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Use of Slim Holes for Reservoir Evaluation at the Steamboat Hills Geothermal Field, Nevada, U.S.A.

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ABSTRACT

Three slim holes were drilled at the Steamboat Hills Geothermal Field in northwestern Nevada about 15 km south of Reno. The slim holes were drilled to investigate the geologic conditions, thermal regime and productive characteristics of the geothermal system. They were completed through a geologic sequence consisting of alluvium cemented by geothermal fluids, volcaniclastic materials, and granodiorite. Numerous fractures, mostly sealed, were encountered throughout the drilled depth; however, several open fractures in the granodiorite, dipping between 65 and 90°, had apertures up to 13 mm in width. The depths of the slim holes vary from 262 to 277 m with open-hole diameters of 76 mm. Pressure and temperature logs gave bottom-hole temperatures ranging from 163 to 166° C. During injection testing, downhole pressures were measured using capillary tubing with a surface quartz transducer while temperatures were measured with a Kuster temperature tool located below the capillary tubing pressure chamber. No pressure increase was measured at reservoir depths in any of the three slim holes while injecting 11 kg/s of 29°C water indicating a very high permeability in the geothermal reservoir. These injection test results suggested that productive geothermal fluids could be found at depths sufficient for well pumping equipment and at temperatures needed for electrical power production using binary-type conversion technology.

INTRODUCTION

The Steamboat Springs Geothermal Area was classified as a Known Geothermal Resource Area ("KGRA") by the United States Geological Survey. The KGRA is located about 15 km south of Reno, Nevada along side of Highway 395 (see, Figure 1). Commercial geothermal development in the Steamboat Springs area began in the early 1900's. Initial development used geothermal fluids from hot spring discharge for heated baths and swimming pools. Wells were drilled beginning in the 1920's in order to obtain more reliable supplies of geothermal fluids. The first geothermal well was drilled in 1920, located at a site about one mile south of the Far West Capital, Inc. ("FWC") geothermal electric power development area. Additional wells located at the Steamboat Spa, just across Highway 395 to the south of the FWC development area, were drilled in the late 1930's through the late 1980's. Several of the Steamboat Spa wells are still in use.

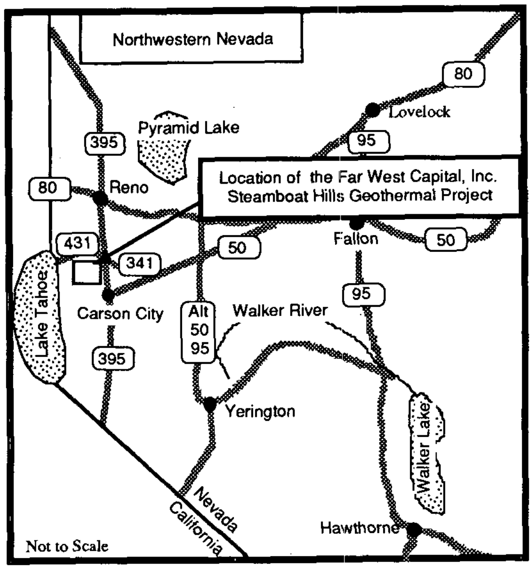

Figure 1. Location map of the Steamboat Hills Geothermal Field, Nevada.

Geothermal investigators from the United States Geological Survey, principally Donald E. White (1967, 1968), have conducted scientific studies of the Steamboat Springs geothermal area beginning in 1945 and continuing through the 1960's and 1970's (Thompson and White, 1964; White, et al., 1964; Silberman, et al., 1979) into the 1990's (Janik and Mariner, 1993). The early exploration efforts consisted of drilling small-diameter auger holes to depths of 4 m and core holes to depths up to 209 m. These shallow holes were completed to assist in defining the hydrogeologic characteristics of the geothermal hot spring system. Temperature versus depth, water level, fluid chemistry and geological data were obtained from the boreholes. Based on his interpretation of the data, White (1973) suggested that the Steamboat Springs hot-water system did not have adequate volume, temperature, or permeability to maintain commercial production of electricity.

Nevertheless, Gulf Oil Company and Phillips Petroleum Company began a joint geothermal drilling project in the late 1970's through the 1980's. About 25 shallow thermal gradient holes were drilled during this period. Additionally, 14 intermediate-depth stratigraphic test holes were drilled in the Steamboat area. Two large-diameter geothermal production wells were drilled in 1979 and 1980. In the mid-1980's, Chevron Geothermal Company acquired the Phillips Petroleum interests in the Steamboat area and Yankee Caithness Joint Venture ("YCJV") acquired the Gulf interests. Caithness Power, Inc. ("CPI") and YCJV acquired the Chevron interest in Steamboat. CPI drilled two additional geothermal production wells southwest of the FWC acreage in the mid-1980's. A 12 MW_{net} single flash steam geothermal power plant began operations in 1988. The CPI power plant operations have produced over 20 billion liters of geothermal fluid to date and about 17 billion liters of the fluid have been injected into the geothermal reservoir below the CPI leases (Goranson, et al., 1990).

During the 1980's, Geothermal Development Associates ("GDA") acquired Sierra Pacific Power Company ("SPPCo") leases that are now a portion of the FWC Steamboat Hills lease area. FWC has geothermal mineral leases on approximately 202 hectares. Three geothermal production and three injection wells were drilled by GDA on the SPPCo leases. Commercial production of electricity was commenced at Steamboat Hills in 1987 at which time a small 5 MW_{net} power plant, Steamboat #1 ("SB#1") was completed, certified and owned by a public partnership formed by FWC. SB#1 began selling electricity to the local public utility, SPPCo. SB#1 consisted of seven air-cooled binary-type Ormat Energy Converter Units utilizing the geothermal fluids to heat the working fluid, n-pentane, a hydrocarbon used to operate the turbines. FWC took over geothermal operations of the SB#1 power plant in the latter portion of 1990. An additional 1.7 MW_{net} unit, Steamboat #1A ("SB#1A"), was added at a later date. These units have been continually operating with the use of geothermal fluids since 1987. To date over 39 billion liters of geothermal fluid have been produced for power plant operations and 33 billion liters have been injected (Goranson, et al., 1991).

In January 1991, FWC entered into two power sales contracts with SPPCo each for 12 MW_{net} electricity capacity to be supplied from two proposed new power plants, Steamboat #2 and #3 ("SB#2/3"), to be situated contiguous and to the east and south of the site of SB#1 and SB#1A. FWC assigned approximately 50 hectares of its Towne geothermal lease for this project (Figure 2).

The slim-hole drilling program was designed to determine whether productive geothermal fluids could be found at depths sufficient for well pumping equipment and at temperatures needed for electrical power production at SB#2/3 utilizing air-cooled, binary-type, turbine-generator units.

PROGRAM DESCRIPTION

Since the major cost of geothermal exploration in fractured volcanic and igneous areas is the high cost associated with conventional rotary drilling, it would be desirable to use low-cost slim holes with diameters less that 100 mm for exploration and definitive reservoir assessment (Combs and Dunn, 1992). While the drilling of slim holes for geothermal exploration and initial reservoir evaluation is common in several countries (Garg and Combs, 1993), the technique has not been widely used in the United States before the present program.

The three slim holes (TH#1, #2, and #3) reported on in the present paper were drilled and injection tested during 1991 to investigate the geological conditions, thermal regime, and productive characteristics of the geothermal system in the northeastern portion of the Steamboat Hills hot-water system. The slim-hole locations (Figure 2) were chosen to investigate the subsurface conditions along a series of northwest trending surface lineaments noted in surface geologic investigations and on air photos (van de Kamp, 1991).

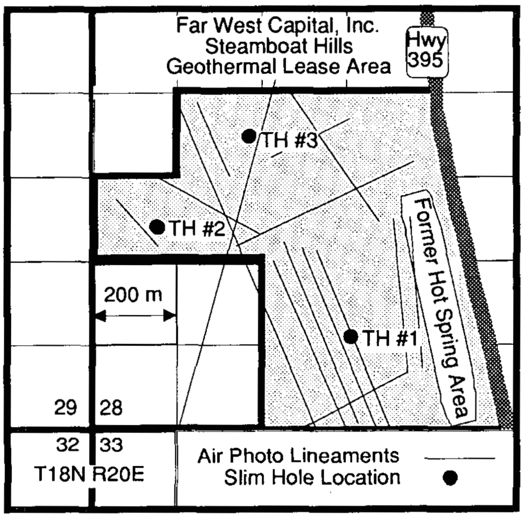

Figure 2. Map of FWC Towne lease showing surface lineaments and locations of the slim holes.

A Longyear vertical mounted core rig was used to drill the slim holes. Since it was known from the drilling of production and injection wells on the offset acreage that the subsurface would consist primarily of fractured granodiorite, the core rig was chosen to be able to obtain geological samples from the productive intervals (something that had not been possible on the existing geothermal wells in the area that had been rotary drilled). Furthermore, the slim-hole core rig was selected for its ability to drill under loss of circulation conditions while still obtaining geologic samples.

The depths and completion programs for the slim hole were designed to test the fracture sets in subsurface between the depths of 200 m to 300 m. The slim holes were cased to about 200m in order to eliminate interzonal flow from the fractures above this depth. If the deeper fracture sets found in the area are productive, it would allow for well pumps to be set to depths greater than 200 m, possibly to depths of 225 m. This would allow the geothermal production wells to be pumped at flow rates higher that existing wells in the area and allow spacing between wells to be less than with existing ones.

GEOLOGICAL AND STRUCTURAL SETTING

A detailed description of the geology, hydrology, and hydrothermal alteration is beyond the scope of this paper, but a general description of the geology and structure of the Steamboat Hills geothermal area is provided based on the work of van de Kamp (1991). The geology of the Steamboat Springs area was mapped in detail by Thompson and White (1964) and their work forms the basis for the geological evaluation of the geothermal system under the FWC leases in the northeastern Steamboat Hills area. The geothermal system covers about 6.5 km^2 and includes hot springs and numerous fumaroles associated with siliceous sinter terraces.

The oldest rock unit present in the northeast Steamboat Hills is the granodiorite of Jurassic-Cretaceous age (estimated as 150 to 80 mya). Younger sediments, volcanic rocks and alluvial deposits overlie the granodiorite. The granodiorite underlies the FWC leases and is penetrated by several geothermal wells. It ranges from very fine to coarse-grained and generally shows little internal structure other than faults, fractures, and joints. Quartz veins as well as aplite and pegmatite dikes are found within the granodiorite. In outcrop, it is apparent that there has been fracturing and faulting in the granodiorite.

An unconformity between the granodiorite and the overlying Miocene Alta Formation represents a time hiatus of about 60 my. The hiatus represents the late Cretaceous and early Tertiary Laramide uplift and erosion event which removed several kilometers thickness of older metamorphic rocks into which the granodiorite was intruded to expose the granodiorite. These volcanic units represent volcanic activity which accompanies the Oligocene-Miocene tectonic extension and faulting in the Basin and Range Province, which began about 17 mya (Stewart, 1980). In the FWC lease area, these volcanics and volcaniclastic sediments are up to 150 m thick. The Alta Formation is an early to mid-Miocene soda trachyte occurring mostly as lava flows and pyroclastics. The Kate Peak Formation, overlying the Alta Formation, is late Miocene to Pliocene age and is composed of andesitic volcanic flows and tuff-breccias up to several tens of meters thick.

Above the Tertiary volcanics, there is an erosional unconformity representing late Pliocene and Pleistocene uplift and erosion. This event caused erosion of volcanics and granodiorite toward the south. Alluvium now covers the erosionally thinned volcanics and granodiorite southward across the FWC lease area. The alluvial deposits range up to 100 m thick and over much of the area are cemented by silica deposited from Pleistocene to Recent hot springs which flowed from fractures in the underlying bedrock. Additionally, there are common silica sinter deposits overlying the alluvium in areas where hot springs flowed to the surface. Silberman, et al. (1979) provide data suggesting that the Steamboat Hills hydrothermal system has been active, probably intermittently, for the last 2.5 my. Faulting appears to be the principal structural control for subsurface fluid flow. Thermal fluids are meteoric in origin, and the heat source is believed to be a slowly cooling, shallow intrusive body, possible of rhyolitic composition.

The northeastern Steamboat Hills which is part of the larger Steamboat Hills structural block was uplifted relative to areas to the east, north, and west in late Tertiary and Recent times. The uplift is bounded by steep dipping north-northeast and east-northeast trending normal faults with displacement of tens to hundreds of meters or more. Bedding strikes range from northeast to northwest, while measured dips range from 45° to 90°. Cenozoic warping and block faulting are responsible for the present mountainous topography. At least three systems of faulting have been recognized in the Steamboat Hills (Figure 2). One set strikes northeast, parallel to the axis of the Steamboat Hills. A second set, essentially at right angles to the first, strikes northwest. The third set of faults strike north-northeast and are prominent on the sinter terrace of the dormant hot springs. In the distant past, this fault zone issued geothermal fluids to the surface where active hot springs and silica sinter precipitation occurred, similar to the modern situation at the Steamboat Hot Springs located to the east of the FWC leases.

DRILLING AND COMPLETION DATA

Each of the slim holes was drilled through a sequence of alluvium and sinter, volcaniclastic materials, and granodiorite (Figure 3). The final completion of the slim holes consisted of a surface casing of 114 mm diameter, an intermediate casing of 89 mm diameter, and a 70 mm open-hole section to total depth. For each of the slim holes, a 101 mm hole was drilled and cored to about 30 m and was then opened to 190 mm with a tricone bit. Only partial core recovery occurred above about 30 m in each of the slim holes. After coring to depths ranging from 30 m in TH#1 and TH#2 and to 49 m in TH#3, a 114 mm-diameter, schedule 40, steel threaded pipe was set and cemented to surface. A 140-mm Hydril blowout preventor with a 122-mm gate valve located below the BOP was used for well control.

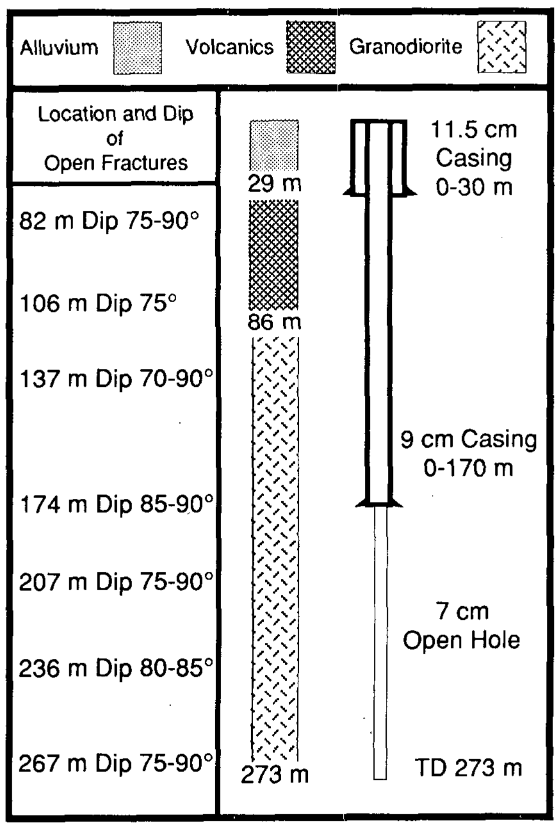

Figure 3. Geological data and slim hole completion for TH#1.

The slim holes were originally planned to have only a 114-mm casing set to about 30 m and then completion with a 101-mm (HQ size) open-hole to total depth. However, due to numerous open fractures being encountered between 82 m and 152 m in TH#1, it was decided to set an intermediate casing of 89-mm diameter to about 175 m. Casing to this depth would allow for an injection test to be performed on open fractures encountered below 175 m. The depth of the intermediate casing was 169 m in TH#1, 183 m in TH#2, and 201 m in TH#3. Only partial returns were obtained during cementing of the casing.

After setting the 89-mm casing, partial to complete loss of circulation was encountered after drilling out into the granodiorite. The slim holes were drilled using a 74-mm (NQ size) core bit to total depths of 272 m in TH#1, 262 m in TH#2, and 277 m in TH#3. Essentially 100% core recovery was obtained through the lower section of each of the slim holes. The slim holes were drilled during the time period of 12 July to 10 August 1991 and completed in 10 to 11.5 days with average drilling rates of 1.8 to 2.4 meters per hour and at a cost of approximately $280 per meter.

SUBSURFACE GEOLOGICAL DATA

Data from geothermal wells drilled in the area indicate that productive geothermal horizons lie below depths of about 125 m in fractured volcanics and granodiorite. The shallow alluvium has been cemented and hydrologically sealed. Granodiorite situated below the shallow alluvium is fractured and also sealed with silicic and carbonaceous materials to depths less than 150 m. To the north of the FWC leases, subsurface data suggest that a hydrologic boundary exists.

The generalized subsurface geological information for the three slim holes is summarized in Table 1. Pleistocene and Holocene alluvium and siliceous sinter deposits make up the geological section from the surface to the underlying volcanics. Much of the alluvium is cemented and/or replaced by silica as vuggy, layered sinter and solid, cherty texture deposits. Measured dips of the layers are 0° to 40° with most in the 5° to 15° range. The sinter is generally hard and granular to glassy in texture with eroded and re-cemented sinter fragments being common.

Gray and gray-green pyroclastic (volcaniclastic) deposits of the Miocene-Pliocene Kate Peak Formation make up the next sequence in the subsurface column. The rocks are generally hard and competent, but there are short intervals of rocks severely altered to clays. These pyroclastic deposits are thin to thick bedded with measured dips of 5° to 40°, many dips are 20° to 30°. There is a sharp, but non-faulted, contact with the slightly weathered granodiorite below.

The upper one-half to one meter of the Cretaceous granodiorite is brown-red, hard, silica-cemented rock, apparently weathered prior to deposition of the overlying Kate Peak Formation. A fine to medium grained granodiorite is the major portion of the rocks penetrated by the slim holes. The granodiorite has no intrinsic permeability, nor is there any appreciable rock matrix porosity. The granodiorite has essentially no fluid storage capacity and all fluid flow within the granodiorite is confined to fractures. The rock is generally hard and only slightly altered to chlorite and clay minerals with abundant minute pyrite crystals. Apparently there was an early stage of chloritic alteration and fracturing in the granodiorite followed much later by fracturing related to geothermal processes. In the later stage of fracturing, there was also chloritic alteration plus filling of fractures with calcite, chlorite, silica, and minor amounts of heavy-metal mineralization.

Table 1. Summary geological data from the slim holes.

Slim Hole Name	Depth Interval (m)	Rock Type
TH#1	0-29	Alluvium and Sinter
	29-86	Volcanics
	86-272	Granodiorite
TH#2	0-21	Alluvium and Sinter
	21-59	Volcanics
	59-262	Granodiorite
TH#3	0-17	Alluvium and Sinter
	17-138	Volcanics
	138-277	Granodiorite

FRACTURE DATA

Numerous fractures were encountered throughout the drilled depth of all of the slim holes. There are fractures in both the volcanics and the granodiorite portion of the slim holes. Most of the fractures are cemented tight with calcite and silica and are thus ineffective for fluid transmission. However, significant open fractures, which occur in the same subsurface intervals as loss of circulation, were found at several depths. For example, the depth intervals and dip of the open fracture zones in slim hole TH#3 are presented in Table 2.

Table 2. Depth interval and dip of the open fracture zones in slim hole TH#3.

Depth Interval (m)	Dip (degrees)
152	55
155	55-60
219	75
222	75
232-234	72-90
242-243	80-90
273-274	65

The data clearly indicate that the open fracture zones are steeply dipping in TH#3. This is also the case for the other two slim holes, TH#1 (see Figure 3) and TH#2. The open fractures range from 1.3 mm to 130 mm in width with calcite and/or silica lining the walls so that the actual open width of the fractures vary between 1.3 mm and 13 mm wide and up to 150 mm in length. Open fractures of this size can provide permeability necessary for subsurface geothermal fluid movement within the granodiorite. Adjacent and parallel to some of these steeply dipping fractures are 50 to 150 mm wide protomylonites indicative of shearing. Dips of the open fractures vary between 65° to 90°. The direction of fracture dip and strike is essentially unknown. However, surface geological mapping and structural information suggest an easterly dip and a north to northwest strike (van de Kamp, 1991). The recovery of cores has allowed for a much better understanding of the nature of the geothermal reservoir system.

TESTING OPERATIONS

The slim holes were first logged for downhole temperature and pressure about 2 or 3 days after drilling was completed. A few days after these initial downhole temperature and pressure logs were run, an injection test was carried out to determine the productivity of the fractures located in the open-hole section in each of the slim hole.

Downhole pressures were measured with capillary tubing attached to a surface quartz transducer. Temperatures were measured with a Kuster temperature tool with a 38-204°C temperature range located below the capillary tubing pressure chamber. Surface wellhead pressure was measured with a 2.1 MPa pressure gauge. Capillary tubing pressure was measured with a 6.2 MPa quartz transducer. The injection pump consisted of a Gardner Denver 5 x 6 duplex mud pump. Injection rate was measured by counting strokes on the duplex pump and by measuring the water level in the 2.4 m x 2.4 m x 12 m long Baker tank used for test water storage.

During the injection testing, fluids at a temperature of 29°C were pumped into the open-hole section of the slim holes at a rate of 11 kg/s for about two hours. The original injection test program for each of the slim holes called for the pressure and temperature tools to be set about 250 m depth; however, as discussed below, this was not possible in TH#1.

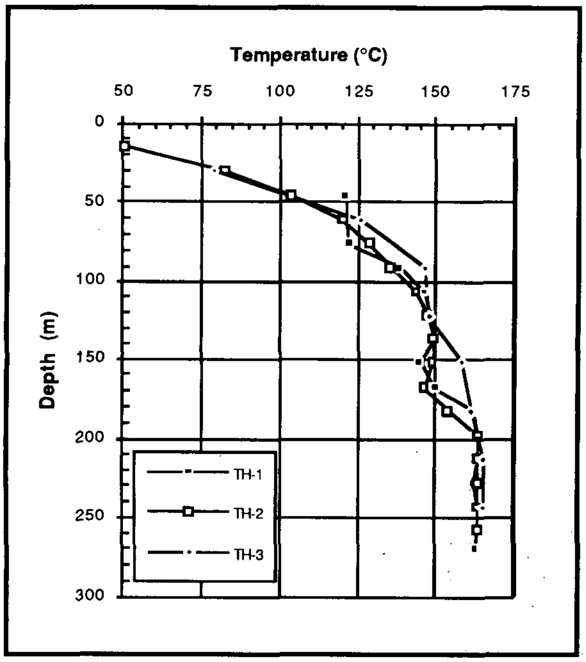

Figure 4. Temperature-depth curves for the three slim holes at Steamboat Hills Geothermal Field.

RESULTS AND DISCUSSION

The maximum downhole temperature in TH#1 was 163°C, 164°C in TH#2, and 166°C in TH#3. However, since the temperatures were measured about 2 or 3 days after drilling was completed, thermal equilibrium would not have been attained. Furthermore, as will be seen from the discussion below and from the shape of the temperature-depth curves (Figure 4), the interzonal flow and mixing of fluids caused by drilling the boreholes have essentially made it impossible to determine the in situ subsurface temperatures. In other words, the actual temperature of fractures below approximately 175 m can not be determined due to the wellbore fluid circulation induced by the open-hole section of the borehole.

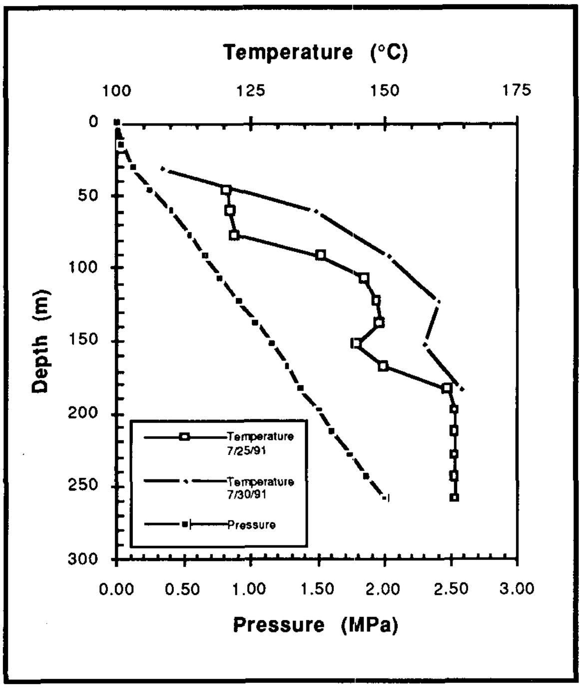

Figure 5. Pressure and temperature versus depth for slim hole TH#1.

Downhole temperature data from large-diameter geothermal production wells in the area suggest that Downhole quasi-equilibrium temperatures will be at a minimum of between 168°C to 171°C. However, chemical geothermometry data from fluid samples taken from the now non-flowing hot springs and from the nearby geothermal production wells of CPI indicate that temperatures as high as 200°C may be encountered in the area (Janik and Mariner, 1993).

The downhole pressure measurements indicate that a single phase hot-water reservoir was encountered in the subsurface between about 60 and 275 m in each of the slim holes. Based on the pressure data, the water level in TH#1 is at 10 m, 9 m in TH#2, and 11 m in TH#3.

The TH#1 slim hole was first logged for downhole temperature and pressure on 25 July 1991. The temperature-depth data are shown in Figure 5; however, the pressure tool failed to operate properly. The data show an isothermal zone between 175 m and 272 m. This isothermal condition (and the injection test data) indicates that fluid is circulating between open fractures, using the wellbore of the slim hole as a flow path.

During the injection test on TH#1, the downhole equipment would not readily pass 186 m. The geological data indicates that a short clay interval exists at this depth. Since there was a possible risk of losing the equipment if this zone was traversed, it was decided to choose this depth as the maximum depth for logging during the injection test. The data obtained during the injection test are presented in Table 3. No wellhead pressure was observed during injection at a rate of 11 kg/s with 29°C fluid. The downhole temperature data show that the slim hole was accepting fluid below the 186-m depth since the temperature cooled to approximately 38°C at 186 m.

Table 3. Time, pressure, temperature, and injection rate data during testing of TH#1.

Time (min)	Press @ 186m (MPa)	Temp @ 186m (°C)	Inj Rate (kg/sec)	Comments
0	1.59	164	0	
5	1.59	164	0	
10	1.59	60	6.3	Start Injection
15	1.49	49	6.3	
20	1.45	149	0	Stop Injection Change Rate
25	1.63	157	0	Purge Tubing
30	1.59	43	11	Start Injection
35	1.58	38	11	
40	1.57	38	11	
45	1.56	38	11	
50	1.56	38	11	
55	1.56	38	11	
60	1.56	38	11	
65	1.56	38	11	
70	1.56	38	11	
75	1.56	38	11	
80	1.55	38	11	
85	1.55	38	11	
90	1.55	38	11	
95	1.80	33	11	Purge Tubing
100	1.60	38	11	
105	1.60	38	11	
110	1.60	38	11	
115	1.60	38	11	
120	1.60	38	11	Stop Injection
125	1.60	82	0	
130	1.60	149	0	
135	1.60	161	0	
140	0.085		0	Atm Reading

The pressure data from TH#1 shows that there was no pressure increase at 186 m due to injection of 11 kg/s. However, the fact that fluid was exiting the slim hole below the pressure measurement point hampers the data interpretation. The analysis is not straight forward due to the fact that the density of the injected water is greater than the density of fluid in the wellbore and reservoir below 186 m. In addition, frictional fluid pressure losses develop due to the fluid flow between the 186-m depth of pressure measurement and the point that fluid exits the wellbore. There are three competing pressure changes due to the flow of injected fluid below the 186-m pressure measurement point; specifically, (1) pressure increase due to frictional fluid flow, (2) pressure increase due to fluid flow into the reservoir system, and (3) pressure decrease due to the difference in injected fluid density versus wellbore and reservoir fluid density. The pressure change that is of interest for this analysis is the increase in pressure due to fluid flow into the fractures in the geothermal reservoir.

The frictional pressure losses and the density induced pressure decreases can be readily calculated. Using the parameters measured in the injection test and assuming that fluid is exiting the slim hole at the 262-m depth, which is a reasonable assumption based on the temperature data showing fluid flow between fractures located at 175 m to 262 m, the decrease in pressure due to density differences is determined to be about minus 0.066 MPa. Then, calculating the Reynolds Number of approximately 190,000 which implies for rough pipe a friction factor of about 0.019, the pressure change due to frictional fluid flow is about plus 0.066 MPa. This analysis indicated that the decrease in pressure due to density changes and the increase in pressure measured at 186 m from frictional losses will offset each other. The fact that there was no pressure increase measured at 186 m (see, Table 3) suggests that there were no increases in pressure due to flow of injected fluid into the reservoir system. Assuming the resolution of the pressure measurement device is 0.007 MPa yields a calculation of the minimum reservoir permeability on the order of 1,200 darcy-meters. This suggests, essentially, infinite permeability; however, the actual zones that fluid exited the wellbore are unknown. It suffices to say that the geothermal reservoir in the vicinity of slim hole TH#1 has a very high permeability.

Another significant technical point is the behavior of the wellbore temperature during the injection test (see, Table 3). Injection started at a rate of 6.3 kg/s, however, injection was stopped for ten minutes to adjust the pump setting, and injection was then resumed at 11 kg/s. The temperature increased immediately after stopping the injection flow. In addition, at the end of the test, the slim hole recovered to its initial temperature immediately after cessation of injection. This indicates that fluid is flowing from fractured intervals above 186 m and exiting below 186 m. The temperature survey data show that the slim hole is isothermal to the bottom of the hole. This suggests that fluid does enter from approximately 175 m and exits through fractures at the bottom of the slim hole.

The temperature-depth data from slim hole TH#2 (see, Figure 4) show an isothermal zone between 213 m and 262 m, suggesting that there is fluid flow between the fractures intersected by the wellbore. The data obtained during the injection test are presented in Figure 6. No wellhead pressure was observed while injecting 29°C fluid at 11 kg/s. The temperature at 259 m was reduced from 164°C to about 66°C during the injection test. It is not clear whether these data indicate that only a portion of injected fluid was flowing into fracture zones located below 259 m or if mixing of injected and down-flowing fluid from the 216-m fracture interval was occurring. Mixing of injected fluid with fluid from the 216-m zone in TH#2 is the most likely cause of the observed temperature data. If we assume that all of the injected fluid was exiting the wellbore below 259 m, a heat balance calculation indicates that approximately 3.8 kg/s of 166°C fluid from the fracture zone located at a depth of 216 m is flowing down the wellbore with the injected fluid. This is a significant volume of fluid circulating within the wellbore. The implication of this information is that there exists a large influx of fluid into the geothermal system. However, the calculation is sensitive to the actual volume of fluid exiting out the bottom of the slim hole, and this volume can only be estimated. In any case, the data suggest that productive fractures exist to the bottom of slim hole TH#2. Furthermore, the pressure data show that there was no pressure increase at 259 m due to injection of 11 kg/s of fluid, indicating that slim hole TH#2 encountered highly productive fractures. Thus, the reservoir in the vicinity of TH#2 has a very high permeability. The productive capacity of this portion of the FWC lease is as high as that found near slim hole TH#1, located in the southern portion of the lease. The overall productive capacity for geothermal fluids in this area is substantial.

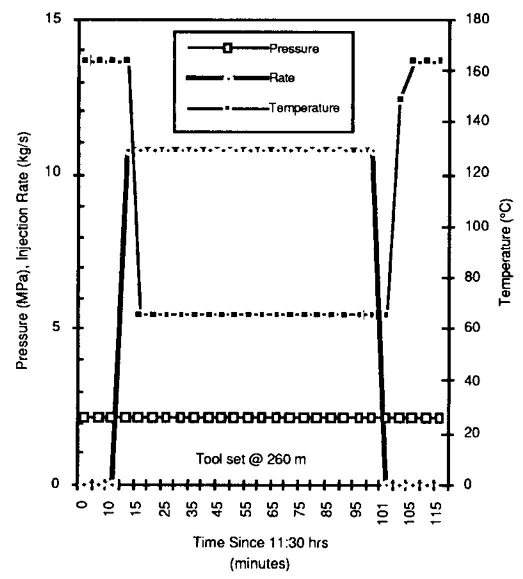

Figure 6. Downhole pressure and temperature as well as injection rate data versus time while testing of TH#2.

The temperature-depth data from slim hole TH#3 (see, Figure 4) show an isothermal zone between 213 and 251 m, which, although the total depth of TH#3 is 277 m, 251 m is the maximum depth the slim hole was surveyed. During the downhole survey, the temperature equipment would not readily pass the 251-m depth. From the thermal data, it is not clear whether this slim hole has fluid flow between the fractures intersected by the wellbore. The data obtained during the injection test are presented in Table 4. No wellhead pressure was observed while injecting 29°C fluid at 11 kg/s. The temperature at 251 m was not reduced during the injection test. These data indicate that injected fluid was not exiting the bottom of the well. Based on the geological data from this slim hole, it is postulated that fluid is exiting the wellbore between 213 and 244 m. The pressure data show that there was essentially no pressure increase at 251 m due to injection of 11 kg/s of fluid at a temperature of 29°C, indicating that this area also has a very high permeability.

Table 4. Time, pressure, temperature, and injection rate data during testing of TH#3.

Time (min)	Press @ 251m (MPa)	Temp @ 251m (°C)	Inj Rate (kg/sec)	Comments
0	2.25	166	0	
5	2.24	166	0	
9.9	2.24	166	0	
10	2.24	166	11	Start Injection
15	2.22	166	11	
20	2.22	166	11	
25	2.40	166	11	Purge Tubing
30	2.23	166	11	
35	2.23	166	11	
40	2.23	166	11	
45	2.23	166	11	
50	2.23	166	11	
55	2.23	166	11	
60	2.23	166	11	
65	2.24	166	11	
70	2.27	166	11	Purge Tubing
75	2.23	166	11	
80	2.24	166	11	
85	2.23	166	11	
90	2.22	166	11	
95	2.27	166	11	Purge Tubing
100	2.24	166	11	
101	2.24	166	0	Stop Injection
102	2.24	166	0	
105	2.24	166	0	
110	2.24	166	0	
115	2.24	166	0	

CONCLUSIONS

Slim holes have been successfully used at the Steamboat Hills Geothermal Field (1) for drilling to targeted depths in fractured volcanic and igneous rocks with partial to complete loss of circulation, (2) to obtain core for geological studies and delineation of the subsurface stratigraphic structure, (3) for characterizing the geothermal reservoir fluid state, and (4) to determine the fracture permeability and productive capacity of the geothermal reservoir in the vicinity of the slim hole.

The data from the injection tests on the three slim holes at Steamboat Hills support the premise that it is possible to obtain a definitive reservoir assessment and forecast the discharge and injection performance of large-diameter production size geothermal wells from slim hole data.

The drilling and testing of the three slim holes has yielded much insight into the geothermal system in the northeast Steamboat Hills. The slim-hole drilling program was designed to determine whether productive geothermal fluids could be found at depths sufficient for well pumping equipment and at temperatures needed for power production. The deeper (173 m to 277 m) fracture sets found in the area of the FWC leases will allow for well pumps to set to depths greater than 200 m, possibly to depth in excess of 225 m.

This will allow the geothermal production wells to be pumped at flow rates higher than existing wells in the area and allow spacing between wells to be less than with existing wells. Based on all of the available data obtained to date, the reservoir should easily supply fluid in sufficient quantities at temperatures necessary for the development of a 30 MW geothermal power project.

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