful. Once it was realized that the rods were permanently stuck and that logging was no longer

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[1/] All pressure values given in the text and tables are absolute rather than gauge.

possible, it was decided to flow the well through the 4.45 cm (1.75 inch) bit opening and up the 6.07 cm (2.38 inch) inside diameter drill rods. The well design and the position of the drill rods during the flow test are shown in Figure 3.

The wellhead pressure at the beginning of the flow test was approximately 56 bars. Formation pressures were not measured, but the bottom-hole pressure was estimated to be 62 bars, based on the weight of fluid (mostly vapor) in the drill hole as flow began (Sammel, 1981). This is approximately 10 bars greater than the pressure of saturated steam at the measured bottom-hole temperature of 265°C. Some or all of this excess pressure was believed to have been due to the partial pressure of noncondensable gases in the formation (Sammel, 1981).

FLOW TEST

Fluid flow was induced by swabbing the drill hole for approximately 6 hours. The drill rods expanded approximately 1.2 m vertically due to heating during the early part of the flow test. An unknown amount of cold water (probably less than 25 m^3 total) was injected between the drill rods and the casing during the test in an attempt to control this expansion. However, the injected water probably left the wellbore somewhere between the bottom of the casing at around 550 m depth and 700 m depth, where the formation reportedly becomes very impermeable (Keith and others, 1984). It follows that the injected water probably did not flow back up through the drill rods to the surface during the

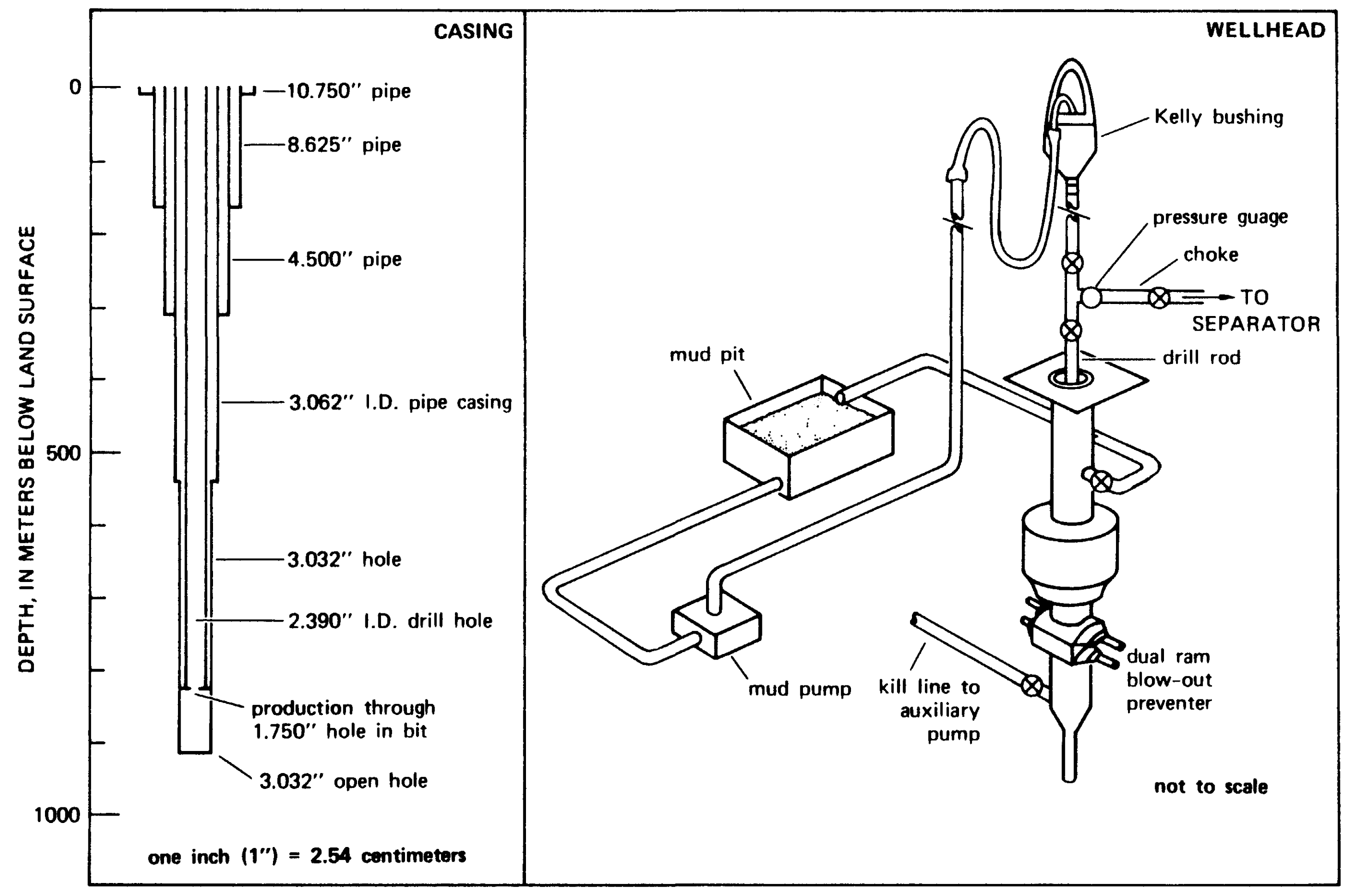

Fig. 3 Diagrams of the casing design and wellhead configuration.

test. We believe that nearly all of the produced fluid must have come from the bottom 2 m of the drillhole.

The separator was bypassed for the first hour of the flow test; during this period wellhead pressure was approximately 56 bars. After the first hour of the test, fluids were fed through the separator shown diagramatically in Figure 4. This two-phase portable separator has a liquid capacity of 0.318 m^3 (2 bbls.), with a float-controlled dumping mechanism operating at 0.03 m^3 (0.2 bbls.) discharge capacity. Total production for the 20-hour flow test was 33,000 kg, or about 34 m^3 (liquid equivalent at 265^oC). This is approximately 12 times the volume contained within the drill rods and the bottom 91 m of open hole. The mass ratio of liquid to vapor was about 3:2 at the separator and varied little in the course of the flow test.

The total flow rate declined from about 0.8 kg/s to less than 0.3 kg/s during the test (Fig. 5), as the wellhead pressure declined from approximately 56 to 30 bars (Fig. 6). During the first 9 hours of the test the wellhead pressure declined linearly. Between the ninth and seventeenth hours the separator metering system was bypassed and no measurements were made. During the last 3 hours of the test wellhead pressures recovered somewhat. The enthalpy of the flow, based on the proportions of liquid and steam at the separator and assuming saturated conditions at the separator temperature, stayed nearly constant throughout the test (Fig. 5). A complete record of the measurements made at the wellhead and separator is given in Table 1.

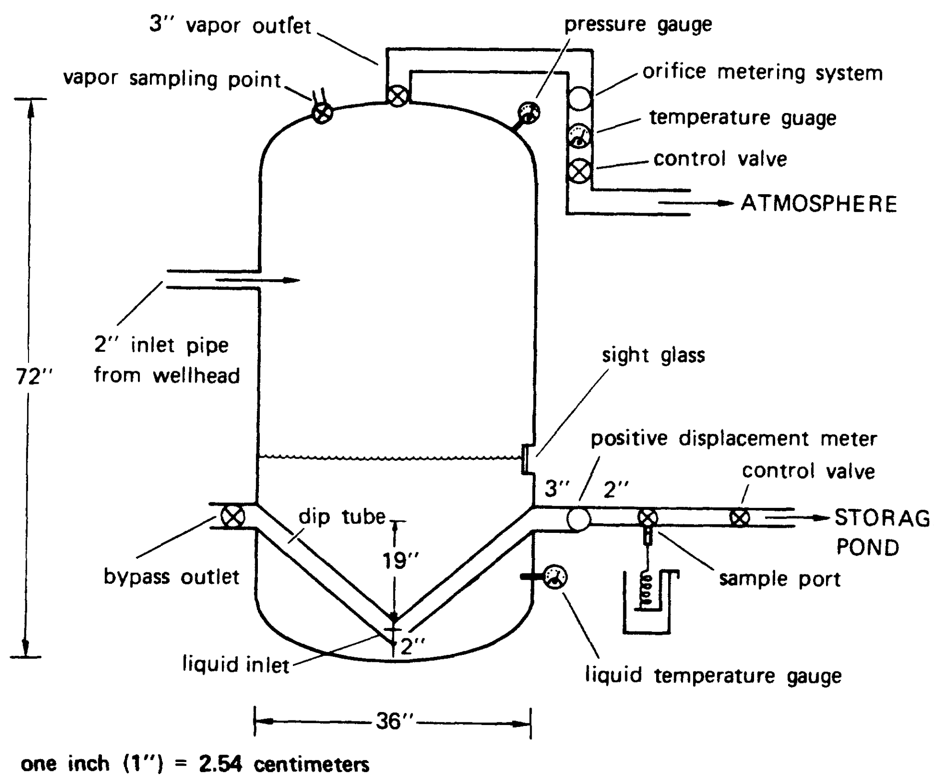

Fig. 4 Diagram of the portable separator used in the flow test. Readings from the liquid temperature gauge and the temperature gauge on the vapor line were identical during the test.

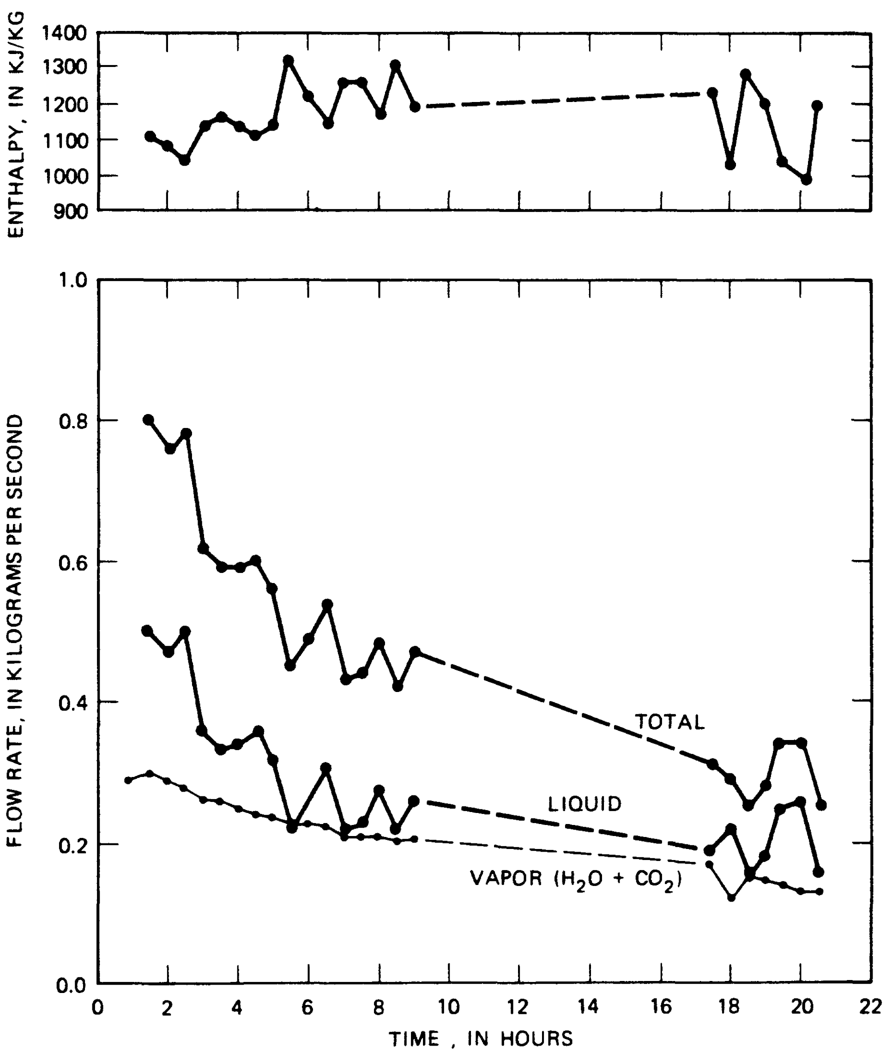

Fig. 5 Flow rates measured at the separator and calculated enthalpy of the steam/water mixture.

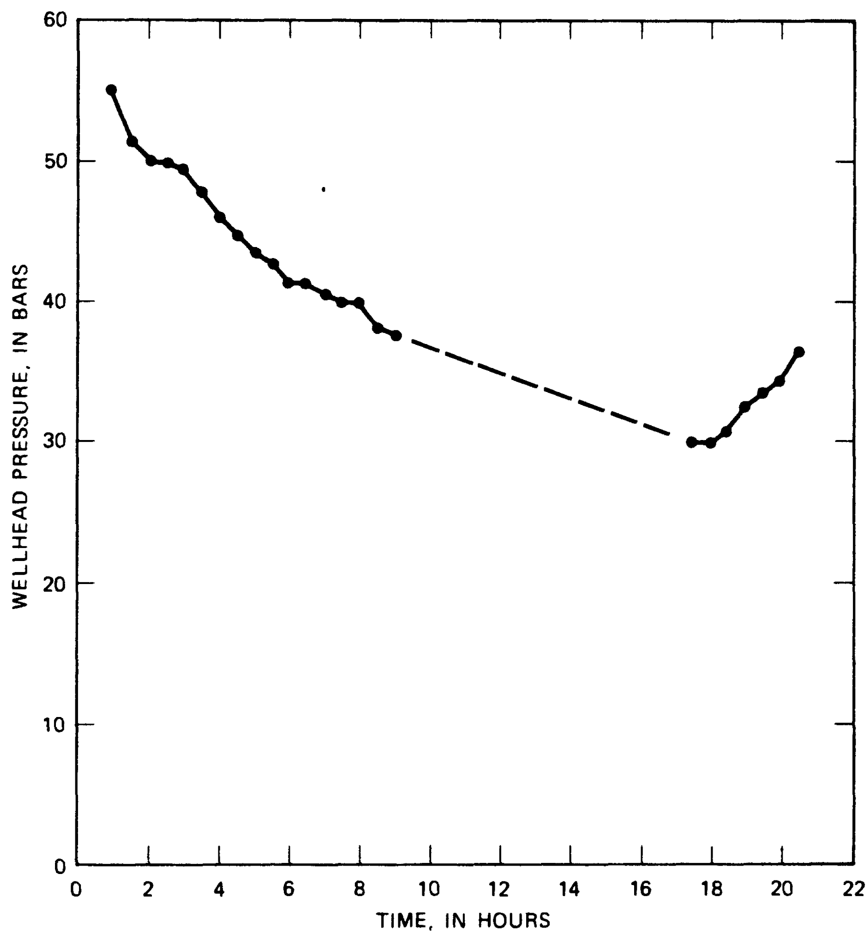

Fig. 6 Pressure decline curve.

Table 1. -- Newberry 2 flow test data, September 29, 1981 to September 30, 1981. Flow began at 1420 hours on September 29.

Time	Wellhead	Separator							
	Pressure, bars	Pressure,1) bars	Temp., °C	Liq. Flow, kg/s	Vapor Flow,2) kg/s	Total Flow, kg/s	Percent Liquid3)	Percent Steam3)	Enthalpy,4) kJ/kg
1530	54.8	6.7	146	-	0.29	-	-	-	-
1600	51.3	3.5	135	0.50	0.30	0.80	77	23	1,110
1630	49.9	4.3	135	0.47	0.29	0.76	76	24	1,080
1700	49.9	4.3	135	0.50	0.28	0.78	78	22	1,040
1730	49.6	4.5	135	0.36	0.26	0.62	73	27	1,140
1800	47.8	4.5	135	0.33	0.26	0.59	72	28	1,170
1830	46.1	4.5	135	0.34	0.25	0.59	73	27	1,140
1900	44.7	4.5	135	0.36	0.24	0.60	75	25	1,110
1930	43.4	4.3	135	0.32	0.24	0.56	73	27	1,140
2000	42.6	4.3	135	0.22	0.23	0.45	65	35	1,320
2030	41.2	4.3	135	0.26	0.23	0.49	70	30	1,220
2100	41.2	4.5	135	0.31	0.23	0.54	73	27	1,140
2130	40.5	4.3	133	0.22	0.21	0.43	68	32	1,260
2200	39.8	4.3	132	0.23	0.21	0.44	68	32	1,260
2230	39.8	4.3	132	0.27	0.21	0.48	72	28	1,170
2300	38.0	4.3	129	0.20	0.22	0.42	65	35	1,310
2330	37.5	4.3	132	0.26	0.21	0.47	71	29	1,190
SEPARATOR METERING SYSTEM BYPASSED									
0800	30.0		131	0.19	0.17	0.36	69	31	1,230
0830	30.0		131	0.22	0.12	0.34	78	22	1,030
0900	30.7		131	0.15	0.15	0.30	66	34	1,280
0930	32.4		131	0.18	0.15	0.33	70	30	1,200
1000	33.5		132	0.25	0.14	0.39	78	22	1,030
1030	34.2		130	0.26	0.13	0.39	80	20	990
1100	36.3		130	0.16	0.13	0.30	70	30	1,190

1) No readings were taken on the second day of the test.

2) Vapor is about half H_2O, half CO_2 by weight.

3) Percent of H_2O mixture.

4) Enthalpy of the H_2O mixture, assuming saturated conditions at the separator temperature.

During the flow test two sets of vapor and liquid samples were collected at the separator sample ports (Fig. 4). The first set of samples was collected 6 to 8 hours into the test, and the second set was obtained just before shutdown. The chemically dilute nature of the samples (Table 2) suggested that the fluid produced was largely condensed steam from the formation and/or drilling fluid.

Attempts to directly measure the noncondensable gas content of the flow are now believed to have been unsuccessful, and the estimates reported by Keith and others (1984) appear to be too low. Throughout the test, separator pressures (P_{total}) were significantly higher than the vapor pressure of water (P_{H_2O}) at the separator temperature (Table 1). The partial pressure of noncondensable gas in the separator is equal to the difference between P_{total} and P_{H_2O}. Assuming that the mole percent of noncondensable gas in the vapor is proportional to the partial pressure (ideal gas behavior), and that the noncondensable gas is essentially all CO_2 (see Table 2), we calculate that the CO_2 content of the discharge from the vapor line ranged from 24 to 61 weight percent and averaged about 50 weight percent CO_2. Since the mass ratio of liquid to vapor was about 3:2 at the separator, CO_2 averaged about 20 weight percent of the total flow. The values for partial pressure of CO_2 obtained from the difference between P_{total} and P_{H_2O} are consistent with values calculated by Henry's Law on the basis of the water chemistry (Table 2).

Table 2. -- Chemical composition of water and gases sampled during Newberry 2 flow test. Strontium carbonate precipitate values are from R.H. Mariner (oral commun., 1986); other data are from Keith and others (1984).

[SiO_2, K, Na, Ca, Cl, and SO_4 concentrations in mg/l; $SrCO_3$ values in grams of precipitate per 100 ml sample; H_2S and CO_2 concentrations in volume percent of the discharged gas; $\delta^{18}O$ and δD in o/oo relative to SMOW]

		SiO_2	K	Na	Ca	$SrCO_3$ 1)	Cl	SO_4	H_2S	CO_2	$\delta^{18}O$	δD
N2 (1)	Liquid	13	1.8	48	1.3	0.2712	2	13			-10.7	-101
	Vapor	0.7	0.04	0.3	0.4	0.4216	4	2	1.84	94.03	-14.0	-112
N2 (2)	Liquid	11	1.4	39	0.8	0.2955	2	9			-10.8	-104
	Vapor	0.7	0.04	0.2	0.2	0.4143	6	5	1.81	93.12	-14.2	-113

N2 (1) samples taken at about 2000 hours (liquid) and 2200 hours (vapor) on September 29, 1981.
N2 (2) samples taken at about 1030 hours (liquid) and 0800 hours (vapor) on September 30, 1981.

1) Values are accurate to within 10 percent. P_{CO_2} in the separator can be calculated using the weight of $SrCO_3$ precipitate from the liquid samples, the yield of CO_2 on conversion of $SrCO_3$ to CO_2 (83 percent), and Henry's Law. The calculated mole fraction of CO_2 in solution is about 2.8×10^{-4} and the Henry's Law constant at 135°C is 6358. P_{CO_2} calculated by this method is about 1.8 bars. This value is a maximum because it is based on the assumption that all dissolved carbon is present as H_2CO_3, when actually some is present as HCO_3.

HEAT LOSS CALCULATIONS

The maximum enthalpy of the steam/water mixture was about 1,320 kJ/kg. At the highest measured formation temperature of 265°C, liquid water has an enthalpy of 1,160 kJ/kg and steam 2,790 kJ/kg. Therefore, the steam/water mixture produced at the separator resulted from either (1) a steam/water mixture entering the drillhole at the bottom or (2) saturated or superheated steam entering the drillhole and partly condensing when flowing to the surface.

The heat transfer aspect of the flow of steam/water or steam from the bottom of the drillhole to the wellhead is of primary concern. The rate of heat conduction from the wellbore to the surrounding rocks over a differential element of depth dz is given by

$$dq = \frac{2\pi \ K_m \ (T_w - T_f) \ dz}{f(t)}$$

where K_m is the thermal conductivity of the formation, T_w is the temperature in the wellbore, and T_f is the undisturbed formation temperature. Ramey (1962) gives values of f(t) as a function of $(\alpha t/r^2)$, where α is the thermal diffusivity of the formation, t is time since the start of flow, and r is the outside radius of the casing.

Estimates of K_m and α were based on a series of laboratory determinations of thermal conductivity, density, and porosity made on the drill core by Robert J. Munroe of the U.S. Geological Survey (written communication, 1986). For the upper 500 m, which is mainly tuff, tuff breccia, and sediments, we used values of 0.92 mW/m-^{o}K for K_m and 0.17 x 10^{-6} m^2/s for α. For the 500 to 932 m interval, which is mainly flow rocks, values of 1.9 mW/m-^{o}K and 0.66 x 10^{-6} m^2/s were used for K_m and α, respectively. The formation temperatures (T_f) were assumed to be those shown in Figure 2, and r was taken to be the radius of the stuck drill rod.

Heat loss calculations were made for a time of about 8 hours after start of flow (Table 1; 2200 to 2330 hours on September 29)[1/]. For this time Ramey's (1962) curves give values of about 3.2 for f(t) in the upper 500 m and 2.4 in the lower 432 m. Wellhead temperature is estimated to be about 230^{o}C, based on measured wellhead pressures and a calculated partial pressure of CO_2 of about 10 bars at the wellhead. We assume a linear temperature drop of 30^{o}C in the wellbore in order to calculate the temperature difference between wellbore and formation.

Using these values and integrating the equation above over the total depth gives an overall heat loss of about 410 kJ/s. Essentially all of this heat must have been given up by the H_2O mixture, as the enthalpy of the CO_2 gas does not vary significantly for a temperature drop of a few 10's of degrees. At a time of about 8 hours after flow began the average mass flux of H_2O was 0.35 kg/s. Dividing the calculated total heat loss by this mass flux rate gives a value of about 1,200 kJ of heat loss per kg of H_2O produced. The average enthalpy of the steam/water

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[1/]Heat loss calculations for other times give comparable results.

mixture at the wellhead was about 1,230 kJ/kg at this time, so the enthalpy of the steam/water mixture at bottom hole is estimated to be at least 2,400 kJ/kg.

The values of heat loss calculated by this method are considered conservatively low, for two reasons. First, the values of f(t) are probably somewhat high; the appropriate value for r is probably larger than the radius of the stuck drill rod, particularly for the cased portion of the wellbore. Second, the injection of cold water around the outside of the drill rod would have increased the rate of cooling above that predicted by this purely conductive model.

IMPLICATIONS OF FLOW TEST RESULTS

The total flow rate during the flow test (Fig. 5, Table 1) was more than an order of magnitude smaller than that of typical geothermal wells, and the CO_2 content was unusually high. The wellhead pressure measured during the flow test was high but not unusual, ranging from 56 to 30 bars. In most geothermal wells a single-phase liquid or a two-phase mixture enters the wellbore, and steam quality increases as fluid flows up the wellbore and pressure drops. Flow in many such wells can be considered essentially adiabatic. The situation at Newberry 2 was very different. Because of the low flowrate and the large temperature gradient into the formation, heat transfer caused a significant drop in enthalpy, and the steam quality of the flowing mixture actually decreased with condensation up the wellbore.

A simple conductive heat loss model for Newberry 2 gives wellbore heat losses of about 1,200 kJ per kg of H_2O produced. This implies an enthalpy of more than 2,400 kJ/kg at bottom hole. At 265°C water has an enthalpy of 1,160 kJ/kg and steam vapor 2,790 kJ/kg, so the steam quality at bottom hole must have been at least 0.70. It is likely that this value is conservative and that the mixture flowing into the wellbore was essentially all steam and CO_2. This would be consistent with the very dilute water chemistry of the fluid samples (Table 2; Keith and others, 1984) and with the isotopic data presented by W. W. Carothers and others (written commun., 1986).

It is not possible to draw conclusions regarding the initial liquid saturation levels in the producing horizon based on the steam quality of the produced fluids. Pruess and Narasimhan (1982) showed that, given a low enough value of matrix permeability, saturated or superheated steam can be produced even where liquid saturations approach 100 percent.

The high CO_2 content of the total flow (about 20 weight percent) does not necessarily imply a very high CO_2 content in the formation. Based on experimental gas solubility data, the concentration of CO_2 gas in vapor at 265°C is about 73 times the concentration of CO_2 in the associated liquid (Giggenbach, 1980). So, assuming that the fluid entering the wellbore was entirely vapor at about 265°C, the CO_2 content of a formation liquid in equilibrium with that vapor would be about 0.3 weight percent (0.0014 moles CO_2/moles total). This would give rise to a partial pressure of CO_2 of about 7 bars in the formation, which seems reasonable based on Sammel's (1981) estimate that bottom-hole pressure as flow began was about 62 bars, or 10 bars greater than the pressure of saturated steam at 265°C.

SUMMARY

A 20 hour flow test of the Newberry 2 research drillhole at Newberry Volcano produced about 33,000 kg of fluid. The flow rate was relatively low - about an order of magnitude lower than that of a typical geothermal well - and declined from about 0.8 kg/s to less than 0.3 kg/s in the course of the test. The mass ratio of liquid water to vapor was about 3:2 at the separator and stayed fairly constant throughout the test. The vapor phase averaged about half steam and half CO_2 by weight, so CO_2 comprised about 20 weight percent of the total flow.

Because of the low flow rate and the large temperature gradient into the surrounding rocks, the steam quality of the fluid mixture must have decreased as it flowed up the wellbore. It is likely that the fluid entering the bottom of the wellbore was largely or entirely steam and CO_2.

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