Chapter 11

HIGHLY DEVIATED AND HORIZONTAL WELLS

The tools and techniques discussed in earlier chapters are normally used to drill directional wells whose maximum inclination is about 60°. Highly deviated wells may be described as those wells whose inclination exceeds 60° for most of their length. It is possible to extend directional drilling techniques to increase the inclination to 60–90°, although alterations may have to be made to drilling practices. Modifications to standard rig equipment may also be necessary to drill these high-angled wells successfully.

A horizontal well may be defined as a well which is drilled to an inclination of 90°, and maintains this inclination for a significant distance. Owing to the need for special equipment and the longer drilling times that must be expected, horizontal wells are considerably more expensive than conventional deviated wells.

The most obvious advantage to be gained by extended reach drilling is the increased in horizontal displacement from a central platform. Consider the example shown in Fig. 11.1. Taking KOP = 2000 ft, build up rate = 2°/100 ft, target TVD = 10,000 ft and inclination = 60°, the horizontal reach is 10,992 ft, corresponding to a drainage area of 13.6 square miles. By increasing the inclination to 80°, a similar well would achieve a horizontal displacement of 31,737 ft, corresponding to a drainage area of 113.5 square miles. Increasing the inclination by 20°, therefore, allows the horizontal reach to increase by a factor of almost 3, and the drainage area to increase by a factor of more than 8. These longer reach wells can reduce the number of platforms required to exploit the reserves in offshore areas (Fig. 11.2).

Another potential benefit of drilling highly deviated wells is the increased length of the completion zone through the reservoir. Assuming the formation is horizontal, an 80° wellbore has almost three times the penetration through the reservoir than that of a wellbore at 60° inclination (Fig. 11.3). This allows much more of the reservoir to contribute to the well's productivity. In some oilfields a small number of horizontal wells could drain the reservoir much more efficiently than a greater number of conventional wells.
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Fig. 11.1. Extended reach of highly deviated wells.

<table>
<thead>
<tr>
<th>Inclination (deg)</th>
<th>Horizontal reach (ft)</th>
<th>Drainage area (square miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>10,992</td>
<td>13.6</td>
</tr>
<tr>
<td>70</td>
<td>16,469</td>
<td>30.6</td>
</tr>
<tr>
<td>80</td>
<td>31,737</td>
<td>113.5</td>
</tr>
</tbody>
</table>

Fig. 11.2. Reducing number of platforms by extended reach drilling. (Platforms A, B and C being replaced by platforms X and Y.)
The potential benefit of increased production has led to a renewed interest in horizontal drilling over recent years. Horizontal drilling dates back to the late 1800s, but the major advances occurred in the 1950s through the efforts of John Eastman and others. The Russians were also involved in some pioneering work. Although these early efforts were technically successful, the relatively low price of oil did not justify the extra costs involved. When oil prices rose in the late 1970s, several companies began examining the possibility of using these techniques.

The major technical problems in drilling highly deviated wells and horizontal wells are related to the effect of gravitational forces as the angle of inclination increases. For directional wells with inclinations of 20–40°, the component of gravity acting along the axis of the borehole is sufficient to allow tools to be run easily into the hole and exert enough WOB. As the angle of the hole increases, the axial component reduces while the lateral component increases. The result of this is:

(a) to increase frictional resistance against the borehole, making it more difficult to run and pull tools;
(b) to increase the tendency for solids to settle out from the drilling fluid and cement slurries;
(c) to make it more difficult to control direction and apply WOB.

In principle, all these problems can be overcome, but only at much higher costs. Surveys from recent horizontal wells show that the cost may be 2–5 times greater than for a comparable vertical well. Horizontal wells will therefore only be drilled where the operator expects a substantial benefit in terms of increased productivity.

Although horizontal wells can provide a solution to many reservoir development problems, their application is not universal. A horizontal well will not be effective in a layered reservoir where vertical permeability is low. If the producing interval is very thin, a horizontal well may easily miss the target. The technical problems, the potential benefits and the additional
risk involved must all be considered before starting a horizontal drilling programme.

APPLICATIONS OF HORIZONTAL WELLS

Increased Production from a Single Well

The greater contact area of the wellbore through the producing zone allows a much longer completion interval than would be possible in a less deviated well. With more of the formation contributing directly to the production, higher flow rates can be expected.

The productivity index \( PI \) for a vertical well is given by:

\[
PI = \frac{7.08 \times 10^{-3} \times kh}{\mu B_o \ln(r_e/r_w)}
\]

where \( PI \) = productivity index (bbl/day/psi)
\( k \) = permeability (millidarcies)
\( h \) = reservoir thickness (ft)
\( \mu \) = viscosity (centipoise)
\( B_o \) = oil formation volume factor
\( r_e \) = drainage radius (ft)
\( r_w \) = wellbore radius (ft).

The productivity is therefore proportional to the product \( kh \), sometimes referred to as transmissibility. The productivity index for a horizontal well can be approximated by

\[
PI = \frac{7.08 \times 10^{-3} \times kL}{\mu B_o \frac{L}{h} \ln \left(1 + \frac{1 - (L/2r_e)^2}{L/2r_e} \right)^{1/2} + \ln \left(\frac{h}{2\pi r_w} \right)}
\]

where \( L \) = length of horizontal section (ft).

The productivity index for a horizontal well may be five times that of a conventional well. Horizontal wells are therefore suited to relatively thin beds that cover a large area, or to formations where the permeability is low. Horizontal drilling can be used as an alternative to hydraulic fracturing as a means of improving production rates from tight formations. Horizontal wells may also be used to improve water injection as a means of improving oil recovery from the reservoir.

Reduction in Coning Problems

When a vertical well is drilled through a relatively thin pay zone overlying an aquifer, there is a tendency for the water to be drawn up into the perforated interval if the vertical permeability is high. This is known as water coning, and leads to an increased water cut in the producing wells.
This unwanted water production can be reduced by cementing off the lower perforations, and re-perforating higher up. This requires shutting in the well and carrying out a workover. A similar problem exists in the case of a formation that has an overlying gas cap, where the gas is drawn down to the upper perforations (Fig. 11.4).

A horizontal well can alleviate both problems, since it can be strategically placed away from both gas- and water-bearing zones. Owing to the longer length of the completion, the drawdown in the reservoir pressure around the wellbore will also be reduced, giving greater oil recovery before the onset of coning problems.

**Intersection of Vertical Fractures**

Many reservoirs contain fractures that are vertical or near-vertical at depths greater than 2000–3000 ft. Although the matrix of the rock may be fairly impermeable, the oil may still be able to flow along the fractures. It has been found that in some reservoirs (e.g. fractured limestone) the most efficient way of producing the oil is to drill highly deviated or horizontal wells to intersect as many fractures as possible. If the orientation of the fractures is known, a horizontal well can be planned to intersect the fractures at right-angles.

**Enhanced Oil Recovery**

Large deposits of highly viscous oil occur in many parts of the world. Since these reservoirs cannot be exploited by conventional means, special techniques have had to be applied, such as the injection of steam or polymers to improve the mobility of the oil. At Cold Lake, in Western Canada, one such project is aimed at recovering oil from a large bitumen deposit.
Surface mining is not feasible since the deposit is located at a depth of over 1000 ft. It was decided to drill a horizontal well near the base of the deposit to act as a producing well. A number of vertical wells were drilled above this well to allow steam injection into the formation. The viscosity of the oil in the vicinity of the steam injectors was reduced, and it drained downwards under gravity towards the horizontal producing well (Fig. 11.5).

**Reducing the Number of Wells and Platforms Required to Develop an Offshore Field**

The increased productivity of horizontal wells may result in fewer wells having to be drilled to develop an offshore field. Although the cost of an individual well might be more expensive, owing to the higher inclination, the overall economics of the project could be improved. In shallow reservoirs that cover a wide area the extended reach of horizontal wells may also mean that fewer platforms are necessary. Horizontal drilling may therefore allow the development of a field that would otherwise be considered uneconomic. In offshore fields where there are large distances between bottom hole locations, horizontal wells may be drilled as an alternative to infill drilling, thus further reducing the number of wells to be drilled.

**Development of Non-petroleum Resources**

Coal seams in certain areas of the world contain large volumes of methane gas. The gas has to be drained off before the coal can be extracted, since a
A concentration of 5–15% methane in air forms an explosive mixture. To remove the methane, a small-diameter horizontal hole can be drilled through the coal seam. Very close directional control is required, since the coal seam may only be a few feet thick. The orientation of the horizontal drainhole can also be planned to coincide with the direction of maximum permeability through the coal seam (Fig. 11.6).

Apart from the safety aspect, the produced methane is a valuable energy resource. It has been estimated that in the USA alone there is about $400 \times 10^{12}$ ft$^3$ of gas contained in underground coal seams.

For coal deposits located at depths beyond conventional mining methods, *in situ* gasification may be used to exploit the reserves. Highly deviated and horizontal wells provide a network of channels for the injection of air and oxygen and for the production of the gas.

**OPERATIONAL PROBLEMS RELATED TO HORIZONTAL WELLS**

The drilling and completion of highly deviated and horizontal wells introduces many problems that are not encountered, or are not so severe, at lower inclinations.

**Drilling Problems**

**Exerting WOB and running in tools**

In normal drilling operations the weight of the drill collars is sufficient to drive the bit and maintain good ROP. As the inclination of the well increases, a larger proportion of the weight is applied to the side of the borehole, and the axial component exerting weight on the bit is reduced. The driving force could be increased by adding more drill collars, but this would only lead to more lateral force, causing increased friction and drag.
The same problem arises when running wireline tools (e.g. surveying instruments). The force distribution is shown in Fig. 11.7.

Downward movement will only occur if the axial component \( (W \cos \alpha) \) is greater than the drag \( (W \sin \alpha f) \). There will also be a frictional force resisting rotational movement of the drill string. To reduce the friction coefficient \( f \) and hence the torque and drag on the drill string, an oil-based mud, or a water-based mud with a significant percentage of lubricant added, is often used. Heavy-weight drill pipe is also used in horizontal wells because it is more flexible and less prone to sticking.

Numerous mechanical devices have been proposed to increase the driving force on the bit. A hydraulically operated drill collar has extended arms or anchors that grip the side of the borehole. A piston mechanism within the collar pushes down to advance the bit. A re-set mechanism allows the process to be repeated. It is not known whether such a system has been successfully tried on a horizontal well.

**Controlling the well path**

Most of the applications of horizontal wells already discussed in this chapter rely for their success on accurate placement within the reservoir. Precise directional control of the wellpath is therefore vital if the horizontal well is to be effective. Owing to the problems of exerting WOB and the tendency for the bit to be deflected by natural features such as bedding planes, it is not always possible to keep the well on course.

The 90° inclination is usually accomplished by having two or more build-up sections. These build-up sections can best be drilled with a downhole motor and bent sub. The bent subs generally have a larger offset angle (2–4°) than those used in conventional wells. Several different sizes of bent sub may be required to follow the planned trajectory.

Close monitoring of the well path using survey tools run on wireline would not be practical, because of:

(a) the time taken to run and retrieve the tools;
(b) the difficulty in lowering them down in a highly deviated hole.

MWD tools can provide both directional and logging data as the well is being drilled. A gamma-ray sensor is especially useful in detecting marker beds and for correlation with offset wells while the hole is being drilled.
Hole cleaning
As the inclination of the wellbore increases, so does the tendency for the drill cuttings to drop onto the Low Side of the hole. Continued build-up of cuttings will increase the risk of getting stuck pipe, since the drill collars will also tend to sag against the Low Side of the hole. A build up of cuttings will also cause problems when running logging tools or liners. The precautions taken to avoid stuck pipe in conventional wells apply also to horizontal wells. In addition to these, however, some other techniques may be employed.

Eccentric tool joints. As the drill string rotates, the eccentric tool joints will stir up any cuttings that have been deposited, returning them to the main flow stream.

Reverse circulation subs. These can be made up as part of the bottom hole assembly to divert flow from the drill string into the annulus to move cuttings off the side of the borehole.

Top drive systems. The pipe often becomes stuck when tripping out of the hole in unstable formations. This may also be due to cuttings settling out after circulation is stopped. When stuck pipe is detected, circulation and rotation of the string should begin as quickly as possible. A top drive system is capable of doing this much faster than making up the kelly and turning the rotary table. The power swivel can be quickly stabbed into the top joint of the drill pipe during a trip to allow rotation and circulation as the pipe is being pulled out of the hole. This process is known as “back-reaming” and it has been used successfully in many high-angle wells when tripping out of the hole. Top drive systems will be discussed more fully in the next chapter.

Mud properties and solids equipment. The properties of the drilling fluid must be carefully chosen to achieve good hole cleaning. The most important parameter is the yield point of the mud, which may have to be increased considerably in a highly deviated well. (A yield point/plastic viscosity ratio greater than 1.0 is commonly used.) Yield points of up to 30 lb/100 ft² have been reported. Turbulent flow in the annulus may also help to lift the cuttings from the Low Side of the hole.

It is essential that the cuttings lifted out of the annulus are effectively removed on surface before re-cycling. The solids content of the mud must be closely monitored. Efficient use of solids control equipment such as shakers, hydrocyclones and mud cleaners is essential.

Logging Problems
It has been observed that above an inclination of 50–60° logging tools run on wireline do not fall under their own weight. In order to run logs at higher inclinations, it is possible to pump the tools down through open-ended drill pipe or tubing. The drill string is run into the hole to the required depth. The logging tools are then lowered down inside the drill string with the aid of sinker bars. If the logging tools do not fall under
gravity, pump pressure is applied to force them out the end of the drill pipe. This procedure is likely to damage the logging tools unless great care is taken. A more reliable system has been developed for logging high-angle wells (Fig. 11.8).

The logging tools are contained within a protective housing that is

Fig. 11.8. Logging technique for horizontal wells (Simphor®, patented and registered trademark of the Institut Français du Pétrole).
mechanically fixed to the end of the drill string. On the upper end of the housing is an electrical (male) plug that will later connect with the female plug on the end of the wireline. The drill string is lowered to the top of the open hole section to be logged. At this stage a special side-entry sub is made up in the drill string to accommodate the conductor cable. A sinker bar and female connector are fitted to the end of the wireline that passes through the side-entry sub. The female connector is then pumped down the drill string until it latches with the male plug on the housing. The logging tools can then be powered up, ready to begin logging. More joints of pipe are then added to the string and the conductor cable passes through the annulus to the logging unit. The hole can be logged either running into the hole or pulling out of the hole. The advantage of this system is that standard logging tools can be used, and no special drill pipe equipment is necessary. This technique has been used successfully to log holes up to 90° inclination.

Completion Problems

The horizontal section of the well is usually completed by running a liner, which is tied back to the previous casing shoe set just above the reservoir. Even at modest inclinations, many operators have encountered problems in obtaining a good cement job on a liner. One of the major problems is to ensure good displacement of the drilling mud by the cement slurry. Before running the liner, therefore, the hole should be cleaned out and the mud conditioned. If mud solids, such as barite, are allowed to build up on the Low Side of the hole the cement slurry will by-pass this area leaving a mud channel within the cemented annulus. The cement slurry itself may be affected by gravity segregation, leaving free water on the upper side of the hole. This will allow communication of reservoir fluids along the annulus.

The displacement of mud by cement could be improved by reciprocating or rotating the liner. Since the setting tool is normally backed off prior to cementing it is not possible to reciprocate the liner. Furthermore, reciprocation of the pipe exerts piston forces along the hole that are undesirable and may cause the liner to stick. Rotation of the liner during cementing is possible by means of a special rotating liner hanger with sealed bearings. Correct use of centralizers will also improve the quality of the cement job.

Because of the problems associated with cementing the liner, some operators have chosen to run a pre-slotted liner. This greatly simplifies the completion operations, but it means that one particular zone cannot be isolated. This can prove to be a problem in a horizontal well, since more than one zone can be encountered owing to steeply dipping formations. External casing packers have been tried to seal off an unwanted zone (e.g. a vertical fracture producing water), but with little success. To be effective the pre-slotted liner must be carefully positioned away from any troublesome zone.

DRILLING PRACTICES FOR HORIZONTAL WELLS

Most of the horizontal wells drilled recently have employed basically the same techniques as used in conventional directional wells. Careful atten-
tion must be paid to the planning of the trajectory, directional surveying, use of downhole motors and turbines, selection of casing seats, choice of mud type and mud properties.

The well trajectory generally consists of more than one build-up section (Fig. 11.9). After setting the surface casing in the vertical part of the hole, a downhole motor and bent sub are used for the initial kick-off. A 2–3° bent sub will give sufficient build up rate (4–6° per 100 ft). Rotary building assemblies can also be employed in the build up section. An intermediate string of casing will then be set, and drilling will continue with a holding assembly. A second build-up section is drilled using a downhole motor and bent sub. This will bring the inclination to almost 90° at a point just above the reservoir. After setting another casing string the horizontal section can be drilled to the target.

Close directional control is required throughout, and so MWD tools are recommended. Any correction runs should be made by downhole motors. Turbodrills have been used to drill the straight sections of the hole. Rotary methods have also been used, although high torque may prove to be a problem.

A variety of different mud types have been tried with varying degrees of success. An oil-based mud reduces torque and drag and helps prevent differential sticking. However, some operators have discovered that a carefully formulated low-solids, water-based system (containing diesel or asphalt as a lubricant) can be equally effective. In some cases, the water based mud has been displaced to oil-based mud prior to drilling the horizontal section through the reservoir. The mud properties must be carefully controlled to provide good hydraulics and hole cleaning capability. Wellbore stability may also have to be considered where sloughing shales or unconsolidated formations are present. There is a risk of hole collapse if such formations are left unsupported by casing for long periods of time.
Drainhole drilling, or short-radius drilling, is another approach to horizontal drilling that requires a very sharp build-up section followed by a relatively short horizontal section. The radius of the build up section can be 20–40 ft (corresponding to a build-up rate of 2–3° per foot drilled). This rapid build up of angle is only possible because of a special bottom hole assembly.

Horizontal drainholes are generally drilled laterally from a vertical well. After logs or DSTs have been carried out to evaluate the formation, the well is plugged back to a point above the oil–water contact (Fig. 11.10). A special whipstock is then run into the hole on a tailpipe and oriented in the required kick-off direction. Alternatively, an orienting guide with a packer can be set. A kick-off assembly is then run into the hole, consisting of a bit, overgauge reamer, knuckle joint and articulated drill collars (Fig. 11.11). The knuckle joint introduces a bend in the assembly and more flexibility is provided by the special drill collars (referred to as “wiggly” collars). These are machined from standard drill collars by cutting a jig-saw pattern to create interlocking sections. The wiggly collars allow bending but still provide sufficient strength to transmit torque. The drilling fluid, however, must flow through a flexible hose that passes through the inside of the collars.

Once the assembly is run into the hole and deflected by the whipstock, it builds angle very quickly, reaching almost horizontal after drilling only 50–60 ft of hole. To avoid further angle-building, this assembly should be replaced by a stabilized BHA before reaching 90°. The reamer and knuckle joint are replaced in this second assembly by a full-gauge stabilizer. The wiggly collars are retained. This assembly is used to hold inclination through the reservoir section.

Normal wireline surveying techniques cannot be used because of the flexible hose that carries the drilling fluid. To take a survey in the drainhole
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section requires tripping out the bottom hole assembly. A single shot instrument can then be run on wireline with sufficient sinker bars to provide weight. The next BHA can be run in after the survey has been taken in the open hole section. Surveying is therefore a very time-consuming job in drainhole drilling. MWD tools currently available cannot be used under such conditions.

Recent horizontal drainholes have been up to 200 ft long. These small diameter holes (4") are generally left uncased. The same technique can be repeated further up the hole for multiple exploration and production from one wellbore. It is possible to drill out of cased hole after a window has been cut.

A summary of some recent horizontal wells drilled in Europe and North America is given in Table 11.1

**QUESTIONS**

11.1. A horizontal well is being planned to intersect a target whose horizontal displacement is 6000 ft at a TVD of 5500 ft. It is planned to have a 1200 ft horizontal section through the reservoir before reaching the target. The initial KOP will be at 1000 ft. There will be two build-up sections; the first at the KOP will be 3° per 100 ft and the second just above the reservoir will be 3° per 100 ft. Calculate the inclination over the tangent section and the total length of the well.
TABLE 11.1 Summary of Some Recent Horizontal Wells

<table>
<thead>
<tr>
<th>Well</th>
<th>Location</th>
<th>Company</th>
<th>Year</th>
<th>Initial KOP (ft)</th>
<th>TVD of target (ft)</th>
<th>Hor. depth of target (ft)</th>
<th>MD of target (ft)</th>
<th>Length of hor. section (ft)</th>
<th>Max. build rate (deg/100 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-29X</td>
<td>Norman Wells, Canada</td>
<td>Esso</td>
<td>1979</td>
<td>98</td>
<td>1604</td>
<td>4616</td>
<td>5578</td>
<td>1860</td>
<td>6.1</td>
</tr>
<tr>
<td>K-142*</td>
<td>New Mexico, USA</td>
<td>Arco</td>
<td>1979</td>
<td>6037</td>
<td>6060</td>
<td>184</td>
<td>6145</td>
<td>106</td>
<td>300</td>
</tr>
<tr>
<td>Lacq 91</td>
<td>France</td>
<td>Elf</td>
<td>1981</td>
<td>279</td>
<td>2182</td>
<td>2707</td>
<td>4101</td>
<td>1214</td>
<td>3</td>
</tr>
<tr>
<td>Castera Lou</td>
<td>France</td>
<td>Elf</td>
<td>1983</td>
<td>5578</td>
<td>9515</td>
<td>4101</td>
<td>12025</td>
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<tr>
<td>HWP-2</td>
<td>Cold Lake, Canada</td>
<td>Esso</td>
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<td>131</td>
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<td>JX-2</td>
<td>Alaska, USA</td>
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<td>4878</td>
<td>11700</td>
<td>1363</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* Horizontal drainhole.
11.2. List the main applications of horizontal drilling for offshore developments.

11.3. Explain some of the major factors that make a horizontal well more expensive than a vertical well.

11.4. Compare the drainage area of a platform whose wells have a maximum inclination of 55° with a platform whose wells have a maximum inclination of 70°. (Assume a Type I profile with a KOP of 1500 ft and a build up rate of 1.5° per 100 ft in each case and a target TVD of 10,000 ft.)

11.5. A horizontal drainhole must be drilled to locate a target 400 ft from the rig at a depth of 9500 ft (TVD). A build rate of 2° per ft can be achieved using a special bottom hole assembly. Calculate:
   (a) the depth of the kick off point;
   (b) the length of the horizontal section;
   (c) the total measured depth to the target.

11.6. Discuss the importance of drilling fluid properties in horizontal drilling.

FURTHER READING

"Mud and cement for horizontal wells", C. Zurdo, C. Georges and M. Martin, S.P.E. paper no. 15464.
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