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DRILLING AND COMPLETION OF MULTIPLE-LEGGED WELLS IN THE NORTHWEST GEYSERS

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ABSTRACT

The technique of completing or recompleting production wells as multiple-legged or "forked" wells has been successfully applied in the Aidlin area of the northwest Geysers field. Wells in the Aidlin area are deeper, hotter and have smaller diameter casings than wells in the southeastern part of the field, where forked wells have been drilled previously. These factors, plus frequently unstable formation conditions at the production casing shoe, add further complications to the forking technique. During 1992-1993, two producing wells at Aidlin were worked over and recompleted as two-legged producers, and one new well was completed with three producing legs. Despite a variety of drilling problems, each of the recompletions resulted in a significant increase in well productivity, with an average increase per well of 58%. In addition to yielding steam production at a cost that is relatively low compared with drilling new wells, multiple-legged recompletions allow for more flexible scheduling, budgeting and permitting of drilling programs.

INTRODUCTION

One of the few improvements in drilling methodology that has helped to lower the cost of steam production at The Geysers in recent years is the drilling or recompletion of wells with two or more producing wellbores. Such multiple-legged wells are often referred to as "forked" or "twinned" wells. The technique of drilling additional open wellbores on new or existing wells was first implemented and reported by the Northern California Power Agency (NCPA) (Yarter, et al., 1988), and it has since been used by at least two other operators in the field.

A forked completion offers the opportunity to obtain additional steam production through an existing wellhead approaching or equal to that of a new makeup well, while spending a fraction of the cost of drilling a new well. The relatively new and difficult method also offers special risks, however, because the steam production of an existing well is put at risk in order to drill an additional leg.

During 1992-93, Geothermal Energy Partners, Ltd. (GEPL) undertook a drilling program to increase the steam supply for its 20 MW (net) Aidlin project. The Aidlin leasehold, located at the northwesternmost limit of the commercially developed Geysers field (figure 1), is not immediately offset by active production wells, and has not suffered severe well productivity declines, compared with other parts of the field (Barker et al, 1991; Enedy, 1991), since the power plant came on line in 1989. Nevertheless, by early 1992, normal decline of the 4 original production wells (Aidlin #1, #5, #6 and #8) and the single makeup well (Aidlin #7, completed in 1990) had left GEPL with a plant output short of nameplate capacity, and the risk of incurring revenue penalties during peak season if even one production well was damaged or otherwise forced out of service.

A new production well (Aidlin #9) was drilled during May-July 1992, adding about 85,000 pounds per hour (3.4 MW) to the steam supply. Thereafter, economic considerations and permitting restrictions made multiple-legged completions the most viable and attractive option for further increasing the steam supply. Candidates suitable for forking were chosen from the existing production wells, and were redrilled in order of their suitability. During August, 1992 to April, 1993, Aidlin #7, #9 and #6 were recompleted as forked wells.

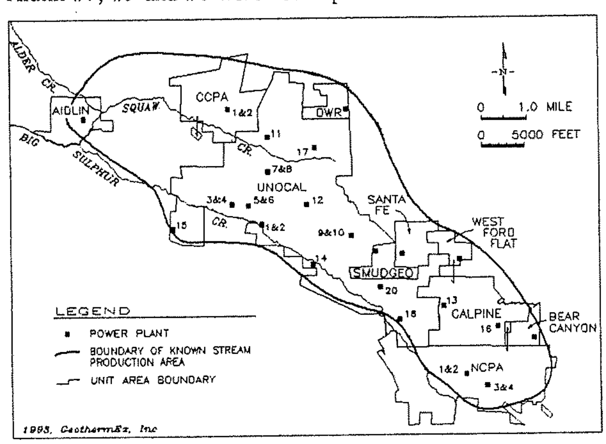

Figure 1: Location of the Aidlin Area in The Geysers Geothermal Field

DRILLING METHODOLOGY

To complete or recomplete a well with two or more producing wellbores, it is necessary to drill a sidetrack that can be entered repeatedly with a drill string (for bit changes or other operations), while leaving the original hole either open or capable of being re-opened. This may be accomplished in one of several ways.

If a new well is planned as a forked well, for example, the sidetrack can in effect be drilled first, before the primary production wellbore. In this method, the well is drilled to its casing depth and the production casing run and cemented, after which a window is milled in the casing at a selected point above the shoe. After setting a cement plug in the window, a production wellbore is then deviated out of the window and drilled to the desired total depth. Then, the cement is drilled from the casing stub below the window, using a stiff drilling assembly to stay within the casing rather than exiting the window, the casing shoe is drilled out, and the "original" hole is drilled as it normally would be.

It is possible in some cases to begin sidetrack from an existing open wellbore, rather than a casing window, and repeatedly enter the sidetrack for drilling. This can be accomplished by dropping the sidetrack below the originalhole, provided that the original hole is at a sufficient departure from the vertical.

Both of the methods described have the drawback of requiring that the second leg of the well be drilled while the first is flowing (assuming normal air drilling procedures for Geysers wells). This may make it difficult to keep the hole clear of cuttings until the second leg encounters significant steam production, and it results in higher costs for H_2S abatement and certain other services. In addition, directional control of the second leg is limited, because, while drilling with air, conventional mud motors cannot be used.

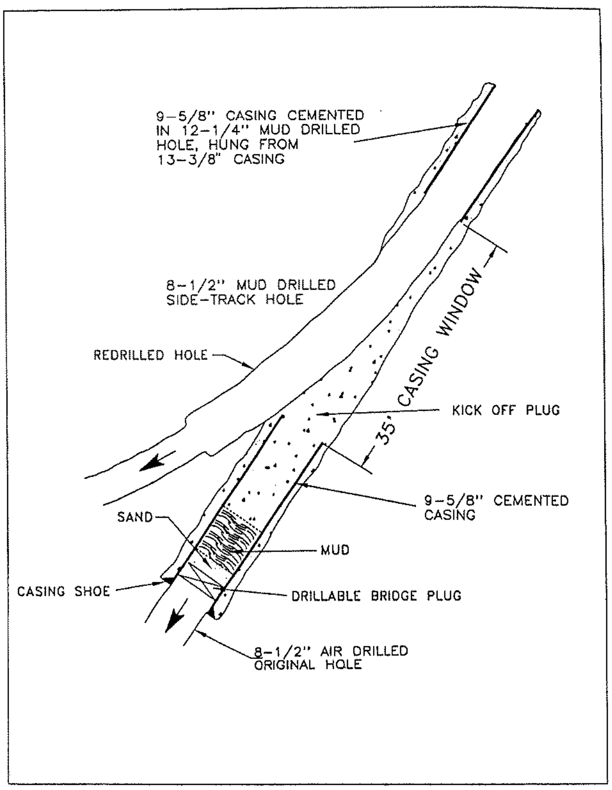

Figure 2: Detail of Sidetrack and Casing Window while Redrilling (modified from Yarter, *et al.*, 1988)

At Aidlin, the method favored by NCPA and described by Yarter et al. (1988) has been used to complete multiple-legged wells. The technique allows for maximum directional control and can be applied to both existing and new wells.

To begin the procedure, a bridge plug is placed in the casing below the intended sidetrack depth, and sand is placed on top of the plug. A window several tens of feet in length is milled in the casing above the bridge plug, and sufficient cement is placed to fill the window (figure 2). 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 well reaches the course desired for the fork. The production interval of the fork sidetrack can then be drilled with air to its total depth, dropping or adding angle but without azimuth control.

After the fork is completed, a stiff drilling assembly is used to clean out the casing window and to enter the casing stub below the window (figure 3). The cement, sand and bridge plug in the stub are drilled out, and the original hole is cleaned out as necessary.

The process described was developed in relatively shallow wells located in the southeastern part of the Geysers field. Wells in the southeast Geysers are usually completed with a 13-3/8-inch production casing run to between 3,000 and 4,000 feet. At Aidlin, production wells are considerably deeper, and are cased to 8,000 feet or more. The standard production casing and open hole diameters are 9-5/8 inches and 8-1/2 inches, respectively. These differences in well completion, along with differences in subsurface conditions, bring additional complications to the already difficult forking process. These include:

- The greater depth of the kickoff point makes directional drilling and other operations more difficult. For example: orienting the drill string when kicking off and deviating can be more time consuming, more expensive and less precise; and the risk of losing tools in the well is greater because of increased risk of sticking or accidental backoff.
- The smaller diameters of the casing and open hole add further difficulty and risk to directional drilling and other operations.
- High static and circulating temperatures, due both to high formation temperatures (in excess of 600°F at Aidlin) and long circulation times, make many operations more difficult. These include, in particular, setting bridge plugs, using mud motors and steering tools for directional drilling, placing and kicking off of cement plugs, and conducting fishing operations if needed.
- The production casings of the Aidlin wells are set in rock formations that are less stable than is typical for many areas of the Geysers. This is because the top of the reservoir is found in relatively incompetent,

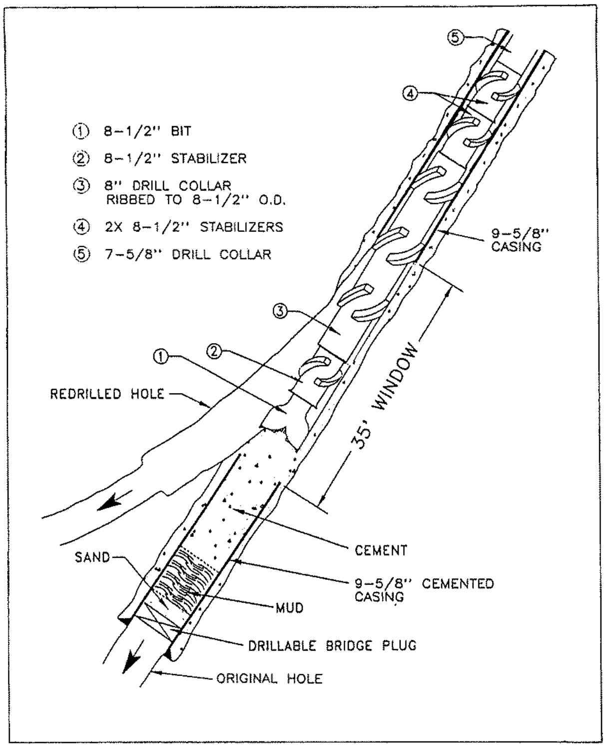

Figure 3: **Re-entering the Original Producing Leg (modified from Yarter *et al.*, 1988)**

argillitic rock. There is therefore an increased risk of instability in the casing window and in the first several hundred feet of the sidetrack, which can lead to entrapment of the drill string or loss of the hole.

- Losses of circulation are common near the production casing shoes of the Aidlin wells. This can limit the extent to which mud motors may be used, and therefore may constrain directional control of the fork.

- Due to deep casing points and to the occurrence of circulation losses, many of the older Aidlin wells have poorly cemented production casings. 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, mud is lost into the original hole, potentially damaging the production from the original hole as well as requiring remedial cementing of the window area before the sidetrack can be started.

Faced with these factors, completion of forked wells on the Aidlin leasehold not only demanded patience and willingness to improve drilling techniques through encountering a variety of new difficulties, but presented an increased probability that problems would occur even if all operations were performed correctly. A brief history of operations in the three recompleted Aidlin wells illustrates the evolution and refinement of the forking process in deep, hot wells.

AIDLIN #7

Well Aidlin #7 was a producer of average to low productivity (95,000 pounds per hour initial, 70,000 lb/hr prior to recompletion) with a standard well design (9-5/8-inch production casing plus a 10-3/4-inch tieback string; 8-1/2-inch open hole). It was chosen as the first well to be re-completed with more than one leg, because its lower productivity than other available wells made its time off production, as well as its possible loss, less critical to the output of the plant. One of Aidlin #7's drawbacks as a forking candidate was that,in the original hole, most of the production appeared to originate from steam entries within 750 feet drilled depth from the casing shoe; therefore the interference between the two producing legs of the well would be strong if the sidetrack found most of its steam at a similar depth.

A further drawback of Aidlin #7 was identified when the operation was begun. After setting the bridge plug above the 9-5/8-inch casing shoe, a window was milled in the casing. In doing so, however, circulation was lost completely after milling less than one foot. Drilling and lithological records from the original hole indicated that the loss was almost certainly through the casing annulus rather than into the formation. Therefore, the open hole condition was investigated by blowing the well dry and drilling out the bridge plug. The hole was found to be bridged several hundred feet below the casing shoe, so it was possible to sand back the wellbore and seal the casing annulus with a remedial cement job. With the casing securely cemented, it was possible to mill the window and kick off the sidetrack as planned.

After milling and cementing the window, the sidetrack was drilled to a depth of 9,932 feet in 12 days. This included both directional drilling with mud to kick off and turn the hole to its intended course, and air drilling through the production interval. Circulation was partially lost as directional drilling was completed, but this did not lead to problems.

A rig test of the sidetrack by itself indicated an initial productivity of 113,000 pounds per hour, significantly more than the 70,000 pounds per hour of the original hole. The original hole was re-entered without difficulty, but several additional days were required to clean the sand and other fill from the hole. A final rig test with both legs producing measured 125,000 pounds per hour. This is much less than the sum of the two legs tested separately, indicating that interference is significant, but in any case represents an 80% increase in productivity as a result of the recompletion. Aidlin #7 remains on line to the plant and has been free of problems.

AIDLIN #9

Well Aidlin #9 was in several ways a better candidate for a forked completion than Aidlin #7. The cementation in the vicinity of the casing shoe was known to be better, and steam production for the most part was located deeper below the shoe, so that less interference between legs was expected. A sidetrack was initiated in September, 1992, at which time the well's productivity was 75,000 pounds per hour.

No difficulties occurred in plugging the well, milling the casing window, and kicking off the sidetrack. The wellbore was deviated as planned, but the drill string became stuck when the directional interval was completed. It was necessary to back off and fish in order to recover the string. The production interval was drilled with air to a depth of 10,348 feet, and a rig test indicated a productivity for the sidetrack of 78,000 pounds per hour.

Based on the success of the forks of Aidlin #7 and #9, and on indications of favorable conditions in Aidlin #9, it was decided to attempt a second fork of the well, and complete Aidlin #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 necessary to seal and fill the window in preparation for kicking off the second sidetrack.

The new fork was deviated to the left of the original hole, opposite to the deviation of the first fork. A high drift angle was also built through the production interval, reaching a maximum of 66° near the total depth of 10,070 feet. No serious drilling problems occurred, but the productivity of the sidetrack was subcommercial, yielding an estimated 10,000 to 15,000 pounds per hour.

The casing stub between the two windows was successfully re-entered and cleaned out. However, while milling the bridge plug above the bottom window, the drill string torqued up suddenly, then released, allowing several hundred feet of drill string to back off and drop into the first sidetrack. A 10-day fishing job retrieved all of the lost drill string except the bit, and it was not possible to clean out the first sidetrack. Instead, a third sidetrack was drilled alongside the first, to replace the production of the abandoned leg. A directional drilling assembly was used through a short interval to orient the wellbore, and then the sidetrack was drilled with air to a total depth of 10,820 feet. The sidetrack was drilled in 16 days, and yielded 74,000 pounds per hour (in combination with the weak second sidetrack), close to the productivity of the lost leg.

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 recover as much production as possible. The fourth sidetrack was therefore drilled in the same manner as the third sidetrack, and was completed in 13 days at a total depth of 10,384 feet.

Aidlin #9 was recompleted with three legs open and producing (sidetracks #2, #3 and #4), in a total elapsed drilling time of 97 days (figure 4). A rig test run after finishing the fourth sidetrack indicated a combined productivity for the three legs of 116,000 pounds per hour, or a net increase of about 55% as a result of the recompletion. Although the operation was less than completely successful and demanded great patience and innovation, it demonstrated that a double-fork completion is technically possible, while at the same time illustrating that the forking technique can magnify the risks associated with routine and largely unavoidable drilling mishaps, and therefore cannot be lightly undertaken.

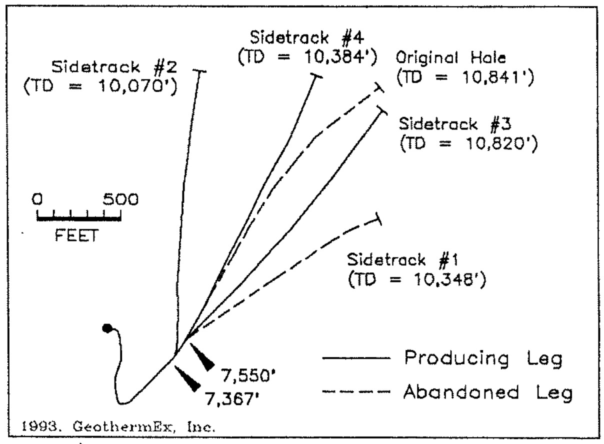

Figure 4: Well Trace Map of Aidlin #9 After Recompletion

Aidlin #6

Of the other production wells on the Aidlin leasehold, only Aidlin #6 was suitably cased to be recompleted as a forked well. However, in addition to being a highly productive well, the drilling records for Aidlin #6 showed that its production casing was likely to be poorly cemented near the shoe. Therefore the recompletion was undertaken with extreme care, in order to minimize the chance of losing all or part of the original hole's production.

As a precaution against losing circulation while milling the casing window, the casing was first gun-perforated below the planned window depth, so that the condition of the casing cement could be checked and, if needed, a remedial cementation could be performed before filling the well with mud. No losses occurred when the perforations were shot; therefore 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 made, and the window was completed.

Further difficulties were encountered when directional drilling began. Aidlin #6 is an extremely hot well, and the mud in the wellbore could not be cooled sufficiently to safely run the measure-while-drilling (MWD) tool normally used for kicking off. It was necessary to use an older-style, wireline steering tool for directional drilling in order to circumvent the temperature problem. As a result of the poorer directional control available with the wireline tool, the drill string failed to clear the casing window sufficiently in the initial kickoff attempt. The window was re-cemented and the kickoff successfully repeated.

Whereas the original hole had not encountered any circulation loss zones through this interval, fluid losses began in the sidetrack less than 100 below the casing window. The losses could not readily be cured, so directional drilling was terminated short prior to reaching the intended well course, and air drilling began. The sidetrack was drilled without difficulty to a total depth of 11,345 feet, and tested at an initial productivity of about 65,000 pounds per hour.

Standard procedures were used to re-enter the original hole; however these were unsuccessful, as the drilling assembly repeatedly failed to penetrate inside of the casing stub. A variety of bottomhole assemblies were tried, over a period of days, in an attempt to enter the stub, but none succeeded. 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, 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, thereby regaining its steam production. Aidlin #6 was therefore completed essentially as planned (figure 5), as a two-legged producer. A final test of the well, with both legs producing, indicated a productivity of about 140,000 pounds per hour, a net increase of about 40% as a result of the fork.

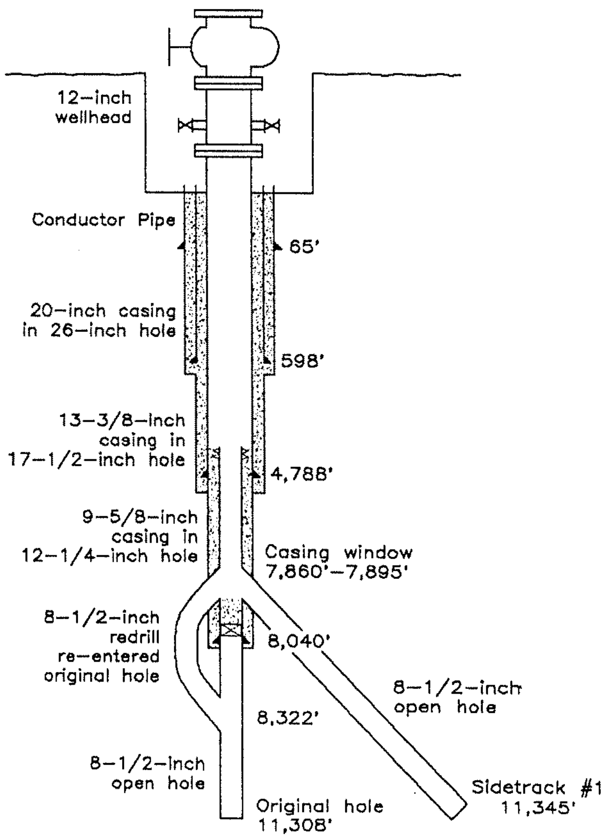

Figure 5: Schematic Diagram of Aidlin #6 After Recompletion

DISCUSSION

Despite a variety of drilling problems, the recompletion of three production wells of the Aidlin project as multiple-legged wells was successful and has contributed significantly to the steam supply for the project. The productivity of each of the wells was increased by a significant percentage as a result of the recompletion. To the knowledge of the authors, these are the deepest and hottest geothermal wells in the world to which the forking method has been successfully applied.

Table 1 summarizes the results of the recompletion program. The combined initial increase in steam supply resulting from the three recompletions was 136,000 pounds per hour, or about 6.8 MW, and the average net productivity increase per well was 58%. For each of the wells, the combined initial productivity of the completed well was somewhat less than the sum of the estimated productivities of each leg; this indicates that some degree of interference between producing legs is present.

The minimum estimated cost to recomplete a well with one additional producing leg is about 25% of the cost of a new well of equivalent depth. Aidlin #7 was recompleted at a cost close to this figure. The recompletion costs of Aidlin #6 and #9 were greater, due to their protracted drilling problems and to Aidlin #9's more complex three-legged completion. In addition to their relatively low drilling costs, the recompletions make the most efficient use possible of existing steamfield facilities, and thereby reduce the long term costs of pad and sump construction, permitting, piping, connection and steamfield maintenance.

CONCLUSIONS

- The methodology of multiple-legged completions in dry steam wells is improving and expanding to deeper, hotter and more technically challenging wells. This increases the opportunity for savings in drilling costs, but also increases the risks associated with failures.
- Forking existing or newly drilled wells in the northwest Geysers can increase initial productivity by 50% or more, at around 25% of the cost of a new well when a problem-free recompletion is carried out.
- Even when problems occur, remedial action can be taken to recover the production from lost wellbores, if necessary.
- Forking may be beneficial for other reasons, including more efficient use of steamfield facilities, more flexible scheduling and budgeting of drilling operations, lessened environmental impacts, and a simpler and quicker regulatory approval process.

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

- Existing wells with the following features are the more attractive candidate for forked recompletion:

    1. Low productivity (due to low initial productivity or due to decline), which lessens the potential economic loss if the original hole should be lost.

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

    3. Stable conditions near the casing shoe, including good cementation, few or no loss zones, and stable formation.

    4. Moderate drift angle and no severe dog legs to the casing shoe depth.

- Improvements in equipment, particularly more temperature-resistant directional drilling equipment, could make forked recompletions simpler and less risky, thereby improving their economic viability.

ACKNOWLEDGEMENTS

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