ROTARY-STEERABLE TECHNOLOGY—Part 1

Technology gains momentum

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Rotary-steerable systems possess clear advantages, both technologically and economically, over many mud motor-based drilling systems.

The service industry is responding to this by providing operators with new tools, expanding their ability to drill extended-reach and underbalanced wells, smooth out well trajectories, and optimize well configurations for production enhancement.

Ultimately, motor-based directional systems may eventually be replaced by rotary-steerable alternatives, except for those cases where a downhole motor is needed for "nondirectional attributes."

This first part of a two-part series describes the technological differences between conventional mud motor-based directional drilling systems and rotary-steerable systems. The second part defines implementation issues that are of concern to the operator.

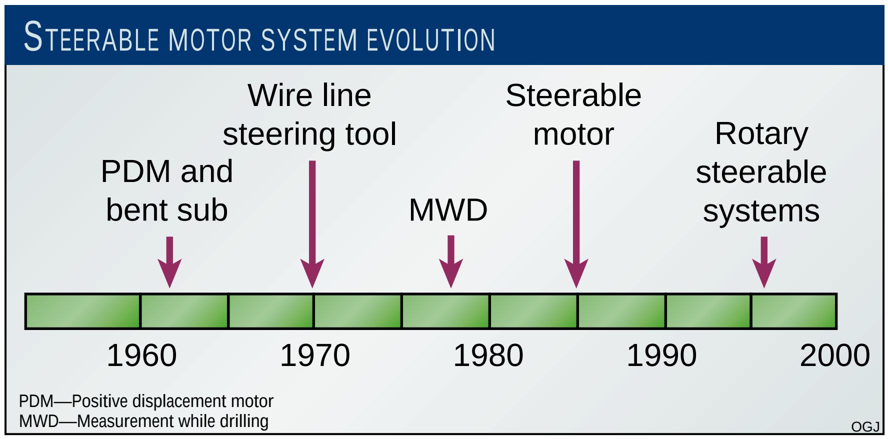
Background

The oil and gas industry relies heavily on directional drilling to develop offshore reserves, facilitate development in environmentally sensitive areas, and provide production enhancement through horizontal and multilateral completions.

Although directional oil wells were first drilled in the California Huntington Beach field in 1933,[1] the introduction of a directional drilling system in 1962, based on the development of a positive-displacement motor (PDM) and bent-sub assembly, provided the first practical capability for developing offshore fields.

Introduced in California, the technology quickly spread to the Gulf of Mexico and continued to evolve into the steerable motor system that is used today.[2] During the evolution of the steerable-motor technology, there have been many enhancements in materials and designs (Fig. 1).

Fig. 1



Fundamental limitations

Steerable motors provide a capability that is essential to the oil industry. Unfortunately, this technology has significant limitations and inefficiencies that affect its ability to continuously support increased operational demands.

Drilling with steerable motors is divided into two activities: Sliding and rotating (Fig. 2). Sliding involves precision guidance of the assembly towards a prescribed target. Rotating involves no active guidance of the trajectory.

Problems associated with each of these states are listed in Table 1 and discussed in greater detail by Warren.[3] Most of the limitations and inefficiencies are related to the need to drill a portion of the well without drillstring rotation or concerns related to motor performance.

Table 1

PROBLEMS

Sliding	Rotation
• Inability to slide	• Vibrations-motor and MWD failures
• Maintaining orientation	• Accelerated bit wear
• Poor hole cleaning	• Poor hole quality for logs
• Low effective ROP	• Poor performance in air
• High tortuosity	
• ECD fluctuations	
• Differential sticking	
• Buckling and lock up	
• Build rate formation sensitive	

Continued evolution of the steerable motor system is not likely to solve most of these problems since they are related to the fundamental characteristics of the steerable-motor directional system.

Rotary-steerable systems

There is an active effort in the industry to overcome some of these limitations by using "rotary-steerable" directional-drilling systems. Rotary-steerable systems are directional tools that allow the well trajectory—inclination and azimuth—to be actively guided while rotating the drillstring.

In fact, the concept for rotary-steerable directional systems predates the common use of mud motors (PDMs). These systems include many of the fundamental concepts that are being used today.

Fig. 3a shows a system, patented in 1955, that used a nonrotating sleeve to direct the bit in a specific direction.[4] The patent describes the objective of the tool as "to cause the drill collar to assume a slightly inclined position with respect to the axis of the hole so the bit will be laterally directed."

Fig. 3b shows another system patented in 1959 that used hydraulically activated guide shoes near the bit to control the drilling trajectory in a similar manner.[5] The guide shoes, located on a nonrotating housing, were powered by mud pressure and could be activated and retracted without tripping the drillstring. The specific objective of

Fig. 2

STEERABLE MOTOR ACTIVITIES

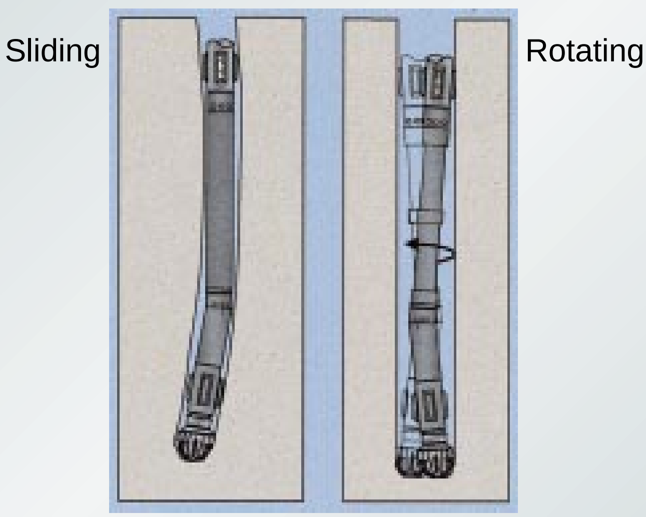
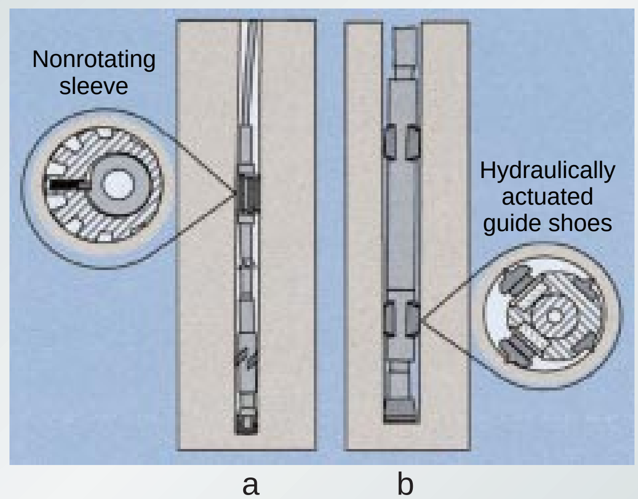


Fig. 3

EARLY CONCEPTS



this tool was to eliminate the need to trip in and out of the hole to set whipstocks for well guidance.

Other examples include a wide range of mechanisms used to alter the borehole trajectory, including mechanically activated guide shoes, hydraulically activated guide shoes, eccentric nonrotating sleeves, nested eccentric cam sleeves, and intermittently activated paddles.[6-12]

These tools were based on concepts very similar to modern rotary-steerable tools, but none were commercially successful. Apparently the lack of effective downhole sensors and control systems impeded development of these technologies, more so than a lack of trajectory control ideas.

Steerable systems vs. motors

The lack of commercial success of the first pre-PDM rotary-steerable tools did not mitigate the attractiveness of actively steering the bit while continuously rotating the drillstring. After more than 30 years of dominance by directional drilling mud motors, a combination of market forces, as follows, has recently initiated a resurgence of interest in the rotary-steerable concept.

- The complexity of many directional wells increased.
- Extended-reach wells exceeded the range with which motors could be oriented.
- The benefits of horizontal wells became better understood and made the economics for redevelopment of reserves from existing platforms more attractive.
- Expertise for running fixed stabilizer assemblies slowly disappeared and operators began to rely upon steerable motors for drilling the entire well.
- Improvements in bit technology provided aggressive PDC (polycrystalline diamond compact) bits with adequate durability to drill a wide range of formations. Unfortunately, these bits were incompatible with motors.
- Interest in simultaneous drilling and underreaming has increased, providing more-flexible casing programs. In some cases, this technology could not be efficiently implemented with motors.

Thus, the point was finally reached where the most challenging operations, using directional motors, could not continue the aggressive development of reserves. At the same time, the capability to design downhole monitoring and control systems had dramatically changed since the rotary-steerable systems were first investigated.

Thus, the demand for increased directional capability and improved ability to design more-sophisticated tools combined to provide a fertile ground for the resurgence of the rotary-steerable concept.

Reemergence

Over the past few years, several companies have started work on rotary-steerable systems aimed at particular niche markets. The high-cost, extended-reach market was one area where rotary-steerable technology was perceived to provide an "enabling" technology, marketable at a premium price.[13] On the other end of the spectrum, work was undertaken to provide a very cheap system aimed at onshore marginal properties.[14]

Competition to provide viable rotary-steerable systems has accelerated, and now there are several commercial systems, including Baker Hughes Inteq, Camco Drilling & Service, and Cambridge Drilling Automation Ltd. Others in the prototype-testing phase include Schlumberger Anadrill and Sperry-Sun Drilling Services.[15]

Another tool type, sometimes classed as a rotary-steerable system, includes downhole adjustable stabilizers that can be used for inclination control. It is reported that about 90% of the downhole trajectory corrections are in fact inclination corrections with the implication that for most cases there is little need for the ability to make azimuth changes.

While it is probably true that most trajectory changes are inclination changes, it is also true that rarely is a directional run made where the operator can guarantee that an azimuth adjustment will not be needed.

Thus, there is certainly a place for the downhole-adjustable stabilizers based on capability, reliability, cost, and directional requirements, but in the following discussions, rotary-steerable systems will be considered as tools capable of making both inclinational and azimuthal changes.

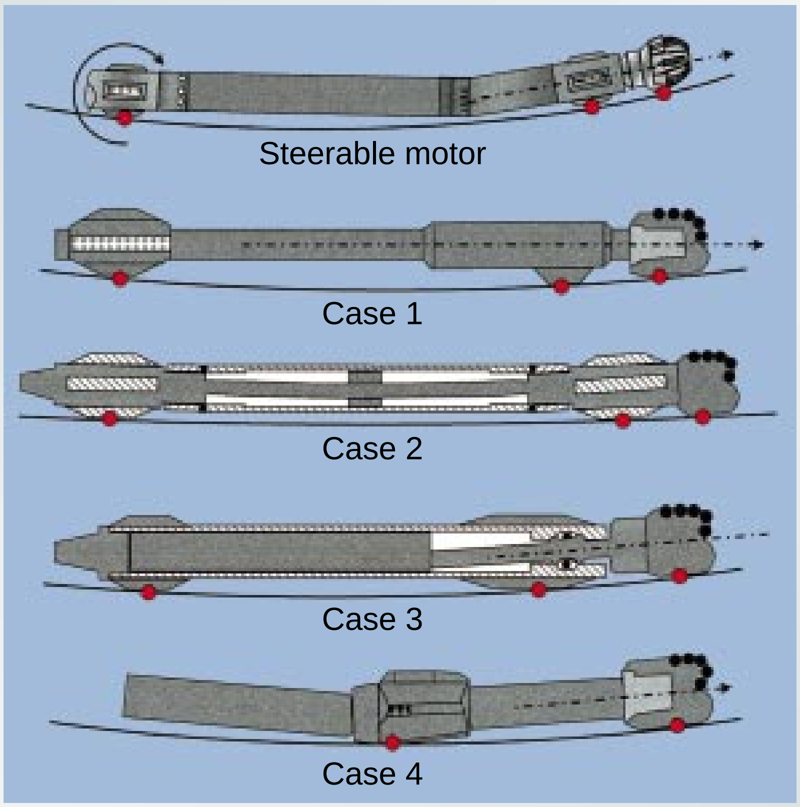
Current concepts

There is a wide variation in the designs of the systems entering the market as compared to steerable motors (Fig. 4). Steerable motors direct the bit along a particular path by providing a relatively rigid "three-point" geometry that biases the bit to drill along the arc of a circle.

The geometry of the tool prescribes the position of the bit relative to the

Fig. 4

TRAJECTORY CONTROL MECHANISMS



two noncutting, upper-contact points. The side-cutting capability of the bit allows it to move along the circular arc trajectory that continually minimizes the side force on the bit.

With the steerable motor system, the bit axis may be aligned with the hole axis; but in most cases, it is not. The bending moment applied to the upper stabilizer by the bottom-hole assembly (BHA), positioned above the motor, tends to provide additional curvature by increasing the deflection of the bit.

This effect must be considered when estimating the curvature for a particular motor BHA. For a typical 6¾-in. steerable motor, the curvature that can be achieved ranges between 0 and 15°/100 ft, using typical tool configurations and bent sub angles (up to 3°). Higher curvatures may be obtained by other BHA designs such as adding a second bend above the motor or articulating the motor to place the upper two contact points closer to the bit.

Steerable tool design

Cases 1-3 in Fig. 4 illustrate rotary-steerable tool applications where the trajectory is determined by the same three-point geometry that controls steerable-motor trajectory. The ideal situation is to align the bit axis with the well path arc, as determined by the three control points. For the tools shown as Case 1, the bit will always be pointed to the outside of the curve.

For Case 2, the bit will still generally be pointed to the outside, but to a lesser degree than Case 1. For Case 3, the bit may be pointed either to the inside or outside portion of the curve, depending on the particular tool design.

In terms of trajectory control for automated guidance systems, the exact direction of bit pointing may not be too important as long as the parameters remain in the active range of the control system. However, increased bit misalignment may increase sensitivity to bit design and formation properties, resulting in a tendency for increased bit vibrations.

In Case 1 the controlling geometrical constraints are provided by one or more pads, positioned near the bit, that independently extend outward to apply a force against the borehole wall. The pads may extend semistatically from a nonrotating housing (OGJ, Mar. 2, p. 65), such as in the Baker Hughes Inteq AutoTrak system, or dynamically from a rotating housing such as in the Camco Steerable Rotary Drilling (SRD) system.

The curvature that can be obtained depends on the geometry of the particular tool, the bending moment from the assembly above, and the amount of pad extension. The pad extension, a critical determinant of directional control, may be directly or indirectly controlled by adjusting the force applied to it, limited by design considerations.

In either case, effective pad extension, hole gauge, and bit-side cutting forces control the trajectory. In general, the maximum build rate from these tools is less than can be obtained from a bent-housing motor.

Case 2 shows a tool where a continuous rotating drive shaft is deflected inside a nonrotating housing (Cambridge Automatic Guidance System). Again, the bit trajectory is determined by the three-point geometry, but the bit axis tends to be more closely aligned with the centerline of the hole.

In general, it is difficult to get as much curvature with this type of tool as with a Case 1 design because of geometrical and strength considerations. However, it can more conveniently accommodate a wider range of hole sizes with the same tool.

Case 3 illustrates another system where the bit axis is maintained in a tilted position relative to the well direction by actively rotating the upper end of the bit shaft counterclockwise and in synchronization with the clockwise rotation of the drillstring (Directional Drilling Dynamics Co.).

This system can provide a relatively high degree of bit tilt, does not require nonrotating contact with the borehole, and can align the bit axis with the borehole axis. This system lags behind the first two cases in terms of commercial implementation.

The trajectory for Case 4 is not controlled by the three-point rigid geometry, but instead is determined solely by bit direction. The bit is designed to minimize side cutting with a flexible joint that isolates the bit from the drillstring bending moment and resulting lateral bit forces to provide a controlled trajectory.

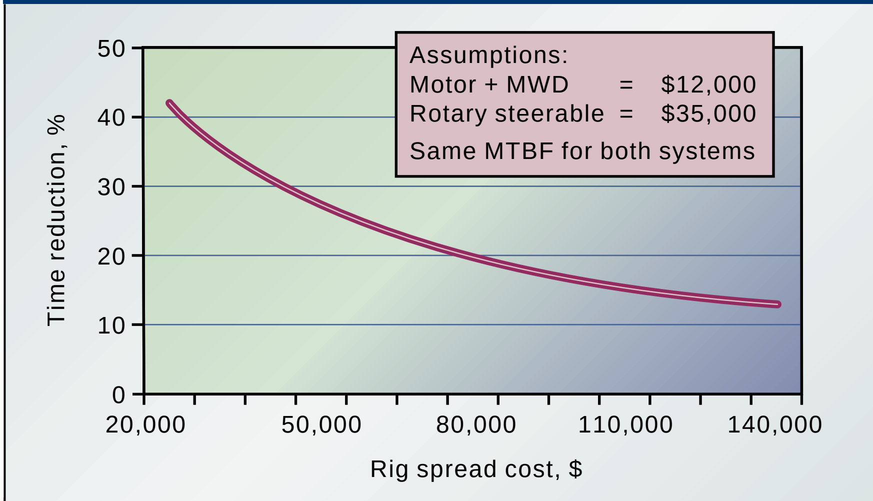
This trajectory control mechanism allows much higher build rates in smaller hole sizes than the other mechanisms, but is not as tolerant of "over-gauge" hole conditions as the rigid three-point systems that have been implemented on manually oriented systems.

Control mechanisms

The tools designed around the Case 1-3 tool design concepts are generally automated guidance tools, meaning they have adequate onboard sensors, power systems, and control systems to dynamically adjust well trajectory ac-

Fig. 5

BREAK-EVEN POINT

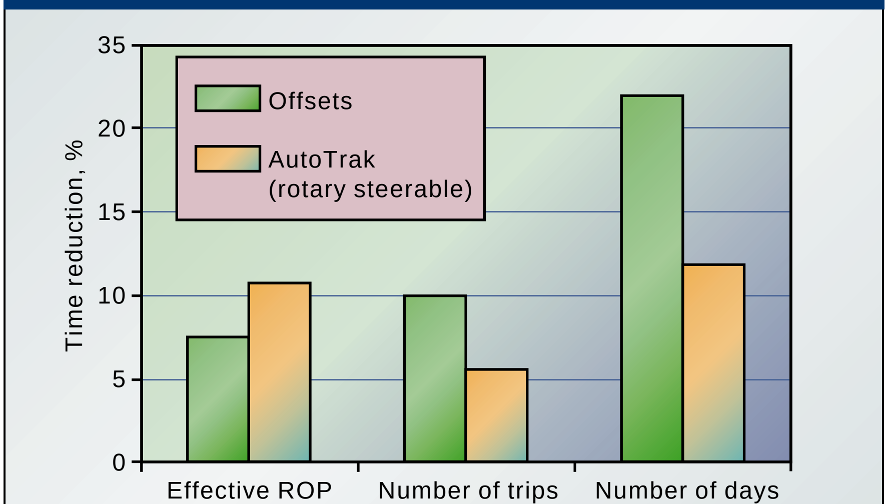


MTBF—Mean time between failure

OGJ

Fig. 6

EFFICIENCY IMPROVEMENTS—NORWAY WELL



Source: Baker Hughes Inteq

OGJ

cording to a particular command.

Commands are generally of two types:

1. Closed loop—Employed by the AutoTrak and the AGS systems. These systems direct the tool to drill to a particular inclination and azimuth at a certain build rate.

2. A fixed-command system that directs the tool to drill in a particular orientation relative to the high-side tool face at a given build rate.

None of the tools have downhole distance measurement sensors needed to actually determine the true build rate. Thus, the build rate generally becomes a surface-specified fraction of the tool's theoretical maximum rate and is adjusted by using surface downlink commands once tool performance becomes known.

The build rate is most often controlled by alternating—on a short-duration time schedule—from a three-point geometry that provides a maximum build rate to one that drills a straight hole.

A few tools, including the AutoTrak, alter the three-point geometry to provide continuous build-rate adjustment. Most of the new tools coming to market are being introduced with the simplest control system, but have capabilities built in for upgrading.

From a trajectory control standpoint, there is little difference between any of the above control systems as long as a directional driller is employed to manage the system. The major differentiating feature will be reliability of the control system.

Market perspective

The introduction of rotary-steerable directional systems will clearly benefit operators, but the situation is somewhat more complicated for service companies investing in the new technology. The rewards that accrue to each depend on the particular path that the technology commercialization process takes.

The following discussion identifies the most important applications for rotary-steerable systems and indicates some of the issues facing both operators and the service sector as the directional market shifts from motors to rotary systems.

Economic opportunities

Rotary-steerable technology can significantly impact an operator's well cost. Directional wells tend to be more expensive than straight holes primarily for two reasons. First, the process of directional drilling with motors is less efficient than drilling a straight hole. Especially since the distance drilled to a particular horizon is greater, and additional equipment and services are required.

Second and more importantly, the daily operating costs for directional wells tend to be higher because they are used in places where surface access and support costs are high, including offshore and environmentally restricted locations. Thus, the incentive to reduce the total number of days on the well may have a greater impact on the overall economics than the cost of using directional equipment.

Fig. 5 shows the break-even point for a rotary-steerable system whose equipment cost is two to three times that of the alternative steerable-motor equipment. Assuming the rotary-steerable equipment is as robust as the alternative, it would require only an overall time savings of 20% to be cost effective for most offshore operations.

Operational experience with the rotary-steerable systems over the last few months demonstrates an efficiency improvement much more than this in many cases (Fig. 6), but also indicates that reliability may not yet be quite as good as that for steerable motors and measurement and logging-while-drilling systems.

Directional tolerance

The growth of horizontal drilling for production enhancement has placed greater requirements on directional drilling capability. A well path that includes long intervals of simultaneous inclination and direction changes is often required to place the horizontal section within the optimal reservoir position and orientation.

Drilling these paths requires an increased amount of sliding. The combination of increased sliding and higher frictional drag makes changes in orientation more difficult with PDM steerable motors. While it is often possible to drill these paths with steerable motors, their efficiency decreases with the complexity of the well and makes positioning the horizontal relative to the gas cap or water level difficult.

Often, only a few feet in elevation at the entry point or a few dips in elevation can make a significant difference in the ultimate production before gas or water breaks through. Rotary-steerable systems have demonstrated the capability to provide infinitely more inclination control than steerable motors because of their ability to provide continuous automatic orientation.

Capital costs

Rotary-steerable technology may also reduce the number of platforms and wells that are needed to drain an asset by increasing the achievable departure for extended-reach wells and allowing increased complexity for designer wells. Capital costs and delayed production associated with setting a platform are often the greatest economic driver for developing an offshore field.

In addition, because many production areas are defined by stacked pay zones where designer wells are needed to optimally encounter each zone, a well path may require multiple direction and inclination changes that are difficult to achieve with steerable motors.

In both of these cases, the use of rotary-steerable technology has the potential to leverage capital cost much greater than the cost of employing the new technology.

Problem formations

There are cases where formation considerations make operating steerable-motor systems particularly troublesome. One example includes situations where the operating window between lost circulation and maintaining hole stability becomes very narrow.

Even though the actual directional trajectory may not be very challenging, the equivalent circulating density (ECD) variations between sliding and rotating the steerable motor may become great enough to make it tedious, if not impossible, to stay within the window.

It only takes a few incidents of packing-off or lost-circulation problems to pay for the additional ECD stability afforded by rotary-steerable systems.

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Tommy Warren is a special research associate for Amoco Production & Exploration Technology Group. He has more than 25 years' experience for Amoco working with drilling technology development in the areas of drill bit mechanics, directional drilling, and drillings systems.

Warren was the 1997 recipient of the SPE Drilling Engineering Award and is currently serving as the program chairman for the 1999 SPE Annual Technical Conference and Exhibition. He is also an SPE Distinguished Lecturer on the topic of rotary steerable systems. Warren holds BS and MS degrees in mineral engineering from the University of Alabama.

Underbalanced drilling

Underbalanced drilling (UBD) has historically been used in formations to improve penetration rates. However, UBD has recently gained prominence as a way to reduce formation damage in horizontal wells, particularly in mature areas where the reservoir pressure is low.

The primary method of providing an underbalanced fluid column is to drill with air or aerated mud. In many cases, nitrogen is used instead of air. The use of these highly compressible fluids causes two types of problems with mud motors.

First, the compressibility of the air significantly affects the efficiency of the motor and causes high rotational speeds when the bit load is removed. This can affect the motor by over heating the stator and is further compounded by absorption of the gas into the stator rubber, causing it to swell. The compressibility of the fluid also makes it difficult to keep the motor properly loaded and oriented, particularly as the reach of horizontal wells increases.

Second, the combination of the motor over-speeding and reduced fluid damping significantly increases lateral vibration problems that are very detrimental to the bits, motors, and steering equipment.

So far, rotary-steerable tools have had limited UBD applications with a single closed loop tool run in Italy (Case 2) and several runs with Case 4 tools. However, rotary-steerable directional systems have the potential to eliminate many of the problems that result from running a PDM with a highly compressible fluid.

Deep hot wells

Directional work in deep, high-temperature wells is limited by the capability of Moineau motors to operate under such conditions, especially where oil-based mud is used. This limitation affects the ability to effectively use horizontal completions in these wells.

In many cases, the pressure environment and subsequent casing programs dictate that this work be done in a small-diameter hole and often at relatively high build rates. Alternative motors such as turbines and other all metal motors may operate more effectively at higher temperatures,[16] but they do nothing to reduce the problems of orienting small diameter motors in deep wells.

Both the motor durability issues and orientation issues may be addressed with one of the rotary-steerable systems being marketed.[17]

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