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USING FLOW TESTS IN SLIMHOLES TO REDUCE GEOTHERMAL EXPLORATION COSTS IN THE BASIN AND RANGE GEOLOGIC PROVINCE OF THE USA

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ABSTRACT

Historical geothermal exploration costs in the Basin and Range Geologic Province have been high. Average industry-wide exploration cost per high-temperature discovery between 1974 and 1981, when most of the exploratory drilling in this province took place, has been estimated at $20 million ($1982). Based on an apparent average discovery size of 64 MW, the exploration cost of finding high-temperature reserves in this province has been about $312/kW. The use of small-diameter exploratory wells, usually referred to as "slimholes", could potentially reduce exploratory drilling costs in this province by 50% and total exploration costs by 28%. The feasibility of conducting normal geothermal well tests in slimholes has been demonstrated by Anadarko Petroleum Corporation at two moderate-temperature geothermal discoveries in the Basin and Range Province.

INTRODUCTION

The drilling of small-diameter temperature gradient holes has been the most commonly employed geophysical exploration method for geothermal resources in the USA. However, the drilling of small-diameter exploratory geothermal wells designed for formation testing, while common in many other countries, has not been common in the USA. The objectives of this paper are to show the potential reduction in geothermal exploratory drilling costs associated with drilling small-diameter exploratory wells and to present two case studies where small-diameter exploratory wells were successfully tested. All of the data in this paper pertain to geothermal exploration in the Basin-and-Range Geologic Province of the USA. However, the conclusions drawn from these data should be applicable to geothermal exploration in many other geologic provinces with geothermal resources.

In this paper, exploratory wells designed for formation testing which have open-hole diameters of less than seven inches will be referred to as "slimholes". The term "slimholes" will not be used in this paper to describe temperature gradient holes or those observation wells which are not also used as test wells.

HISTORICAL BASIN-AND-RANGE EXPLORATION COSTS

Most of the exploratory drilling in the Basin-and-Range Geologic Province which has occurred to date took place between 1974 and 1981, a period characterized by both the initial leasing of federal lands for geothermal development and increasing energy prices. In an earlier study I found that between 1974 and 1981 the drilling of 53 exploratory wells resulted in six announced discoveries with reservoir temperatures above 350°F for an industry-wide exploratory well success rate of 11.3% (Edmiston, 1982). Since more than one exploratory well was drilled at some prospects, the prospect success ratio was somewhat higher at 17.1%, or about one discovery per six drilled prospects. The 53 exploratory wells included in my earlier paper excluded wells drilled within three miles of established production and small-diameter wells less than 3,000 ft in depth. Some pre-1982 discoveries with temperatures below 350°F were subsequently developed using binary power plants. However, the exploration statistics for the 1974 through 1981 period remain valid as given in 1982 since most of the drilling prior to 1982 was carried out with the intention of finding reservoirs with temperatures above 350°F.

In my 1982 paper, I estimated an industry-wide exploration cost per discovery of $20 million ($1982) consisting of $11 million in exploratory well costs and $9 million in leasing and exploration survey costs. The exploratory well cost estimate was based on an average exploratory well depth of 6,212 ft, average dry-hole cost of $200/ft, and a success rate of 11.3%. The leasing and survey costs were based on average expenditures of $750,000 on each drilled prospect and additional expenditures of $750,000 per drilled prospect on reconnaissance surveys and exploration at prospects which failed to reach the drilling stage.

In the petroleum industry, the most commonly used estimate of exploration and development efficiency is "finding cost", expressed in dollars per barrel of developed reserves. Unfortunately, the exploration portion of geothermal finding costs is difficult to estimate because of the lapse of time between the time when a discovery is made and full development of that discovery. The average capacity developed since 1982 at five of the six high-temperature discoveries made between 1974 and 1981 (Desert Peak, Dixie Valley, Steamboat, Coso, and Roosevelt) is about 64 MW. Based on an average industry-wide exploration cost of $20 million per discovery and an apparent average discovery size of 64 MW, the exploration cost of finding geothermal reserves in the Basin-and-Range Province between 1974 and 1981 was $312/kW. However, if the Coso field is excluded from the calculation, average apparent discovery size falls to 23 MW and exploration cost of finding climbs to $870/kW. The latter number is about equal to published estimates of average wellfield development costs for geothermal projects.

There are only three ways to lower the cost of finding geothermal reserves on a dollar per kW basis: (1) improve the success rate for costly full-size wells, (2) find more reserves per discovery, and (3) lower the costs of individual items in the exploration budget (wells, surveys, and lease acquisition). One of the most effective tools available to the geothermal resource manager to lower finding cost is the use of slimhole drilling in place of the drilling of full-size exploratory wells.

COST REDUCTION USING SLIMHOLE DRILLING PROGRAMS

The reduction in costs which can be realized by using slimholes in place of full-size exploratory wells are shown in Figures 1 and 2. In both figures all wells are assumed to have depths of 5,000 ft and all slimholes are assumed to cost $100/ft. The estimated cost for slimholes is based on Anadarko's geothermal experience and assumes no unusual drilling problems or operating restraints by regulatory agencies. Figure 1 shows expected total drilling cost per discovery as a function of exploratory success rate for two drilling programs; a slimhole program in which all prospects are initially tested with slimholes and a full-size well program in which all prospects are tested with only full-size wells. The slimhole program includes the drilling of one full-size well to confirm each discovery. In Figure 1,

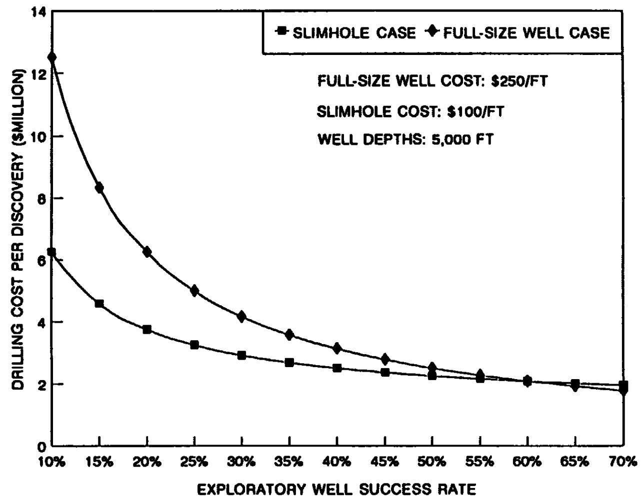

Figure 1. Expected drilling cost per discovery as a function of exploratory well success rate for a drilling program using slimholes and a program using all full-size wells.

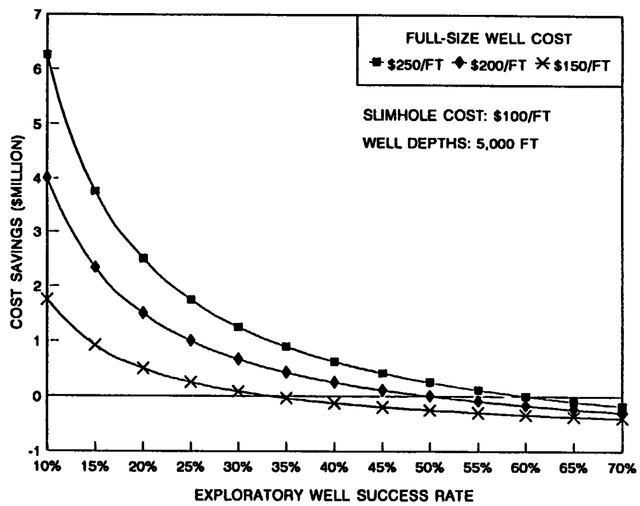

Figure 2. Expected cost savings per discovery resulting from the use of slimholes rather than full-size wells at exploratory well dry-hole costs of $150/ft, $200/ft, and $250/ft.

full-size exploratory wells at remote Basin-and-Range locations are estimated to have dry-hole costs of $250/ft. This estimate is taken from the high end of a range of estimated drilling costs for all geothermal wells given by Capuano (1992).

Under the assumptions used in Figure 1, slimhole drilling begins to become economically attractive at exploratory success rates of less than 60%. At an exploratory success rate of 25% the use of slimholes reduces expected exploratory drilling cost from $5.0 million to $3.25 million for a reduction of 35%. At a 10% exploratory success rate, which is close to the actual success rate in the Basin-and-Range Province, exploratory drilling cost is reduced from $12.5 million to $6.25 million for a reduction of 50%.

Figure 2 shows the expected cost savings per discovery for the case given in Figure 1 and for lower full-size well costs of $150/ft and $200/ft. At exploratory success rates of 25%, savings are reduced to $1.0 million when full-size wells cost $200/ft, and only $250,000 when full-size wells cost $150/ft. At exploratory success rates of 10% savings increase to $4.0 and $1.75 million for these two cases. Figure 2 shows that slimhole drilling is clearly favored when (1) slimhole costs are less than 50% of full-size well costs and (2) exploratory success rates are estimated to be 35%, or less. These calculations have not taken into account savings in full-size well cost due to optimization of the design for the full-size well when it is drilled near an existing slimhole.

OTHER BENEFITS OF SLIMHOLES

In addition to reducing overall exploratory drilling cost, slimholes (1) have fewer environmental impacts than full-size wells, (2) provide data for the optimization of full-size well designs, and (3) can be available as observation wells during the testing of full-size wells. In addition, the use of wireline continuous coring to drill slimholes has the added benefits of more definitive geological data, particularly data on fractures, and sample recovery in most lost-circulation zones. The reduced environmental impacts of slimholes are due to smaller locations, the ability to use more primitive roads, less vehicular traffic, and smaller volumes of mud and drill cuttings.

CONVENTIONAL ROTARY DRILLING VS. WIRELINE CORE DRILLING

One of the first decisions to be made in planning a slimhole is whether to drill the entire well with conventional rotary tools or drill at least a portion of it using wireline continuous coring. The differences between these two drilling techniques, as applied to geothermal drilling, are summarized by Polk and Brown (1991). Many of the differences between conventional rotary drilling and wireline core drilling are related to the small size of the annulus between the wall of the hole and the drillpipe when using wireline tools. Several papers have recently been published in the petroleum journals on problems posed by the small annulus in wireline coreholes in preventing blowouts caused by high-pressure gas entries when wireline coring is used in petroleum exploration. As described by Bode, Noffke, and Nickens (1991), the well control methods used in petroleum drilling focus on maintaining continuous circulation of the drilling mud. However, in geothermal drilling, both large and small diameter wells are often drilled with a complete loss of mud circulation. In geothermal drilling, the small annular area of wireline coreholes along with the small area of the open-hole enhance safety by restricting flow. In one of the case studies presented in this paper, the flow through unobstructed 4-1/2 inch tubing in a slimhole was only one-seventh of the natural flow from a nearby production well with 13-3/8 inch casing.

The decision to use either conventional rotary drilling or wireline coring will be influenced by the type of drilling problems expected and the formation testing to be conducted. Hard, fractured volcanic formations with numerous lost-circulation zones generally are more suited to wireline coring while sedimentary or volcaniclastic formations found in Tertiary basins can be drilled more economically with conventional rotary tools. Swelling formations are a particular problem when core drilling and may require drilling with conventional rotary tools. When the open-hole portion of the well is drilled using wireline coring, testing will most likely be done through a cemented string of casing. If the open-hole is drilled with a rockbit having a diameter of more than 6 inches, the testing can be conducted using an open-hole packer on the end of a string of tubing. Both testing procedures are described in the case studies presented below.

Unfortunately, it may not be possible to realize the environmental and economic benefits of drilling exploratory wells using wireline core drilling in many areas due to difficulty in complying with drilling regulations written for full-size rotary-drilled wells. Regulatory agencies should encourage the use of slimholes for formation testing by adopting regulations appropriate to slimholes, including coreholes, rather than insisting on complete adherence to regulations intended for production wells.

CASE STUDIES OF TWO SLIMHOLE DISCOVERY WELLS

Anadarko Petroleum Corporation has made two moderate-temperature geothermal discoveries in the Basin-and-Range Province using slimholes. The first discovery was made in the Salt Wells basin in western Nevada in a 530 ft rotary-drilled hole which was tested using an open-hole packer. The second discovery was made in Pueblo Valley in southeast Oregon in a 1,479 ft hole which was drilled using a combination of conventional rotary and wireline core drilling. The Salt Wells discovery was subsequently confirmed by a successful 100-hour pump test in an adjacent production well. Unfortunately, further drilling at the Pueblo Valley discovery has been delayed over 29 months by appeals filed with the US Interior Board of Land Appeals by the Sierra Club and others seeking to prevent the issuance of permits for two additional slimholes. The locations of both discoveries are shown in Figure 3.

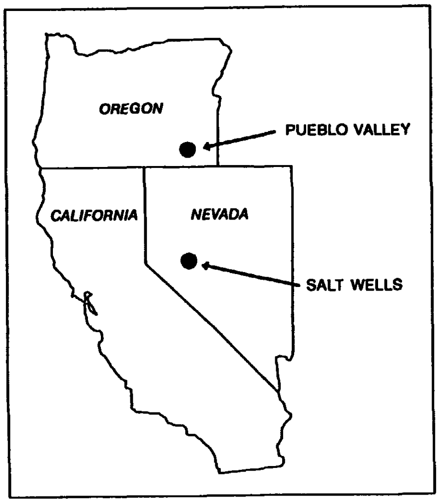

Figure 3. Location of the Salt Wells and Pueblo Valley geothermal discoveries.

Salt Wells, Nevada

At Salt Wells, Nevada a shallow geothermal reservoir in fractured basalts with temperatures of up to 287°F is being recharged at several points by upwelling hot water from deeper reservoirs with silica-estimated base temperatures of up to 400°F. A deep exploratory well drilled in 1981 produced non-commercial flows of hot water from fractured granodiorite found beneath the shallow reservoir. Maximum temperature in the deep well was 357°F at 8,500 ft.

In 1985, two successful 24-hour tests were conducted in a 530 ft slimhole completed in the shallow reservoir to evaluate an expiring lease. Following these tests, Anadarko extended the expiring lease by drilling and successfully testing a production well 105 ft from the slimhole. Figure 4 is a diagrammatic section through both the slimhole, 84-26, and the production well, Federal 14-25, showing the casing programs in both wells and the geologic log from the slimhole. Summary data on the tests conducted in both holes are given in Table 1.

The slimhole, 84-26, was originally drilled as a cased temperature gradient hole with 6-5/8 inch casing set at 83 ft in a silica-cemented sandstone. After drilling out of the casing with a 6-1/8 inch bit, siliceous sinter was encountered at 135 ft followed by red clay at 180 ft and a second interval of siliceous sinter at 265 ft. At 371 ft a fracture zone was encountered followed by basalt. Circulation, which had been lost and regained several times above the basalt, was lost again in a fracture zone extending from 436 ft to 445 ft. A third major fracture zone was encountered between 463 ft and 473 ft where the bit dropped from six inches to one foot as it encountered voids in the basalt. The hole was initially completed for temperature observation at 530 ft using 2 inch line pipe. Initial logging ten days after completion of the hole showed an isothermal interval at 261°F extending from 400 to 480 ft in the basalt.

The line pipe was later removed from the hole and a Lynes inflatable packer was set on the end of a 4-1/2 inch tubing string at 401 ft. After the tubing was hung on the wellhead, 42 ft of 1 inch line pipe was run inside the tubing to initiate flow in the well using air. The fluid level in the slimhole at this time was found to be 12 ft below the ground surface. The well begin flowing as soon as air was injected into the bubble pipe and continued flowing when the air was stopped after four minutes. The test was continued for 24 hours during which flow was estimated at about 40 gpm. Thermometers lowered in the well shortly after the test recorded maximum temperatures of about 270°F.

The first test of the 84-26 was a qualitative success. However, it was obvious that additional measurements could be made to extract more information from the well and a second 24-hour test was performed. Prior to the second test the bubble pipe was rerun to a greater depth of 105 ft and fitted with a pressure gauge. Also, a weir was installed on the outlet of the test pit. During the second test, the pressure gauge on the bubble pipe showed a drawdown of 3.9 ft at an average flow rate of 49 gpm for a productivity index of 13 gpm/ft. The maximum stabilized temperature in the slimhole after the second test was 271°F.

The full-size confirmation well, Salt Wells Federal 14-25, spudded on August 29, 1985 and was completed to a total depth of 700 ft in twelve days. The well was completed with 13-3/8 inch casing set at 385 ft based on data from the slimhole. Immediately following completion, the well was tested for two hours during which it flowed at an unassisted rate of 347 gpm. On September 26th a 100-hour pump test was begun in the Federal 14-25 under the supervision of Mr. Gerald Niimi. Figure 5 shows the flow rates during the pump test and fluid levels in the slimhole which was now in use as an observation well. Flow rates were estimated by an orifice meter and by sight gauges on two storage tanks.

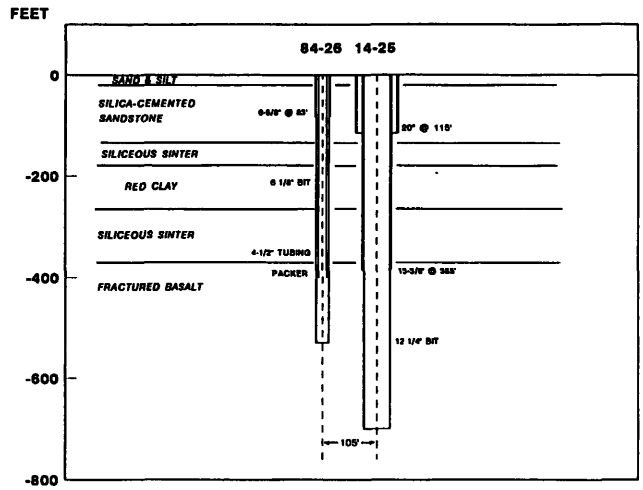

Figure 4. Diagrammatic section at Salt Wells showing the formations penetrated by observation well 84-26 and the casing programs in observation well 84-26 and production well Federal 14-25.

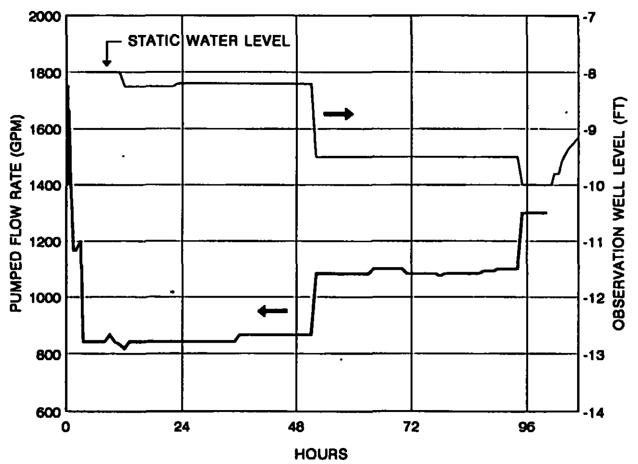

Figure 5. Production rates at Salt Wells from production well Federal 14-25 during a 100-hour pump test and corresponding water levels in observation well 84-26.

At the start of the pump test, the well was found to be producing at 1,750 gpm. This was a higher rate than the surface tanks and disposal line were designed to handle and the pump was gradually slowed to produce the well at a rate of about 850 gpm. After 48 hours of flowing the well at 850 gpm, the flow rate was increased to 1,088 gpm. The drawdown in the observation well immediately increased by 1.3 ft when the flow rate was increased. After 43 hours at 1,088 gpm the flow rate was increased to 1,300 gpm for the final four hours of the test and the drawdown in the observation well immediately increased by 0.5 ft. The fluid levels in the producing well during the test fluctuated between 21 ft and 25 ft without showing a consistent trend (Niimi, 1985). However, the pressure data from the observation well allowed Mr. Niimi to estimate reservoir transmissivities of 821,000 to 894,000 md-ft. Wellhead temperatures measured during the test varied from 254°F to 264°F and were gradually increasing near the end of the test. Equilibrium temperature surveys in the Federal 14-25 show a maximum temperature of 268°F at the casing seat at 385 ft.

Pueblo Valley, Oregon

Anadarko's discovery well at Pueblo Valley, unlike the slimhole discovery well at Salt Wells, was planned and initially permitted as a test well. The objective of the Pueblo Valley well was to test a fractured interval in volcanic formations found while drilling a temperature gradient hole in 1980. The temperature gradient hole had to be partially plugged when it encountered artesian pressures while drilling in basalt at a depth of 1,140 ft. The top of the basalt was found at 1,100 ft. The selection of the site for the temperature gradient hole was based on gravity models showing a buried horst block within the basin and an anomalous increase in temperature gradient in the bottom of a 500 ft temperature gradient hole previously completed at that site. A second intermediate-depth temperature gradient hole, drilled by Unocal between Anadarko's hole and the nearest hot springs, did not encounter the basalt found in Anadarko's hole or any zones of artesian pressure and was completed at 2,000 ft where the temperature was found to be 320°F.

Following the drilling of the 1,140 ft temperature gradient hole and acquisition of the lease on which it was drilled. Anadarko conducted a seismic reflection survey which further confirmed the existence of the horst block and provided evidence of faulting within the block. Data on the thermal anomaly at Pueblo Valley are given by Blackwell, Kelley and Edmiston (1986). Their description of the thermal anomaly remains valid, however, several of their geologic interpretations based on Anadarko's seismic data are no longer current following reprocessing and enhancement of the seismic data in 1991 using seismic processing software which was not available when the seismic data were collected in 1982.

The Pueblo Valley discovery well was drilled 500 ft from the earlier temperature gradient hole at a site where seismic data indicated the top of the basalt would again be at about 1,100 ft. The well, designated Federal 25-22A, was spudded on October 8, 1989 by Tonto Drilling Services Rig No. 20, a Universal Model 1500 drilling rig capable of both conventional rotary and wireline core drilling. The conductor hole was drilled to 33 ft using a 9-5/8 inch rockbit where 30 ft of 8-5/8 inch casing was set and cemented as a conductor. The surface hole was then drilled with a 7-5/8 inch rockbit to 302 ft where 6-5/8 inch casing was set. After installing and testing a double ram blowout preventer, the intermediate hole was drilled in hydrothermally altered sediments using a 5-5/8 inch rockbit.

The drilling program called for setting 4-1/2 inch casing at 1,100 ft and converting to core drilling with a HQ (3.8 inch) core bit. However, the top of the volcanics was encountered at 1,087 ft and the well attempted to flow while being deepened an additional five feet prior to running casing. In order to ensure a good cement job on the critical intermediate casing string, a cement plug was set and partially drilled out prior to running 4-1/2 inch casing at 1,087 ft. This resulted in good circulation returns to the surface throughout the cementing of the casing. After testing the blowout preventer and drilling out the cement inside the casing, drilling continued with HQ wireline coring tools as planned. Mud weight was continually monitored and adjusted to keep the mud column in approximate hydrostatic balance with formation pressures while the hole was drilled to a final depth of 1,479 ft. There were no circulation returns while drilling most of the cored interval. However, the well attempted to flow through the drillpipe when the core tube was recovered due to the swabbing action of the core tube. The cores recovered between 1,092 ft and 1,479 ft had intervals of open, quartz-lined fractures in hydrothermally altered volcanic formations of varying composition.

After reaching final depth on October 23, 1989, the well was rigged for flow testing and a 22-hour flow test was begun the following day. Summary data from the test are given in Table 1. Downhole and wellhead pressure measurements were recorded continuously during the test using quartz transducers and capillary tubing. The well begin flowing as soon as the wellhead valve was opened and flowed at a peak rate of 400 gpm through a 4 inch flowline and 3 inch orifice plate. The well was shut-in twice during the test to record pressure buildup data.

Figure 6 is a photograph taken near the start of the test showing the drilling rig and a storage tank used to measure the water discharged from the well. A small separator, visible to the left of the tank, was used to separate the steam and hot water prior to their being discharged into the tank. The use of the separator eliminated surging in the storage tank and allowed more accurate measurement of the water level in the tank using a sight gauge. Flow rates were also measured using a weir, which is not visible in the photograph, and the orifice meter on the flowline. Flowing wellhead pressures during the test varied from 69 to 75 psig and wellhead temperatures varied from 300°F to 305°F. Stabilized shut-in wellhead pressures after the test were found to average 64 psig. The test was supervised by Mr. Gerald Niimi who calculated transmissivities in excess of 1,000,000 md-ft from the test data (Niimi, 1989).

The Pueblo Valley Federal 25-22A is believed to be the first geothermal slimhole in the USA to be completed by wireline core drilling and successfully tested using standard geothermal testing procedures.

CONCLUSIONS

1. Historical geothermal exploration costs in the Basin and Range Province have been high. Total industry-wide exploration cost has been about $20 million per discovery ($1982) of which about $11 million has been spent on exploratory wells.

2. The industry-wide exploration cost of finding geothermal reserves in this province, based on an average developed capacity of 64 MW for five discoveries made between 1974 and 1981, has been about $312/kW ($1982). If the largest of the five discoveries is excluded, average developed capacity falls to 23 MW and exploration cost of finding climbs to $870/kW.

3. The only ways to lower the cost of finding geothermal reserves are to (1) improve the success rate for costly full-size wells, (2) find more reserves per discovery, and (3) lower the costs of lease acquisition, exploration surveys and wells.

4. At the 11.3% exploratory success rate estimated for this province between 1974 and 1981, the use of slimholes to test all exploration targets could potentially reduce total exploratory drilling cost by about 50% and total exploration costs per discovery by about 28%.

Figure 6. Testing of the slimhole discovery well at the Pueblo Valley geothermal discovery on October 24, 1989.

Table 1. Summary data on slimhole discovery wells at the Salt Wells and Pueblo Valley geothermal discoveries and a full-size confirmation well at Salt Wells.

	SALT WELLS 84–26	SALT WELLS FED. 14–25	PUEBLO VALLEY FED. 25–22A
Well Data			
Well Type:	Slimhole	Production	Slimhole
Casing/Tubing Diameter:	4–1/2" Tubing	13–3/8"	4–1/2" Casing
Casing/Tubing Depth:	402'	385'	1,092'
Casing/Tubing, Other:	2" ID Packer	–	–
Open–hole, Bit Size:	6–1/8"	12–1/4"	3.8" (HQ)
Total Depth:	530'	700'	1,479'
Reservoir:	Fractured basalt	Fractured basalt	Fractured volcanics
Test Results			
Date of Test:	5/23/85	9/26/85	10/24/89
Type of Test:	Unassisted	Pumped	Unassisted
Duration of Test:	26 hrs	100 hrs	22 hrs
Maximum Flow–rate:	49 gpm	1,750 gpm	400 gpm
Average Flow–rate:	49 gpm	1,300 gpm	374 gpm
Drawdown:	3.9' (ave)	13' (ave)	10' (max)
Productivity Index:	13 gpm/ft	100 gpm/ft	40 gpm/ft
Transmissivity (kh):	–	821,000 md–ft	>1,000,000 md–ft
Flowing W/H Temperature:	230F	254–264F	300–305F
Flowing W/H Pressure:	8 psig	40 psig	69–75 psig
Shut–in W/H Pressure:	0 psig	0 psig	64 psig

5. Slimholes also (1) have fewer environmental impacts than full-size wells, (2) provide data to optimize full-size well designs, and (3) can be used as observation wells during the testing of full-size wells.

6. Successful tests in two slimhole discovery wells, one completed by conventional rotary drilling and one completed by wireline coring, demonstrate the feasibility of testing moderate-temperature geothermal reservoirs in the Basin-and-Range Province with slimholes using presently available technology.

ACKNOWLEDGEMENTS

All of the drilling and testing operations described in this paper were performed under the capable supervision of Mr. James H. Moss. Mr. Moss was employed by Anadarko Petroleum Corporation as a drilling supervisor during the drilling of the two Salt Wells wells and was retained as a consultant during the drilling of the Pueblo Valley well. The author acknowledges the support of Anadarko Petroleum Corporation in allowing publication of this paper.

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