ADVANCES IN MULTIPLE-LEGGED WELL COMPLETION METHODOLOGY AT THE GEYSERS GEOTHERMAL FIELD, CALIFORNIA

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Key Words: Geysers, drilling, multiple-legged wells, forked wells, Aidlin project

ABSTRACT

Drilling or recompletion of production wells with two or more producing wellbores is a technique that has been used successfully by several operators in the southwestern part of the Geysers field to increase well productivities and decrease the unit cost of steam production. The northwestern part of the field poses special difficulties for drilling multiple-legged or "forked" wells, because of greater reservoir depth, higher reservoir temperatures, the need for narrower well completions, and less stable rock conditions.

Three wells within the Aidlin project area of the northwest Geysers were recompleted as 2- and 3-legged producers during 1992-1993, using both existing and new methods for coping with the conditions in this part of the field. Total drilled depths of the producing legs were as much as 11,345 feet (3,458 m), and kickoff points were as deep as 7,895 feet (2,405 m) from 9-5/8-inch production casings. Reservoir temperatures in directionally drilled intervals reached in excess of 600°F (315°C).

Drilling problems related to the challenging conditions were experienced, and were resolved by a combination of preventive and remedial measures, particularly in directional drilling techniques and the treatment of circulation losses and poorly cemented casings. The drilling of the additional legs resulted in an average increase of 58% over the original well productivities, making the technique cost-effective in spite of the associated problems and risks. Improvements in drilling technology, particularly in high-temperature directional drilling equipment, could further improve the viability of deep and hot multiple-legged wells.

1. INTRODUCTION

The Geysers geothermal field in northern California (Figure 1) is a dry steam field in a mature stage of development. Extensive exploration and development drilling has delineated the field and led to a detailed understanding of its production characteristics and subsurface geology. Because subsurface conditions are well known, the steamfield operators have been able to adopt standardized well designs and drilling methodologies that maximize the productivity of new steam wells while minimizing drilling costs and mechanical well problems. In many parts of the field, basic well designs have undergone little or no change in the past decade. The rate of drilling success, measured as the proportion of wells that are commercially productive, has been consistently high throughout most of the field, even as average well productivity has declined in response to production.

The relatively stable development environment and the declining output of the field have encouraged the field operators in recent years to investigate new techniques of increasing well productivities. Operational techniques, particularly strategic management of water injection, have yielded notable benefits. The primary and most successful drilling methodology used to improve well outputs has been the completion of wells with two or more producing legs feeding a single cased wellbore. Such multiple-legged wells are often referred to as "forked" or "twinned" wells.

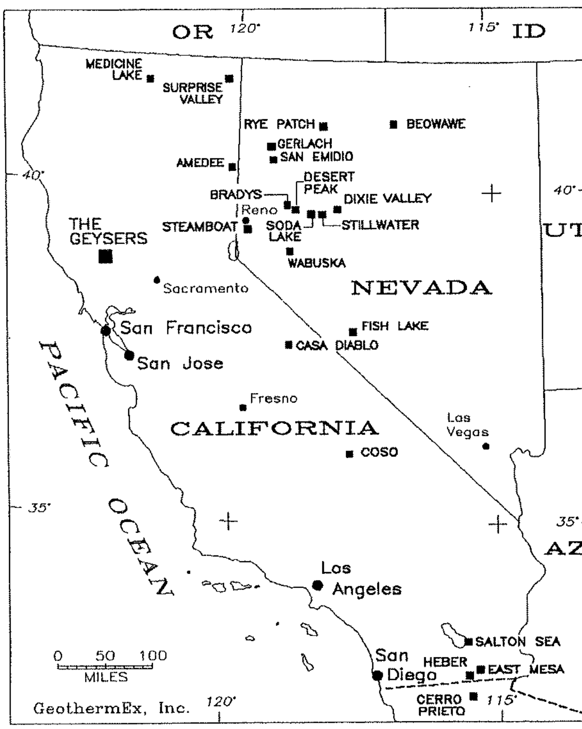


Figure 1. Location of The Geysers geothermal field. Also shown are other significant developed or explored geothermal fields in California and Nevada.

Forked wells offer a steam productivity that can approach the productivity of two separately drilled wells, at a cost substantially lower than that of two wells. Furthermore, total steam production from a well may be increased by extending the useful lifetime of a well before it reaches an abandonment condition dictated by a low flow rate. Additional cost savings result from more efficient use of surface facilities, and from reduced planning and permitting costs. However, the procedures required to drill a second wellbore while maintaining the original wellbore in a useful condition can be complex and risky. Therefore, the technique for completing multiple-legged wells is still under development and refinement, and its use is expanding slowly though steadily.

The drilling and completion of multiple-legged wells was first attempted in the southeastern portion of the Geysers field (Figure 2). In this part of the field, the reservoir is relatively shallow, permitting exploitation by shallower wells with larger production casing diameters, and competent rock is found throughout the production interval. These factors favored experimentation with and refinement of the forking technique, which was first developed and described by the Northern California Power Agency (NCPA) (Yarter *et al.*, 1988). Other operators in the southeastern Geysers have since adopted the technique, experimenting with variations in procedures and equipment (*e.g.* Steffen, 1992).

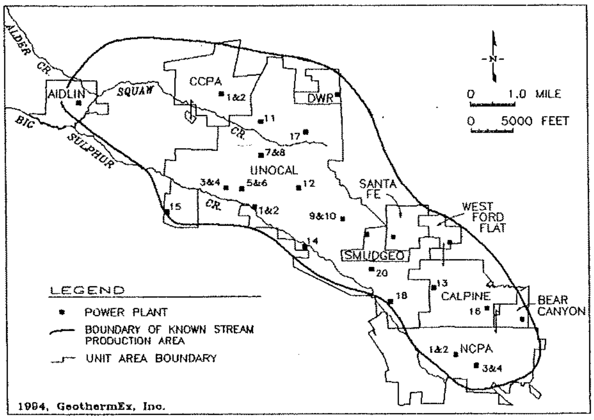


Figure 2. Map of The Geysers field, showing the location of the Aidlin leasehold and other operating areas.

In the northwestern part of The Geysers, drilling conditions are more severe. The reservoir is deeper and hotter, and unstable rock is often present near or within the reservoir zone. These conditions add extra difficulty and risk to drilling multiple-legged wells. Nevertheless, recent experience in the northwest Geysers has shown that wells there can be successfully forked to yield an economically significant improvement in well productivity.

During 1992-1993, Geothermal Energy Partners, Ltd. (GEPL), the owner of the 20 MW (net) Aidlin geothermal project, carried out an infill drilling program that included drilling forks on three of the five production wells supplying the power plant at that time. These multi-legged completions were made in wells deeper and hotter than any to which the technique had previously been applied.

2. THE AIDLIN PROJECT

The Aidlin leasehold is located in the northwestern corner of the developed Geysers geothermal field (Figure 2). Certain aspects of the Aidlin area, including unusually high reservoir pressures, have led to speculation that it may be somewhat separate structurally and thermodynamically from the rest of The Geysers, but for the most part its characteristics resemble those elsewhere in the field. Wells produce dry, moderately superheated steam from fractures of apparently random orientation in a reservoir composed of graywacke, lesser argillite and minor greenstone, all of Mesozoic age. Concentrations of non-condensible gases, predominantly CO_2 and H_2S, are generally high compared with the rest of The Geysers and vary considerably from well to well; the anticipated spatial distribution of gases is taken into consideration when siting new wells in order to minimize the overall concentration in the plant steam supply. Reservoir temperatures are also higher than in much of the rest of the field, reaching at least 600°F (315°C) in some wells.

Exploration of the Aidlin area began in the mid-1970s, with development continuing until the 20 MW (net) power plant began operation in 1989. In contrast to some other plants at The Geysers, power from the Aidlin plant is sold under a relatively favorable contract that makes it economically viable at present to drill new wells as needed to maintain full plant output. Initially, four production wells supplied the power plant; the gassiest of these has since been converted to an injection well. Two new production wells were added in 1990 and 1992, and a third is being drilled and should be completed before the end of 1994.

All of the production wells and the two injection wells used by the project are drilled directionally from just two well pads to reach their targets, with well deviations reaching as much as 40° from vertical. Drilling experience has led to a standard well design that incorporates a 20-inch surface casing, a 13-3/8-inch intermediate string set at 4,500 to 5,000 feet (1,370 to 1,520 m) depth, and a 9-5/8-inch production casing cemented at 7,500 to 9,500 feet (2,300 to 2,750 m). The 8-1/2-inch unlined production wellbores are drilled with air to depths as great as 11,350 feet (3,450 m).

After completing the second infill well in 1992, GEPL chose to further augment the available steam supply by drilling forks on the three wells that had suitable casing designs.

3. DRILLING METHODOLOGY

Completing a well with two or more producing wellbores requires that a second or subsequent wellbore be sidetracked from the original wellbore, while maintaining the original hole either open or capable of being re-opened without damage. The need to selectively enter one of two branching wellbores is normally fulfilled by using directional drilling techniques to ensure that one wellbore is strongly deviated and cannot be entered with a stiff drilling assembly. The stiff assembly can then be used to preferentially enter the straighter of the two legs. Several slightly different

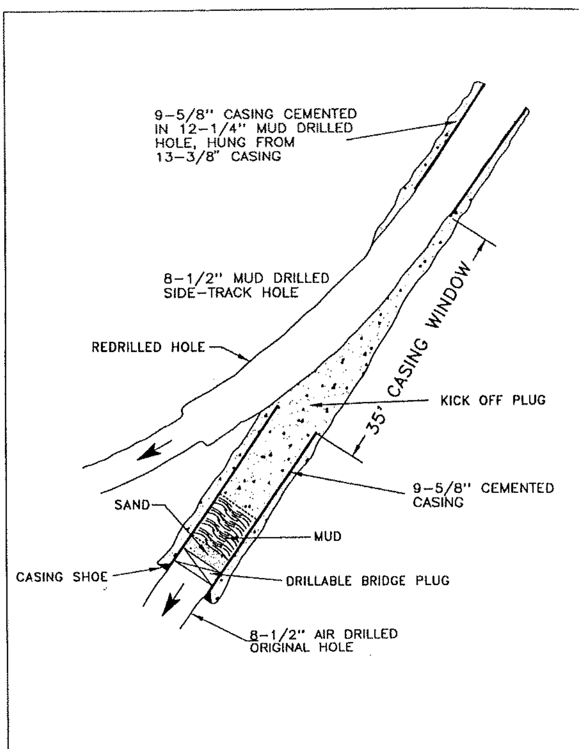


Figure 3. Detail of sidetrack and casing window (modified from Yarter *et al.*, 1988).

techniques for drilling forks have been developed based on this concept. The technique described here has been proven effective in a number of wells in the southeast Geysers (Yarter *et al.*, 1988), and was used successfully in the Aidlin area wells.

To begin the procedure, a drillable bridge plug is placed in the production casing below the intended kickoff depth of the sidetrack (fork), and sand is placed on top of the plug. A window about 35 feet (9 to 10 m) long is milled in the casing above the bridge plug, and sufficient cement is spotted to cover the sand and fill the window (Figure 3). After cleaning out the cement to the top of the window, a directional drilling assembly with a mud motor is used to deviate out of the original wellbore and begin the sidetrack. Directional drilling with mud continues until the sidetrack reaches its desired course. The wellbore can then be deepened by air drilling to its total depth; in this stage, the deviation angle may be controlled using different drilling assemblies, but azimuth control is not normally possible.

After the fork is completed, a stiff drilling assembly (incorporating closely spaced stabilizers and large-diameter drill collars) is used to clean out the casing window and to enter the casing stub below the window (Figure 4). The cement, sand and bridge plug in the stub are drilled out, and the original hole is cleaned out as necessary.

It should be noted that this procedure, and others used at The Geysers for drilling multi-legged wells, are appropriate for dry steam wells that require no perforated liners in their production zones, but may not be readily applicable to production wells in water-dominated fields, particularly if liners are required to prevent hole collapse. It is probable that some experimentation would be necessary before a secure and effective method of completing multiple-legged wells could be developed in any particular hot-water field, and the benefits obtained would depend on the characteristics of the individual field.

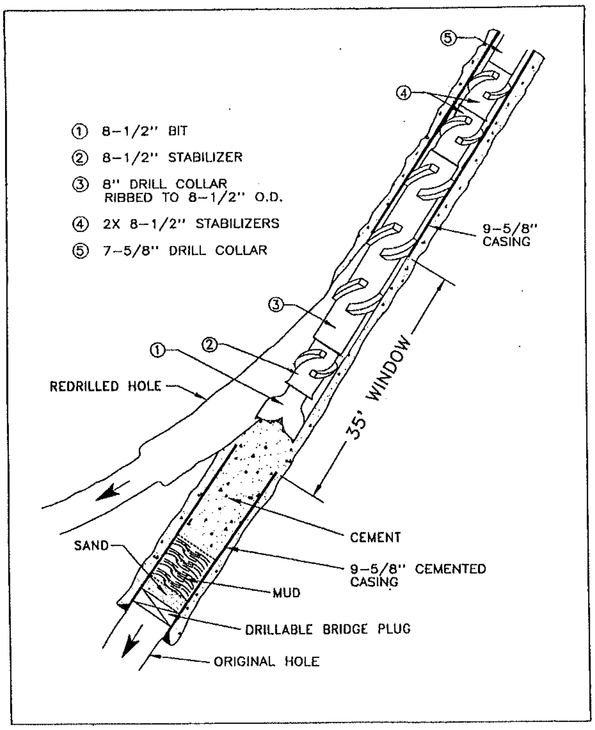


Figure 4. Re-entering the original hole (modified from Yarter *et al.*, 1988).

4. SITE-SPECIFIC PROBLEMS

Several aspects of the Aidlin area posed challenges to the application of the technique described above. Specifically:

- Because the wells and their production casings are deeper than in the southeastern part of The Geysers, the directional drilling necessary to begin a fork must take place at a greater depth. This makes directional drilling operations more difficult, more expensive and less precise, and the risk of losing tools in the well is greater. Also, because of the wells' greater depths, their production casings are of a smaller diameter, further complicating directional operations.
- Higher reservoir temperatures in this part of the field also contribute to difficulties in directional drilling, as well as in other operations such as setting plugs.
- The rocks at the depth of the production casing shoes are predominantly argillitic, and frequently unstable. This increases the risk of hole collapse within the casing window or the first several hundred feet of the fork. Such collapse can lead to entrapment of the drill string or loss of the wellbore.
- Losses of circulation near the depth of the production casing shoe are common. This can complicate or limit directional drilling, and may contribute to wellbore instability.
- Unfavorable subsurface conditions have resulted in poor cementation of the production casings in several of the older wells. Where cementation is poor in the vicinity of the casing shoe, circulation can be lost through the casing annulus when milling the window to begin the fork sidetrack. When this occurs, it becomes necessary to perform a remedial cementation of the casing window. In addition, mud lost through the casing annulus may damage the original hole.

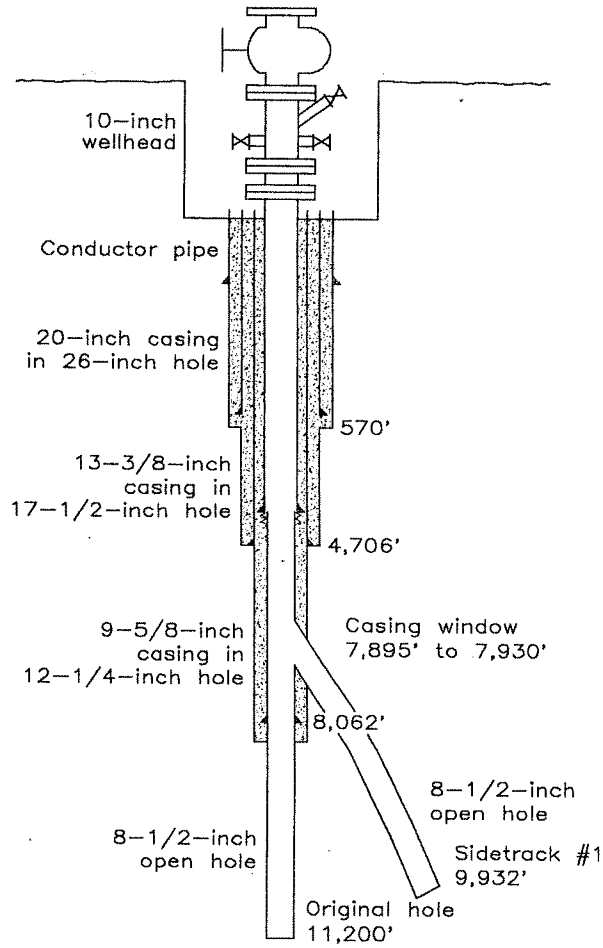
These problems, added to the normal difficulty and risk inherent in drilling forked wells, required that the drilling operations be conducted with particular patience and care in order to obtain satisfactory results.

5. FORKING OF AIDLIN No. 7

Aidlin No. 7 was the least productive of the wells available for forking. Therefore, it was selected as the first well to be recompleted.

Problems related to poor cementation of the production casing were encountered in the initial stages of the operation. As soon as the milling of the window in the production casing was begun, circulation was lost completely through the casing annulus, causing drilling mud to flow into the original productive wellbore. The bridge plug set in the production casing was drilled out in order to investigate the condition of the open hole, which was found to be bridged several hundred feet below the production casing shoe. The hole was backfilled with sand placed on top of the bridge, and a cement plug was placed to seal and secure the zone around the production casing shoe. The milling of the casing window and drilling of the fork then proceeded as planned.

The fork was kicked off and drilled directionally to its intended course without difficulty, then drilled with air to its final depth of 9,932 feet (3,027 m). A short flow test of the



1994, GeothermEx, Inc.

Figure 5. Schematic diagram of Aidlin No. 7 after recompletion.

fork was performed, after which the original hole was successfully re-entered. Several days were spent cleaning sand and other fill from the original hole in order to re-establish its productivity. The total drilling time required to recomplete the well as a forked producer was 31 days. Figure 5 shows the final configuration of Aidlin No. 7, and Figure 6 shows the trace of the well in plan view.

A flow test of the completed well indicated that the recompletion resulted in an increase of productivity from 70,000 pounds per hour (32,000 kg/hr) to 125,000 lb/hr (57,000 kg/hr), or an increase of 79%. However, the final flow rate was less than the sum of the flows of the two legs measured separately (Table 1). This indicates that some interference exists between the two producing legs. Such interference was expected, because the major productive zones of Aidlin No. 7 are located not far below the production casing shoe; therefore the separation of the two legs of the well is small where most of the steam production originates.

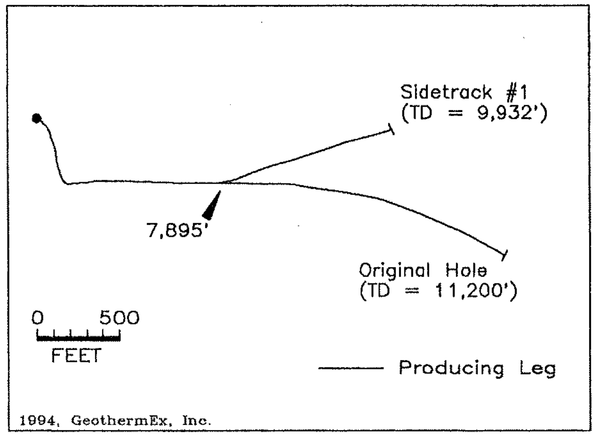


Figure 6. Well trace map of Aidlin No. 7 after recompletion.

6. FORKING OF AIDLIN No. 9

Immediately following the completion of work on Aidlin No. 7, a forking operation was begun on Aidlin No. 9. No problems occurred while plugging the production casing, milling the casing window and kicking off the sidetrack. However, as the directional drilling of the sidetrack was completed, the drill string became stuck, and it was necessary to back off and fish the bottomhole assembly before continuing. The production interval of the fork was drilled with air to a depth of 10,348 feet (3,154 m). A flow test showed the fork to be of approximately the same productivity as the original hole.

Based on the success of the forks of Aidlin No. 7 and 9, and on indications of favorable conditions in Aidlin No. 9, it was decided to attempt a second fork of the well in order to

Table 1. Summary of Multiple-Legged Recompletions, Aidlin Area

Well	Number of Producing Legs	Original Hole Depth (feet KB)	Kickoff Depth (feet KB)	Fork Depth (feet KB)	Days to Recomplete	Original Hole Productivity (lb/hr)[a]	Fork Productivity (lb/hr)[b]	Combined Productivity (lb/hr)	Percent Increase in Productivity
Aidlin #7	2	11,200	7,895	9,932	31	70,000	113,000	125,000	79
Aidlin #9	3[c]	10,841	7,367[d]	10,820[e]	97	75,000	74,000[f]	116,000[g]	55
Aidlin #6	2	11,308	7,860	11,345	49	100,000	65,000	140,000	40

[a] Productivity when last online before recompletion
[b] Productivity of fork(s) tested alone
[c] Drilled 4 sidetracks total to yield 3 producing legs
[d] Kickoff depth of Sidetrack #2
[e] Depth of Sidetrack #3
[f] Combined productivity of Sidetracks #2 and #3
[g] Combined productivity of Sidetracks #2, #3 and #4

complete Aidlin No. 9 as a three-legged producer. The process of drilling a second fork is identical to that of drilling the first, and is carried out before re-entering the original hole, so that both the first fork and the original hole may be cleaned out after the second fork is completed. Therefore, a bridge plug was set above the casing window of the first sidetrack, and a second window was milled above the plug. Circulation was lost as the window was milled, and two cement plugs were required to seal and fill the window in preparation for kicking off the second sidetrack.

The new fork was deviated to the opposite side of the original hole from the first fork (Figure 7), and was inclined to a maximum drift angle of 66° from the vertical near its total depth of 10,070 feet (3,069 m). Although no serious drilling problems occurred, the productivity of the fork was a subcommercial 10,000 to 15,000 lb/hr (4,500 to 7,000 kg/hr).

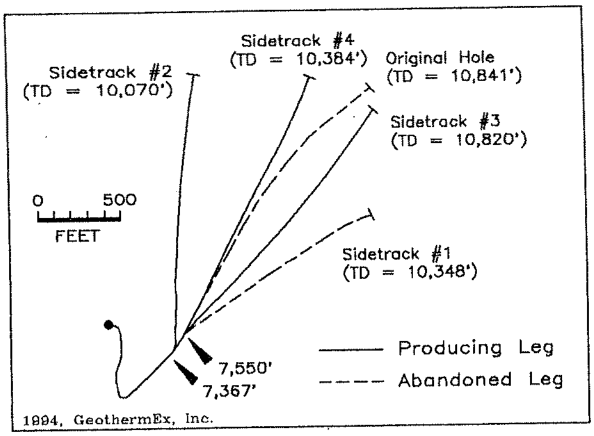


Figure 7. Well trace map of Aidlin No. 9 after recompletion.

The casing stub between the two windows was successfully re-entered. Howevever, while milling the bridge plug set above the bottom window, the drill string torqued up suddenly, then released, allowing several hundred feet of drill string to back off and fall into the first fork. A 10-day fishing job failed to retrieve all of the lost string, so it was not possible to clean out the first fork. Instead, a third sidetrack was drilled alongside the the first, to a depth of 10,820 feet (3,298 m; Figure 7). This sidetrack, in combination with the subcommercial second fork, yielded a steam flow approximately equal to that of the abandoned first fork.

It remained to re-enter and clean out the original hole in order to complete the forking operation. However, by this time the casing stub below the bottom window was too damaged by drilling and fishing to be re-entered, despite repeated attempts. It was decided that the most prudent option was to drill an additional sidetrack, close to the course of the original hole, in order to replace its lost production. The fourth sidetrack was therefore drilled in the same manner as the third, reaching a total depth of 10,384 feet (3,165 m) in a drilling time of 13 days.

Aidlin No. 9 was recompleted with three legs open and producing (Figure 7) in a total elapsed drilling time of 97 days. A flow test performed after finishing the fourth sidetrack indicated a combined productivity for the three legs of 116,000 lb/hr (53,000 kg/hr), a net increase of about 55% as the result of the recompletion.

7. FORKING OF AIDLIN No. 6

The third and final forking operation in the Aidlin project was carried out on Aidlin No. 6, the most productive well in the leasehold.

Records from the original drilling of the well indicated that its production casing was likely to be poorly cemented near the shoe. Therefore, the potential for loss of mud through the casing annulus was checked by gun-perforating the casing below the planned window depth. No loss of fluid occurred as a result of the perforation, so it was judged safe to proceed with milling the window. However, circulation was lost completely as soon as milling began. A cementation of the annulus was performed, and the window was completed.

Additional difficulties were encountered when directional drilling began. Aidlin No. 6 is an extremely hot well, and the mud in the wellbore could not be cooled sufficiently to safely run the measurement-while-drilling (MWD) tool used in the other wells for kicking off and deviating the fork. It was necessary to use instead an older-style wireline steering tool. As a result of the poorer orienting capability of the wireline tool, the drill string failed to clear the casing window in the initial kickoff attempt. The window was re-cemented and the kickoff successfully repeated.

Still further problems occurred when circulation was lost while drilling directionally less than 100 feet (30 m) below the casing window. The losses could not readily be cured, so directional drilling was terminated before the fork could be deviated to its intended course, and air drilling was initiated. The fork was deepened without further problems to a depth of 11,345 feet (3,458 m), and a flow test showed it to be commercially productive (Table 1).

Standard procedures were used to try to re-enter the original hole. However, the drilling assembly failed to penetrate inside of the casing stub, even as a variety of bottomhole assemblies were tried over a period of several days. Eventually it was decided to redrill the original hole rather than continue to try to re-enter it. A sidetrack from the casing window was begun and drilled with air, following as much as possible the original hole's course.

After drilling about 400 feet (120 m), the new wellbore intercepted the original hole. Fortuitously, it was possible to run the drill string into the remainder of the original hole and clean it out, regaining its steam production. Aidlin No. 6 was completed as a two-legged producer, with a productivity approximately 40% greater than before recompletion (Table 1).

8. DISCUSSION AND CONCLUSIONS

The results of the multiple-legged well recompletion program carried out in the Aidlin project during 1992-1993 are summarized in Table 1. The combined initial increase in steam productivity provided by the new legs added to Aidlin No. 6, 7 and 9 was 136,000 pounds per hour (62,000 kg/hr), equivalent to about 6.8 megawatts. The average net productivity increase per well was 58%. The final tested productivity of each well was between 68% and 85% of the sum of the estimated separate productivities of its individual legs.

The minimum estimated cost to recomplete a well with a single fork is about 25% of the cost of a new well of equal depth and equivalent design. Aidlin No. 7 was forked at a cost close to this figure. The recompletion costs of Aidlin No. 6 and 9 were greater, due to their more extensive drilling problems, and to the more complex three-legged completion of Aidlin No. 9. Additional savings over the cost of a new well can be achieved when the fork is drilled in the same operation as the drilling of the original hole, eliminating the expense of an extra rig move.

The benefit that may be obtained versus the cost and risk associated with drilling a fork varies from well to well. Any of the following characteristics makes a well a more attractive candidate to be recompleted with two or more legs:

1. A moderate drift angle, and an absence of severe dog legs to the depth where the fork is to be initiated.

2. Stable conditions near the casing shoe, including good cementation, few or no loss zones, and stable rock formations.

3. The occurrence of the most important production zones deeper in the production interval, rather than immediately below the production casing shoe. This minimizes the potential for interference between legs.

4. Low productivity (due to low initial productivity or due to decline). This lessens the potential economic loss if the original hole should be lost during the forking process.

GEPL's experience in the Aidlin leasehold has shown that multiple-legged completions can economically increase productivities, even in wells that are problematic and do not exhibit all of the above characteristics. The recompletions of the Aidlin wells demonstrate that potential problems in the forking process can often be avoided by attention to proper drilling procedures, and that, when problems do occur, remedial action can be taken to avert the possible loss of steam production.

With more wells being completed or recompleted as multiple-legged producers, the technique is becoming a useful tool in steamfield development and management at The Geysers. Improvements in drilling technology, especially in directional drilling, may make the technique still more economical and versatile.

Acknowledgements

The authors would like to thank the management of Geothermal Energy Partners, Ltd., for approving and supporting the use of this drilling methodology for the Aidlin project, and for permission to publish this paper. The drilling personnel of NCPA should be credited for the development of the methodology, and for their excellent work on the Aidlin wells.

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