

Drilling Sideways -- A Review of Horizontal Well Technology and Its Domestic Application

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Preface

Drilling Sideways -- A Review of Horizontal Well Technology and Its Domestic Application is the second Office of Oil and Gas review of a cutting-edge upstream oil and gas industry technology and its current and possible future impacts. The first such review, *Three-Dimensional Seismology -- A New Perspective*, authored by Robert Haar, appeared as a feature article in the December 1992 issues of the Energy Information Administration's *Natural Gas Monthly* and *Petroleum Supply Monthly*. Additional technology reviews will be issued as warranted by new developments and lack in the extant literature of reviews of a similar nature and breadth.

The technology reviews are intended for use by a wide and varied audience of energy analysts and specialists located in government, academia, and industry. They are syntheses based on an extensive literature search and direct consultations with developers and users of the technology. Each seeks to outline, as concisely as possible, the involved basic principles, the current state of technology development, the current status of technology application, and the probable impacts of the technology. Where possible, the economics of technology application are explicitly addressed.

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Highlights

The use of horizontal drilling technology in oil exploration, development, and production operations has grown rapidly over the past 5 years. This report reviews the technology, its history, and its current domestic application. It also considers related technologies that will increasingly affect horizontal drilling's future.

Horizontal drilling technology achieved commercial viability during the late 1980's. Its successful employment, particularly in the Bakken Shale of North Dakota and the Austin Chalk of Texas, has encouraged testing of it in many domestic geographic regions and geologic situations. Of the three major categories of horizontal drilling, short-, medium-, and long-radius, the medium-radius well has been most widely used and productive. Achievable horizontal bore hole length grew rapidly as familiarity with the technique increased; horizontal displacements have now been extended to over 8,000 feet. Some wells have featured multiple horizontal bores. Completion and production techniques have been modified for the horizontal environment, with more change required as the well radius decreases; the specific geologic environment and production history of the reservoir also determine the completion methods employed. Most horizontal wells have targeted crude oil reservoirs. The commercial viability of horizontal wells for production of natural gas has not been well demonstrated yet, although some horizontal wells have been used to produce coal seam gas. The Department of Energy has provided funding for several experimental horizontal gas wells.

The technical objective of horizontal drilling is to expose significantly more reservoir rock to the well bore surface than can be achieved via drilling of a conventional vertical well. The desire to achieve this objective stems from the intended achievement of other, more important technical objectives that relate to specific physical characteristics of the target reservoir, and that provide economic benefits. Examples of these technical objectives are the need to intersect multiple fracture systems within a reservoir and the need to avoid unnecessarily premature water or gas intrusion that would interfere with oil production. In both examples, an economic benefit of horizontal drilling success is increased productivity of the reservoir. In the latter example, prolongation of the reservoir's commercial life is also an economic benefit.

Domestic applications of horizontal drilling technology have included the drilling of fractured conventional reservoirs, fractured source rocks, stratigraphic traps, heterogeneous reservoirs, coalbeds (to produce their methane content), older fields (to boost their recovery factors), and fluid and heat injection wells intended to boost both production rates and recovery factors. Significant successes include many horizontal wells drilled into the fractured Austin Chalk of Texas' Giddings Field, which have produced at 2.5 to 7 times the rate of vertical wells, wells drilled into North Dakota's Bakken Shale, from which horizontal oil production increased from nothing in 1986 to account for 10 percent of the State's 1991 production, and wells drilled into Alaska's North Slope fields.

An offset to the benefits provided by successful horizontal drilling is its higher cost. But the average cost is going down. By 1990, the cost premium associated with horizontal wells had shrunk from the 300-percent level experienced with some early experimental wells to an annual average of 17 percent. Learning curves are apparent, as indicated by incurred costs, as new companies try horizontal drilling and as companies move to new target reservoirs. It is probable that the cost premium associated with horizontal drilling will continue to decline, leading to its increased use. Two allied technologies are currently being adapted to horizontal drilling in the effort to reduce costs. They are the use of coiled tubing rather than conventional drill pipe for both drilling and completion operations and the use of smaller than conventional diameter (slim) holes.

1. Introduction

The application of horizontal drilling technology to the discovery and productive development of oil reserves has become a frequent, worldwide event over the past 5 years. This report focuses primarily on domestic horizontal drilling applications, past and present, and on salient aspects of current and near-future horizontal drilling and completion technology.

Definition and Immediate Technical Objective

A widely accepted definition of what qualifies as horizontal drilling has yet to be written. The following combines the essential components of two previously published definitions:¹

Horizontal drilling is the process of drilling and completing, for production, a well that begins as a vertical or inclined linear bore which extends from the surface to a subsurface location just above the target oil or gas reservoir called the "kickoff point," then bears off on an arc to intersect the reservoir at the "entry point," and, thereafter, continues at a near-horizontal attitude tangent to the arc, to substantially or entirely remain within the reservoir until the desired bottom hole location is reached.

Most oil and gas reservoirs are much more extensive in their horizontal (areal) dimensions than in their vertical (thickness) dimension. By drilling that portion of a well which intersects such a reservoir parallel to its plane of more extensive dimension, horizontal drilling's immediate technical objective is achieved. That objective is to expose significantly more reservoir rock to the wellbore surface than would be the case with a conventional vertical well penetrating the reservoir perpendicular to its plane of more extensive dimension (Figure 1). The desire to attain this immediate technical objective is almost always motivated by the intended achievement of more important objectives (such as avoidance of water production) related to specific physical characteristics of the target reservoir. Several examples of these are discussed later on.

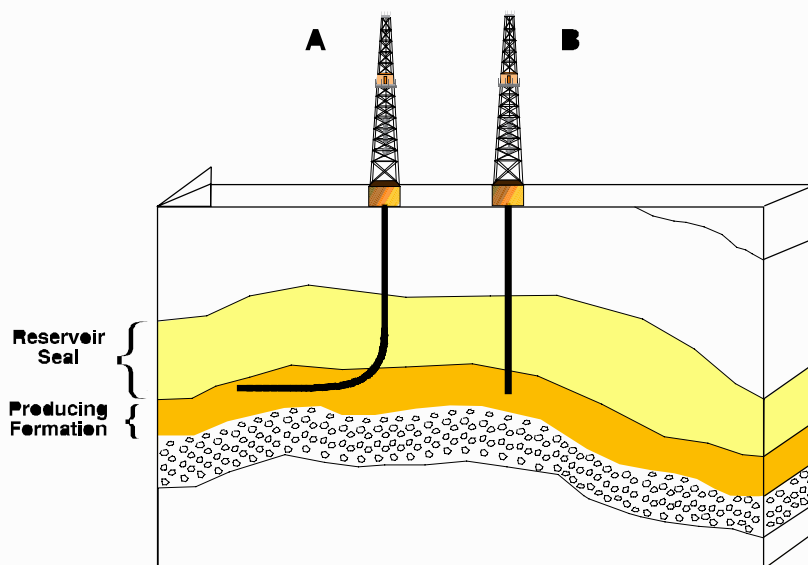
Drilling Methods and Some Associated Hardware

The initial linear portion of a horizontal well, unless very short, is typically drilled using the same rotary drilling technique that is used to drill most vertical wells, wherein the entire drill string is rotated at the surface. The drill string minimally consists of many joints of steel alloy drill pipe, any drill collars (essentially, heavy cylinders) needed to provide downward force on the drill bit, and the drill bit itself.

Depending on the intended radius of curvature and the hole diameter, the arc section of a horizontal well may be drilled either conventionally or by use of a drilling fluid-driven axial hydraulic motor or turbine motor mounted downhole directly above the bit. In the latter instance, the drill pipe above the downhole motor is held rotationally stationary at the surface. The near-horizontal portions of a well are drilled using a downhole motor in virtually all instances.

¹Joshi, S.D., *Horizontal Well Technology*, PennWell Books, Tulsa, Oklahoma, p. 1.; Shelkholeslami, B.A., B.W. Schlottman, F.A. Seidel and D.M. Button, "Drilling and Production of Horizontal Wells in the Austin Chalk," *Journal of Petroleum Technology*, July 1991, p. 773.

Figure 1. Greater Length of Producing Formation Exposed to the Wellbore in a Horizontal Well (A) Than in a Vertical Well (B).



Source: Energy Information Administration, Office of Oil and Gas.

It is possible to drill the arc section of the well bore because the apparently rigid drill pipe sections are, in fact, sufficiently flexible that each can be bent a distance off the initial axis without significant risk of incurring a structural failure such as buckling or twisting off. The smaller the pipe diameter and the more ductile the steel alloy, the greater the deviation that can be achieved within a given drilled distance. That is, the smaller the arc's radius can be made, or the larger the arc's build angle² can be.

Downhole instrument packages that telemeter various sensor readings to operators at the surface are included in the drill string near the bit, at least while drilling the arc and near-horizontal portions of the hole. Minimally, a sensor provides the subsurface location of the drill bit so that the hole's direction, as reflected in its azimuth and vertical angle relative to hole length and starting location, can be tightly controlled. Control of hole direction (steering) is accomplished through the employment of at least one of the following:

- a steerable downhole motor
- various "bent subs"
- pipe stabilizers.

"Bent subs" are short sub-assemblies that, when placed in the drill string above the bit and motor, introduce small angular deviations into the string. Pipe stabilizers are short sub-assemblies that are wider than the drill pipe, but usually slightly narrower than the bit diameter. They are included at intervals along the drill string wherever precise lateral positioning of the pipe in the hole is needed. If they are symmetrical, they simply center the pipe within the drilled hole. If asymmetrical, they will induce a small

²Domestically, build angle is measured in degrees of angular change per 100 feet drilled.

angle between the pipe and the hole wall. All of these devices can be obtained in lower cost versions where the induced angular deviation can only be adjusted at the surface, or in higher cost versions that can be remotely adjusted while they are downhole. The additional cost of remote control capability may, in many instances, be outweighed by time-related savings, due to a substantial reduction of the number of trips³ needed, many of which would be made for the sole purpose of direction adjustment.

Additional downhole sensors can be, and often are, optionally included in the drill string. They may provide information on the downhole environment (for example, bottom hole temperature and pressure, weight on the bit, bit rotation speed, and rotational torque). They may also provide any of several measures of the physical characteristics of the surrounding rock and its fluid content, similar to those obtained via conventional wireline well logging methods, but in this case obtained in real time while drilling ahead. The downhole instrument package, whatever its composition, is referred to as a measurement-while-drilling (MWD) package.

Some New Terminology

The advent of commercial horizontal drilling has inevitably added new abbreviated terms to the "oil patch" lexicon. Expanding beyond the "old standard" vertical well statistic TD, denoting the total depth of a hole as measured along the length of the bore, the following terms, which appear frequently elsewhere in this article, are now widely used to quantify the results of horizontal drilling:

Abbreviated Term:	Stands for:	Denotes:
TVD	Total Vertical Depth	Total depth reached as measured along a line drawn to the bottom of the hole that is also perpendicular to the earth's surface.
MSD	Measured Depth	Total distance drilled as measured along the well bore. Note that in a vertical hole, MSD would equal TD.
HD	Horizontal Displacement	Total distance drilled along the quasi-horizontal portion of the well bore.

³A "trip" encompasses removal of the entire drill string from the hole, usually for the purposes of adjustment or change of hardware, followed by reinsertion. A typical trip to a depth of several thousand feet can consume several hours, during which time no forward progress is made while the operating and rig rental costs continue unabated.

The Essential Economics of Horizontal Drilling

The Cost Premium

The achievement of desired technical objectives via horizontal drilling comes at a price: a horizontal well can be anywhere from 25 percent to 300 percent more costly to drill and complete for production than would be a vertical well directed to the same target horizon. Some costs presumably typical of a horizontal well drilled in the Bakken Formation of North Dakota (a Mississippian shale) were reported in the form of an example authorization for expenditure by the *Oil and Gas Investor*, (Table 1). The example well would have a measured depth (MSD) of 13,600 feet and a horizontal displacement (HD) of 2,500 feet.

Petroleum Engineer International (PEI) reported in November 1990 that, according to a PEI survey, horizontal wells drilled in the U.S. during the prior year had averaged slightly over \$1 million per well to drill, plus an additional \$140,000 per well to complete for production. The average cost per foot of horizontal displacement was \$475 nationally, and \$360 for horizontal wells drilled into the Upper Cretaceous Austin Chalk Formation of Texas⁴, while some experienced companies got close to \$300/foot in 1990.⁵ The cost difference, which in part implies that horizontal wells targeted at other than the Austin Chalk were more expensive, reflects a combination of sometimes radically different drilling conditions. At this early stage of technology application, each new type of target begets a "learning curve" which must be followed to develop optimal drilling and completion techniques for that target. Costs of successive wells tend to fall as more is learned and technique is optimized on the basis of that knowledge.

Also, the industry's *Joint Association Survey on 1990 Drilling Costs*⁶ reported that average horizontal drilling cost per foot was \$88.16 as compared to \$75.40 for wells not drilled horizontally, a 17-percent cost premium. Total expenditures on horizontal drilling reached \$662 million in 1990, representing 6 percent of the total drilling expenditure of \$10.937 billion.

Desired Compensating Benefits

Even when drilling technique has been optimized for a target, the expected financial benefits of horizontal drilling must at least offset the increased well costs before such a project will be undertaken. In successful horizontal drilling applications, the "offset or better" happens due to the occurrence of one or more of a number of factors.

First, operators often are able to develop a reservoir with a sufficiently smaller number of horizontal wells, since each well can drain a larger rock volume about its bore than a vertical well could. When this is the case, per well proved reserves are higher than for a vertical well. An added advantage relative to the environmental costs or land use problems that may pertain in some situations is that the aggregate surface "footprint" of an oil or gas recovery operation can be reduced by use of horizontal wells.

⁴Steven D. Moore, "Horizontal Drilling Activity Booms," *Petroleum Engineer International*, (November 1990), pp. 15-16.

⁵Steven D. Moore, "The Horizontal Approach," *Petroleum Engineer International*, (November 1990), p. 6.

⁶Finance, Accounting and Statistics Department, American Petroleum Institute, *Joint Association Survey on 1990 Drilling Costs*, (November 1991), pp. 4-5.

Second, a horizontal well may produce at rates several times greater than a vertical well, due to the increased wellbore surface area within the producing interval. For example, in the Austin Chalk reservoir of Texas' Giddings Field, under equal pressure conditions, horizontal completions of 500 to 2,200 foot HD produce at initial rates 2½ to 7 times higher than vertical completions.⁷ Chairman Robert Hauptfuhrer of Oryx Energy Co. noted that "Our costs in the [Austin] chalk now are 50 percent more than a vertical well, but we have three to five or more times the daily production and reserves than a vertical well."⁸ A faster producing rate translates financially to a higher rate of return on the horizontal project than would be achieved by a vertical project.

Third, use of a horizontal well may preclude or significantly delay the onset of production problems (interferences) that engender low production rates, low recovery efficiencies, and/or premature well abandonment, reducing or even eliminating, as a result of their occurrence, return on investment and total return.

⁷B.A. Shelkholeslami and others, "Drilling and Production Aspects of Horizontal Wells in the Austin Chalk," *Journal of Petroleum Technology*, (July 1991), SPE Paper Number, p. 779.

⁸Oryx's Hauptfuhrer: Big increase due in U.S. horizontal drilling," *Oil & Gas Journal*, (January 15, 1990), p. 28.

Table 1. Bakken Shale Horizontal Well Costs
(1990 Dollars)

Cost Category	Drill & Test	Complete	Total
Survey & Permits	3,900	0	3,900
Building Road & Location	23,850	2,500	26,350
Footage Contract	145,085	0	145,085
Day Work Contract	101,200	0	101,200
Rig For Completion	0	20,500	20,500
Drill Bits	37,020	450	37,470
Rental Equipment	60,325	16,700	77,025
Labor & Travel	45,300	28,200	73,500
Trucking & Hauling	23,650	9,500	33,150
Power,Fuel & Water	3,300	0	3,300
Mud & Chemicals	97,000	0	97,000
Drill Pipe	16,930	0	16,930
Mud Logging	14,550	0	14,550
Logs	12,600	11,000	23,600
Bottom Hole Pressure Test	0	5,000	5,000
Directional Services	200,000	0	200,000
Engineering and Geology	12,900	2,000	14,900
Cementing Surface Casing	14,000	0	14,000
Cementing Production Casing	0	53,400	53,400
Cleaning Location	4,600	500	5,100
Environment & Safety Eq	7,200	0	7,200
Misc. Material & Service	16,825	4,200	21,025
Total Intangibles	840,235	153,950	994,185
Surface Casing 9 5/8"	47,320	0	47,320
Production Casing 5 1/2"	0	198,435	198,435
Tubing 2 7/8"	0	42,840	42,840
Christmas Tree & Tubing Head	2,300	17,400	19,700
Tanks	0	17,000	17,000
Heater-Treater	0	20,000	20,000
Flowline	0	3,000	3,000
Packer	0	5,000	5,000
Misc.Equipment	0	15,000	15,000
Total Tangibles	49,620	318,675	368,295
Total Well Cost	889,855	472,625	1,362,480

Source: Sandra Johnson, "Bakken Shale," *Oil and Gas Investor*, (June 1990), p. 36,
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2. History of Technology Development and Deployment

Halting Steps

The modern concept of non-straight line, relatively short-radius drilling, dates back at least to September 8, 1891, when the first U.S. patent for the use of flexible shafts to rotate drilling bits was issued to John Smalley Campbell (Patent Number 459,152). While the prime application described in the patent was dental, the patent also carefully covered use of his flexible shafts at much larger and heavier physical scales "... such, for example, as those used in engineer's shops for drilling holes in boiler-plates or other like heavy work. The flexible shafts or cables ordinarily employed are not capable of being bent to and working at a curve of very short radius ..."

The first recorded true horizontal oil well, drilled near Texon, Texas, was completed in 1929.⁹ Another was drilled in 1944 in the Franklin Heavy Oil Field, Venango County, Pennsylvania, at a depth of 500 feet.¹⁰ China tried horizontal drilling as early as 1957, and later the Soviet Union tried the technique.¹¹ Generally, however, little practical application occurred until the early 1980's, by which time the advent of improved downhole drilling motors and the invention of other necessary supporting equipment, materials, and technologies, particularly downhole telemetry equipment, had brought some kinds of applications within the imaginable realm of commercial viability.

Early Commercial Horizontal Wells

Tests, which indicated that commercial horizontal drilling success could be achieved in more than isolated instances, were carried out between 1980 and 1983 by the French firm Elf Aquitaine in four horizontal wells drilled in three European fields: the Lacq Superieur Oil Field (2 wells) and the Castera Lou Oil Field, both located in southwestern France, and the Rospo Mare Oil Field, located offshore Italy in the Mediterranean Sea. In the latter instance, output was very considerably enhanced.¹² Early production well drilling using horizontal techniques was subsequently undertaken by British Petroleum in Alaska's Prudhoe Bay Field, in a successful attempt to minimize unwanted water and gas intrusions into the Sadlerochit reservoir.¹³

⁹"The Austin Chalk & Horizontal Drilling," *Popular Horizontal*, (January/March 1991), p. 30.

¹⁰A.B. Yost, II, W.K. Overbey, and R.S. Carden, "Drilling a 2000-foot Horizontal Well in the Devonian Shale," *Society of Petroleum Engineers Paper Number 16681*, presented at the SPE 62nd Annual Technical Conference, Dallas, Texas, (September 1987) pp. 291-301.

¹¹"Horizontal Drilling Contributes to North Sea Development Strategies," *Journal of Petroleum Technology*, (September, 1990), p. 1154.

¹²"Horizontal Drilling Contributes to North Sea Development Strategies," *Journal of Petroleum Technology*, (September, 1990), p. 1154.

¹³These are referred to as "water-coning" and "gas-coning" due to the hydraulic profile of these fluids that develops in rocks in the vicinity of an active conventional production well. In such cases, the increased stand-off from the fluid contacts in the reservoir that is provided by a horizontal well bore can improve production rates without inducing coning, as the additional wellbore length serves to reduce the drawdown for a given production rate. Dave W. Sherrard, Bradley W. Brice, and David G. MacDonald, "Application of Horizontal Wells at Prudhoe Bay," *Journal of Petroleum Technology*, (November 1987), pp. 1417-1425.

The Recent Growth of Commercial Horizontal Drilling

Taking a cue from these initial successes, horizontal drilling has been undertaken with increasing frequency by more and more operators. They and the drilling and service firms that support them have expanded application of the technology to many additional types of geological and reservoir engineering factor-related drilling objectives. Domestic horizontal wells have now been planned and completed in at least 57 counties or offshore areas located in or off 20 States.

Horizontal drilling in the United States has thus far been focused almost entirely on crude oil applications. In 1990, worldwide, more than 1,000 horizontal wells were drilled. Some 850 of them were targeted at Texas' Upper Cretaceous Austin Chalk Formation alone.¹⁴ Less than 1 percent of the domestic horizontal wells drilled were completed for gas, as compared to 45.3 percent of all successful wells (oil plus gas) drilled.¹⁵ Of the 54.7 percent of all successful wells that were completed for oil, 6.2 percent were horizontal wells. Market penetration of the new technology has had a noticeable impact on the drilling market and on the production of crude oil in certain regions. For example, in mid-August of 1990, crude oil production from horizontal wells in Texas had reached a rate of over 70,000 barrels per day.¹⁶

Types of Horizontal Wells and Their Application Favorabilities

For classification purposes that are related both to the involved technologies and to differential application favorabilities, petroleum engineers have developed a categorization of horizontal wells according to the radius of the arc described by the wellbore as it passes from the vertical to the horizontal. Wells with arcs of 3 to 40 foot radius are defined as short-radius horizontal wells, with those having 1 to 2 foot radii being considered "ultrashort-radius" wells. Some of these short-radius horizontal wells may have angle increases from the vertical, called "build rates", of as much as 3 degrees per foot drilled. Medium-radius wells have arcs of 200 to 1,000 foot radius (that is, build rates of 8 to 30 degrees per 100 feet drilled), while long-radius wells have arcs of 1,000 to 2,500 feet (with build rates up to 6 degrees per 100 feet).¹⁷ The required horizontal displacement, the required length of the horizontal section, the position of the kickoff point, and completion constraints are generally considered when selecting a radius of curvature. Most new wells are drilled with longer radii, while recompletions of existing wells most often employ medium or short radii. Longer radii tend to be conducive to the development of longer horizontal sections and to easier completion for production.

Short-Radius Horizontal Wells

Short-radius horizontal wells are commonly used when re-entering existing vertical wells in order to use the latter as the physical base for the drilling of add-on arc and horizontal hole sections. The steel casing (lining) of an old vertical well facilitates attainment of a higher departure (or "kick off") angle than can be had in an uncased hole, so that a short-radius profile can more quickly attain horizontality, and thereby

¹⁴Steven D. Moore, "Technology for the Coming Decade," *Petroleum Engineer International*, (January 1991), p. 17.

¹⁵Finance, Accounting and Statistics Department, American Petroleum Institute, *Joint Association Survey on 1990 Drilling Costs*, (November 1991), p. 4-5.

¹⁶"The Austin Chalk & Horizontal Drilling," *Popular Horizontal*, (January/March 1991), p. 30.

¹⁷For medium- and long-radius: B.A. Shelkholeslami, B.W. Schlottman, F.A. Seidel, and D.M. Button, "Drilling and Production Aspects of Horizontal Wells in the Austin Chalk," *Journal of Petroleum Technology*, (July 1991), SPE Paper Number 19825, p. 773.; other: S.D. Joshi, *Horizontal Well Technology*, Pennwell Publishing Company, (1991), Tulsa Oklahoma, pp. 13-18; for all: Lynn Watney, "Horizontal Drilling Is Feasible in Kansas," *The American Oil & Gas Reporter*, (August 1992), pp. 84-86.

rapidly reach or remain within a pay zone. The small displacement required to reach a near-horizontal attitude also favors the use of short-radius drilling in small lease blocks. A need to avoid extended drilling in a difficult overlying formation also favors use of a short-radius well that kicks off near the bottom of, or below, the difficult formation. Short-radius horizontal drilling also has certain economic advantages. These include a lower capital cost,¹⁸ the fact that the suction head for downhole production pumps is smaller, and that use of an MWD system is frequently not required if long horizontal sections are not to be drilled.

A current drawback to the use of a short-radius horizontal well is that the target formation should be suitable for an open hole or slotted liner completion, since adequate tools do not yet exist to reliably do producing zone isolation, remedial, or stimulation work in short-radius holes. Also, hole diameter can only range up to about 6 inches, and the hole cannot be logged since sufficiently small measurement tools are not yet available.

Medium-Radius Horizontal Wells

Medium-radius horizontal wells allow the use of larger hole diameters, near-conventional bottom hole (production) assemblies, and more sophisticated and complex completion methods. It is also possible to log the hole. Albeit that the drilling of medium-radius horizontal wells does require the use of an MWD system, which increases drilling cost,¹⁹ medium-radius holes are perhaps the most popular current option. They can be drilled on leases as small as 20 acres.²⁰ One firm, Meridian Oil, Inc., accounted for 43 percent of all medium-radius horizontal wells drilled in 1989 in the United States, according to the *Oil and Gas Investor*.²¹

Long-Radius Horizontal Wells

Long-radius holes can be drilled using either conventional drilling tools and methods, or the newer steerable systems. Long-radius wells, in the form of deviated wells (not, however, deviated to the horizontal), have been around quite a while. They are not suited to leases of less than 160 acres due to their low build rates.

Attainable Length of Horizontal Displacement

The attainable horizontal displacement, particularly for medium- and long-radius wells, has grown significantly, as operators and the drilling and service contractors have devised, tested, and refined their procedures, and as improved equipment has been designed and used. For example, it was found that some rotation of the drill string, while using a downhole motor to turn the bit, itself aids in passage of the drill string through the arc from vertical to horizontal. It avoids potentially damaging and power consumptive stick-slip behavior when the string contacts the side of the hole. Some operators have also found the use

¹⁸"Horizontal Drilling and Completions: A Review of Available Technology," *Petroleum Engineer International*, (February 1991), pp. 14-15.

¹⁹Rainer Jurgens and others, "Horizontal Drilling and Completions: A Review of Available Technology," *Petroleum Engineer International*, (February 1991), p. 18.

²⁰Lynn Watney, "Horizontal Drilling Is Feasible in Kansas," *The American Oil & Gas Reporter*, (August 1992), p. 84.

²¹Sandra Johnson, "Bakken Shale," *Oil and Gas Investor*, Vol. 9, No. 11, (June 1990), p. 36.

of coiled tubing drill strings in lieu of conventional jointed drill pipe an advantage in extending the horizontal displacement of the well (about which more is said later on). Routinely achievable horizontal displacements have rapidly climbed from 400 to over 8,000 feet.²²

The Completion of Horizontal Wells for Production

Drilling and completion methods, including drilling underbalanced,²³ have been developed or customized for horizontal applications to minimize formation damage during drilling and completion. These methods can be categorized into the areas of "well logging and formation testing," "well cleanup and well stimulation," "open hole completion," and "cased completion."

Well Logging and Formation Testing

Well logs are usually run prior to completion of a well. They continuously record a suite of measurements along the length of the hole, and are interpreted to provide a complete record of the lithologies penetrated and their fluid content. Target horizons for completion are usually selected based on the logs. Additionally, formation testers often are used to determine the ability of selected target zones to produce fluids into the well, as well as to secure samples of the fluids.

Wall Cleanup and Well Stimulation

Mechanical scraping, acid treatment, and other methods may be used to clean the wall of the well bore within target producing intervals, so that "virgin" formation is exposed in the well. Fractures around the well bore in those intervals may also be induced or expanded by explosive, chemical, or hydraulic means, in order to increase the effective well radius by increasing the permeability of the formation.

For example, in the Giddings Field's Austin Chalk reservoir, where the oil resides in the natural fracture system and not in the rock matrix, both horizontal and vertical wells are stimulated successfully by pumping several tens of thousands of barrels of fresh water into the formation using wax beads as a diverter, alternating with stages of 10 to 15 percent hydrochloric acid. This process opens existing fractures, connects some fractures, and dissolves salt crystals in natural fractures. The result is an increase in the drainage area for a well and, therefore, in reserves per well. One company achieved an average

²²Rob Buitenkamp, Steve Fischer and Jim Reynolds, "Well claims world record for horizontal displacement," *World Oil*, (October 1992), p. 41.

²³Normally, conventional vertical wells are drilled at internal wellbore pressures (usually created by adding dense weighting agents such as barite to the drilling fluid) higher than those expected to be encountered in the penetrated formations. This makes it easier to control any gas "kicks" that are encountered and, thus, minimizes the probability of blowouts. One of the completion problems caused by this procedure is that some drilling fluid is inevitably injected into the pores of the producing interval, reducing its permeability to the well bore, and, therefore, the achievable production flow. Since fluid is exiting to the formation, a "cake" of solids may also coat the hole opposite the formation. Such damage has to be corrected during well completion. However, a 10-foot vertical pay zone is a lot easier and cheaper to clean up than a horizontal interval of several hundred feet. Most horizontal wells are therefore drilled "underbalanced," that is, the wellbore pressure during drilling is held at a level slightly less than that in the formations encountered. This allows formation fluids to flow into the wellbore during drilling, keeping the formation clear of drilling fluid. The goal, of course, is to just barely underbalance, so that a serious safety hazard is not created when entering or passing through a gas-bearing interval.

reserve addition per well, over a run of 57 horizontal wells, of 74,000 barrels of oil equivalent per fracture treatment, at a cost of \$ 1.69 per barrel added.²⁴

Also in the Austin Chalk, in Texas' Pearsall Field, water fracture treatments and other more conventional stimulation methods yielded inconsistent results. Consequently, closed fracture acidizing was successfully tried. The acid treatment is injected into the formation at pressures insufficient to induce fracturing, and is allowed to remain for some time so that it can etch out the natural fractures in the rock and clean the fracture faces.²⁵

Open Hole Completion

Open hole completions are those in which nothing is done to modify the raw well bore in the target producing zone. They can only be attempted in formations which are structurally competent and, therefore, not prone to collapse or the spalling of rock particles from the hole wall as produced fluids flow alongside, and which will not produce fines along with the fluids that could clog the well or producing equipment. Open hole completion is, of course, the cheapest alternative if one is certain that future problems will not occur.

Cased Completion

Cased completions are more the norm. The installation (setting) of relatively thin-walled casing in the well bore allows most possible production problems to be avoided. The casing process consists of hanging the casing in the hole, cementing it in place, isolating the producing horizon with some combination of cement plugs and tools called packers, perforating the casing and any cement opposite the desired producing interval and, perhaps, installing a production liner. Aspects of each of these are discussed below.

Casing

Well casing consists of thin-walled tubing, usually constructed of steel, that is used to line the drilled hole. The casing supports the wall of the well, checks the caving tendencies of unconsolidated formations, prevents unwanted exchange of fluids between the various penetrated formations, excludes the inflow of fluids and fines from all but the target producing intervals, and provides the mounting base for surface well control equipment. Normally, the casing is $\frac{3}{4}$ inch or more smaller in diameter than the drilled hole.

Cementing

Cased wells are nearly always cemented (i.e., cement is pumped down through the well into the annular space between the casing and the hole wall). The cement serves to mechanically stabilize the casing string within the hole and seals off water flows from the adjacent formations.

²⁴Pat Chisholm and Kevin Dunn, "Halliburton Chalk Stimulation - Stimulating the Austin Chalk," *Popular Horizontal*, (April/June 1991), p. 24; and Louise Durham, "Horizontal action heats up in Louisiana," *World Oil*, (July 1992), pp. 39-42.

²⁵Chisholm & Dunn, *op. cit.*, p. 28.

Packers

Packers are devices that can be placed at a desired position within a well and then be expanded in diameter to seal off the well bore or casing string at that point. Some are designed to allow passage of smaller diameter production tubing through them.

Perforations and Liners

In a fully cased well, there are two ways to access target producing intervals. The first is to perforate the casing and any cement opposite the selected producing horizons, utilizing a perforating gun which contains a number of shaped explosive charges. The second is to set an uncemented well liner at the selected horizon in lieu of casing. Liners are pre-perforated, or have slots cut in their sides, or have screen inserts. These openings may or may not be backed up by screens and/or immobile granular packings. The screens and packings serve to keep rock particles from entering the well along with the produced fluids, thereby avoiding contamination of the product stream and possible clogging of, or damage to, the well and producing equipment.

Well completion plans for long radius horizontal wells are determined mainly by the length of the horizontal section; they differ little from conventional well completions in terms of difficulty. But for medium radius horizontal well completions, problems begin "with running casing and increase with build rate because conventional equipment no longer works."²⁶ Some of the problems reported in the literature include:

Production rate-sensitive sand coproduction, which occurs when formation stresses exceed formation strength.²⁷

Restriction of fluid flow by prepacked production screens, due to the average pore throats of commonly used gravels being quite small (from 50 to 100 microns), or failure of the plastic coat on the gravel due to flexing of the gravel pack as the screen is lowered into the production zone, or failure of the plastic coated gravel filling due to mud acid action.²⁸

The need for completion fluids with special properties relative to viscosity and shear thinning effects. The viscosity-density enhancers commonly used for vertical completions, such as barite and bentonite, cause more than acceptable formation damage in horizontal applications. Something like a sized-salt polymer system is needed instead.²⁹

Centralization of pipe in cased horizontal completions is "difficult to achieve, and most designs are not strong enough to get to the bottom and still work. Medium radius horizontal completions also present the conflicting objectives of successfully clearing the

²⁶T.E. Zaleski, Jr., and Edward Spatz, "Horizontal completions challenge for industry," *Oil & Gas Journal*, (May 2, 1988), p. 58.

²⁷M.R. Islam and A.E. George, "Sand Control in Horizontal Wells in Heavy-Oil Reservoirs," *Journal of Petroleum Technology*, (July 1991), p. 844.

²⁸Derry D. Sparlin and Raymond W. Hagen, Jr., "Prepacked screens in high angle and horizontal well completions," *Offshore*, (April 1991), pp. 57-58.)

²⁹Jay Dobson and T.C. Mondshine, "Unique Completion Fluid Suits Horizontal Wells," *Petroleum Engineer International*, (September 1990),p. 42.

curved portion of the well and having a high density of centralizers on the casing string."³⁰

Current Domestic Applications

As noted previously, horizontal drilling is usually undertaken to achieve important technical objectives related to specific characteristics of a target reservoir. These characteristics typically involve:

- the reservoir rock's permeability, which is its capacity to conduct fluid flow through the interconnections of its pore spaces (termed its "matrix permeability"), or through fractures (its "fracture permeability"), and/or
- the expected propensity of the reservoir to develop water or gas influxes deleterious to production, either from other parts of the reservoir or from adjacent rocks, as production takes place (an event called "coning").

Due to its higher cost, horizontal drilling is currently restricted to situations where these characteristics indicate that vertical wells would not be as financially successful. In an oil reservoir which has good matrix permeability in all directions, no gas cap and no water drive, drilling of horizontal wells would likely be financial folly, since a vertical well program could achieve a similar recovery of oil at lower cost. But when low matrix permeability exists in the reservoir rock (especially in the horizontal plane), or when coning of gas or water can be expected to interfere with full recovery, horizontal drilling becomes a financially viable or even preferred current option. Most existing domestic applications of horizontal drilling reflect this "philosophy of application."

"Chalk Formations"

By far the most intensive domestic application of horizontal drilling has been in a few Texas oil fields in which the Upper Cretaceous Austin Chalk Formation is the reservoir rock. At year-end 1990, some 85 percent of all domestic horizontal wells had been drilled to the Austin. The formation is a massive, oil-bearing limestone that, in some locations, is extensively vertically fractured. Most of the productive permeability in the formation is fracture permeability, rather than matrix permeability. As a consequence, horizontal wells drilled to intersect several vertical fractures at an approximate right angle have typically demonstrated much larger initial production rates than were provided by previously drilled vertical wells. The latter, of course, at best intersected only one vertical fracture.

Production from Austin Chalk horizontal wells in the Pearsall Field has been responsible for the recent increase of oil production experienced in Texas Railroad Commission District 1. A number of the wells tested at flows of over 1,000 barrels per day, a relatively unusual event in the modern day lower 48 States onshore. For example, the Winn Exploration Co. 10 Leta Glasscock tested at 5,472 barrels of oil per day accompanied by 2,368,000 cubic feet per day of gas.³¹ Typically, in Pearsall Field, the Austin Chalk has produced better after acid treatment of the producing intervals.³²

³⁰Zaleski and Spatz, *op. cit.*, p. 62.

³¹"TEXAS," *Oil & Gas Journal*, (January 1, 1990), p. 84.

³²Chisholm and Dunn, *op. cit.*, p. 31.

Another Austin Chalk field, the Giddings Field, has served as a comparative testing arena for two application modes of horizontal drilling. In the first, a lateral displacement of about 300 feet was used to reach a comparatively small area of faulted and fractured rock, with the small horizontal reach in the target formation being little beyond that achievable with a vertical well. In the second, the longest possible horizontal reach was drilled in the pay zone, perpendicular to fracture direction. An eight-well Amoco Production Company program showed an increase of productivity with increased length of horizontal displacement, relative to offsetting vertical wells. The productivity ratio (quantity obtained from the horizontal hole relative to quantity obtained from the offset vertical hole) measured at 500 feet of HD was 2½, whereas at 2,000 feet of HD it was 7.0.^{33 34} No stimulations were performed on any of the Amoco wells, as "the direct connection between the horizontal wellbore and natural fracture systems [was] sufficient to yield expected producing rates."³⁵ Amoco also noted that "it was both cost-effective and operationally attractive to install pumping equipment immediately after drilling, because it eliminated the cost of swabbing or gas injection to kick the well off."

Others have completed their Giddings Field wells using fracture treatments. Chisholm and Dunn noted that, in their experience, "In general, the Giddings side of the Chalk can best be stimulated with a simple high rate, high volume water fracture."³⁶ "A water fracturing treatment is the process of pumping large volumes of fresh water at high rates into the wellbore, alternating with stages of 10 to 15 percent HCl (hydrochloric acid). Hydraulic fractures created by water fracturing tie smaller fractures to each other and to major fracture systems."³⁷

Table 2. Giddings Field Horizontal Well Production, 6-Month Average

Item	County				Total
	Lee	Burleson	Fayette	Brazos	
Oil production, barrels	88,694	2,386,098	498,681	51,100	3,024,573
Gas production, thousand cubic feet	75,258	8,236,483	1,440,941	85,025	9,944,707
Production, barrels of oil equivalent	95,920	3,209,746	653,775	59,603	4,019,044
Number of wells	7	71	12	1	91
Production, barrels of oil equivalent per well	13,574	45,208	54,481	59,603	44,165

Note: Washington County deleted from table as values are all equal to zero. Study includes only wells with 6 months of production history drilled after August 1989.

Source: William T. Maloy, "Horizontal wells up odds for profit in Giddings Austin Chalk," *Oil & Gas Journal*, (February 17, 1992), p. 68. Reproduced by permission.

³³B.A. Shelkholeslami and others, *op. cit.*, p. 778.

³⁴Shelkholeslami, et al., *op. cit.*, p. 778.

³⁵Shelkholeslami, et. al., *op. cit.*, p. 778.

³⁶Chisholm and Dunn, *op. cit.*, p. 31.

³⁷Chisholm and Dunn, *op. cit.*, p. 24.

Horizontal drilling in the Giddings Field has not only significantly improved average well recoveries, it has more than offset the increased drilling costs. A study of 91 horizontal wells, all drilled after August 1989, and all with at least 6 months of production history, showed an average 195,000 barrels of oil equivalent recovery over the economic well life. Three-fourths of this amount is obtained in the first 3 years. (Table 2). The study indicated that an average Giddings Field Austin Chalk horizontal well would return an after-tax investment (discounted at 10 percent) of 1.6:1, would have a net present value of \$650,923, and would pay out its cost in 1.1 years.³⁸

Additional "chalk" formations in which horizontal drilling is being attempted include the Annona and Saratoga members of the Upper Cretaceous Selma Group in Louisiana, the Lower Cretaceous Buda and Georgetown Formations (both Washita Group) in Texas, and the Upper Cretaceous Niobrara Formation in Colorado and Wyoming. In the latter instance, the technique is being tested amidst much tougher drilling conditions than prevail in the Austin Chalk. Drilling problems encountered in the northeastern Denver Basin's Silo Field include sloughing of the overlying Pierre Shale, problems in the Niobrara itself with over- and underpressured intervals, and karst, vuggy, or fractured zones that can cause loss of drilling fluid circulation or hole stability problems.³⁹

Other Applications

Beyond the fractured, low matrix permeability class of reservoirs exemplified by the various chalk formations, there are numerous other geologic situations in which horizontal drilling is being applied, albeit with less frequency. Early applications at Prudhoe Bay Field to avoid or minimize either water or gas coning have already been mentioned; many similar applications have since been executed elsewhere for the same purpose. Several specific examples of types of applications which appear to form the bulk of additional domestic horizontal drilling to date are discussed hereafter.

Source Rock Applications

One type of application attempts to produce oil that has not yet migrated to a conventional trap, but instead remains in the porosity of the source rock unit in which it was generated. A prime example is the Mississippian Bakken Formation of North Dakota and Montana, which, in generationally mature areas, is an oil-wet shale believed to contain several billion barrels of oil-in-place.

Meridian Oil, Inc., indicated that its Bakken horizontal drilling program had added net reserves of more than 16.6 million barrels of oil equivalent by March 1992.⁴⁰ Meridian's program followed a very clear learning curve. The first 10 wells had an after-tax rate of return of 30.6 percent, which climbed to 44.2 percent for the second 10 wells, and again to 66.6 percent for the third 10 wells. Pacific Enterprises Oil Co. indicated that, compared to vertical wells on 160 acre spacings, its Bakken horizontal wells, spaced at 320 acres, provided a 40-percent greater return on investment.⁴¹ Note that horizontal wells generally require larger well spacings than conventional vertical wells in order to avoid drainage of neighboring leases and fluid communication with neighboring wells; in at least one case, fluids injected at high pressure into a horizontal well during its completion to fracture the surrounding rock were produced by

³⁸William T. Maloy, "Horizontal wells up odds for profit in Giddings Austin Chalk," *Oil & Gas Journal*, (February 17, 1992), pp. 67-70.

³⁹G. Alan Petzet, "Horizontal Niobrara play proceeding with caution," *Oil & Gas Journal*, (November 11, 1991), p.68.

⁴⁰M.G. Whitmire, "Fractured zones draw horizontal technology to Marietta basin," *Oil & Gas Journal*, (March 30, 1992), p. 78.

⁴¹Sandra Johnson, "Bakken Shale," *Western Oil World*, (June 1990), pp. 31-45.

a nearby existing well. In North Dakota, oil production from horizontal completions has risen steadily until this year, as seen in Table 3.

Stratigraphic Trap Applications

On the basis of first principles, it would seem that horizontal drilling would be the method of choice for the drilling of certain kinds of stratigraphic traps such as porosity pinchouts and reefs. Yet, remarkably few domestic examples of pure stratigraphic trap horizontal drilling have been reported in the trade literature. Some effort (10 wells over the past 5 years) has been reported to develop Silurian Niagaran reef structures in the Michigan Basin. The first such well, drilled by Trendwell, was successful, but has yet to produce due to high hydrogen sulfide content and a lack of suitable treatment facilities.⁴² A recent success, the Conoco 2-18 HD1 Lovette, was drilled in Vevay Township, Ingham County. It had an HD of 1,100 feet, and produced 149 barrels per day of crude oil accompanied by 77,000 cubic feet per day of natural gas. The relatively low production rates of the existing Niagaran horizontal wells have not enhanced the attractiveness of horizontal drilling for these kinds of targets.⁴³ Eventual drilling of a "flush" (highly productive) well or two would, no doubt, rapidly alter that situation.

Heterogeneous Reservoirs

Another type of application seeks to overcome problems caused by reservoir heterogeneity. For example, Amoco reentered an existing Ryckman Creek Field (Wyoming) well and drilled a lateral about 500 feet into the Upper Triassic Nugget Formation, with multiple objectives of seeking to open more pay zone, penetrate more "sweet" spots (so called because they are the more productive areas of the heterogeneous reservoir), attain better maintenance of reservoir pressure, and reduce water and gas coning.⁴⁴

Coalbed Methane Production

Short and medium radius horizontal drilling techniques for coalbed methane recovery have been successfully demonstrated. Short radius technique was used by Gas Resources Institute (GRI)/Resource Enterprises, Inc. in the No. 3 Deep Seam gas well drilled into the Cameo "D" Coal Seam, Piceance Basin, Colorado. The Department of Energy and GRI used medium radius technique successfully at their Rocky Mountain No. 1 site in the Hanna Basin, Wyoming, targeting the Hanna coal seam at 363 foot depth. Subsequently, commercial horizontal wells have been drilled into the Fruitland Coal of New Mexico's San Juan Basin by several firms.⁴⁵ Meridian Oil, Inc., brought in one such well that produced at a rate of 7 million cubic feet per day, as opposed to the average conventional well rate of 1.05 million cubic feet per day.⁴⁶

⁴²Scott Ballenger, Michigan Oil & Gas News, personal communication, (June 24, 1992),

⁴³Ballenger, *op. cit.*

⁴⁴Russ Rountree, "Amoco tests horizontal drilling," *Western Oil World*, (September 1987), p. 18.

⁴⁵Terry L. Logan, "Horizontal Drainhole Drilling Techniques Used in Rocky Mountains Coal Seams," *1988-Coal-Bed Methane, San Juan Basin*, Rocky Mountain Association of Geologists, pp. 133-141.

⁴⁶"Meridian tests new technology," *Western Oil World*, (June 1990), p. 13.

Table 3. Horizontal Oil Activity and Production, North Dakota

Time Period	Dry Holes	Producing Wells	Production (Barrels)	Percent of Total State Production
1986	0	0	0	0.0
1987	0	1	10516	<0.1
1988	0	9	222805	0.6
1989	3	29	969075	2.6
1990	12	65	2744317	7.5
1991	3	45	3706820	10.3
1992	0	34	3004867	9.1

Source: North Dakota Industrial Commission, Oil and Gas Division.

Boosting Recovery Factor

Yet another type of horizontal drilling application attempts to increase the recovery factor (the produced fraction of oil-in-place) experienced in already mature reservoirs. An example occurred in the Pennsylvanian Bartlesville sand, a fluvial-dominated deltaic sandstone reservoir characterized by low permeability and underlain by a sandstone aquifer. In the Flatrock Field of Osage County, Oklahoma, the Bartlesville is located at a depth of 1,400 feet. The field, discovered in 1904, was considered fully developed by 1925, with over 1,000 conventional wells; it has produced over 30 million barrels of oil. The old vertical wells were typically fractured using explosives, which increased initial oil production rates to economic levels and usually avoided deleterious over-break into the underlying water-bearing unit. However, they also typically developed a large water cut (water as a fraction of all produced liquids) by their 12th month of service. It was hoped that a horizontal well would both increase unstimulated initial oil production and reduce total water production.⁴⁷ A well was completed in the 10-foot thick Bartlesville Sand at a HD of 1,050 feet. Unstimulated initial oil production was not materially increased in this instance (on the order of 6 to 9 barrels of oil per day), but the watercut was substantially lessened (after 90 days, from roughly 75 percent for vertical wells, to 14 percent with the horizontal well). After explosive stimulation intended to improve oil production, the watercut increased to high levels because the aquifer was unintentionally breached.

Fluid and Heat Injection Applications

Horizontal drilling technology has also inspired new approaches to the injection of fluids or heat into oil or tar sand reservoirs to enable or improve recovery. One of the more recent technologies is heated annulus steam drive (HAS drive), now under pilot study by Chevron Canada at Steepbank Field in northeast Alberta, Canada. The process involves circulating steam in an unperforated horizontal tar sand well. The pilot well has a horizontal section of 1,600 feet and a TD of 2,800 feet. In this instance, the horizontal well is located below conventional vertical perforated steam injection and production wells.⁴⁸

⁴⁷John E. Rougeot and Kurt A. Lauterbach, "The Drilling of a Horizontal Well in a Mature Field," (January 1991), DOE/BC/14458-1, p. 1.

⁴⁸"Horizontal Well Used as Heating Coil in Bitumen Recovery," *Petroleum Engineer International*, (May 1992), p. 15.

The Glenn Pool Field, Tulsa County, Oklahoma, is the site of a Department of Energy-funded project to enhance oil production from fluvial-dominated deltaic reservoirs utilizing reservoir characterization studies and horizontal water injection technology.⁴⁹

Dramatic oil production gains have been reported in the New Hope Field, Franklin County, Texas, by Texaco Exploration & Production Inc., utilizing two horizontal injection wells drilled into the Lower Cretaceous Pittsburg reservoir. The Pittsburg is a relatively thin, low permeability sandstone. The horizontal wells were placed about 8,000 feet deep, lower on the anticlinal structure of the field than existing producing wells. Reservoir simulations were used to select the locations for the wells, which are considered true line drive waterfloods, and were completed open hole. Since introduction of the horizontal injection wells, production per producing well has increased from about 100 to 400 barrels of oil per day via submersible pumping units, the highest production rates in the history of the field.⁵⁰ Costs of the development are estimated at \$2 to \$3 per barrel of incremental reserves added. Company officials estimate that the productive life of the New Hope shallow unit has been extended by 10 to 15 years.⁵¹

Win Energy, Inc., has reported a plan to drill up to eight horizontal water injection wells into the Permian Flippen Limestone in the combined Bullard Unit/Propst-Anson Fields, Jones County, Texas. The company estimates that 1½ million barrels of additional oil production will come from the combined fields, which are believed to have had original oil-in-place of 6 million barrels and a present recovery factor of 32 percent. The wells will be located at a relatively shallow 2,540 feet and will be offset horizontally about 1,500 feet.⁵²

Cyclic steam injection through multiple ultrashort radius horizontal radials has been tested in a Department of Energy-sponsored project at the Midway-Sunset Field, California. The field has a history of successful thermal operations and is California's second largest current producer. A set of eight radials was drilled into a cold zone within the 400-foot thick Upper Miocene Potter C reservoir interval, which is a fairly clean quartz sandstone containing about 10 percent shale, located at a depth of 884 feet. Temperature logging in an observation well located 50 feet from the end of one of the radials showed a substantial temperature increase in the 800- to 875-foot interval, demonstrating effective containment of steam in the target interval. Decrease of steam override effects near vertical well bores was also a goal of the well, one which so far has been attained. Production from the well started out very low in the first week and then increased over the next 3 weeks to a peak of 60 barrels of oil per day with a 30½ percent water cut. Production stayed strong from mid-July 1990, through the first week of October.⁵³

Multiple Objectives

In some instances, it has been possible to target reservoirs exhibiting more than one characteristic favorable to the application of horizontal drilling technology. A good example is the Grassy Creek Trail Field located in Emery and Carbon counties, Utah, which produces oil from several members of the Lower Triassic Moenkopi Formation. The field is located on a small, low dip structural nose at the north end of the San Rafael Swell. Lithologies in the producing zones are predominately siltstones and shales that have low matrix porosity and permeability. The oil appears to have been sourced within the Moenkopi

⁴⁹"DOE chooses 14 EOR projects for backing," *Oil & Gas Journal*, (April 27, 1992), p. 28.

⁵⁰"Horizontal Wells Inject New Life Into Mature Field," *Petroleum Engineer International*, (April 1992), pp. 49-50.

⁵¹"Texaco completes horizontal injector in Southeast Texas oil field," *Oil & Gas Journal*, (February 24, 1992), p. 44.

⁵²"Horizontal waterflood scheduled in Texas carbonate reservoir," *Oil & Gas Journal*, (September 2, 1991), p. 34.

⁵³Wade Dickinson, Eric Dickinson, Herman Dykstra, and John M. Nees, "Horizontal radials enhance oil production from a thermal project," *Oil & Gas Journal*, (May 4, 1992), pp. 116-124.

itself, and the producing zones are vertically fractured. Depth to production is relatively shallow, on the order of 3,900 feet.

The field was discovered by Cities Service Oil Company in 1953, after which four development wells were completed. The five vertical wells produced about 141,000 barrels of oil between 1961 and 1976. Skyline Oil Company began a second development program in 1982 that applied multiple short (several hundred foot) lateral borehole completions executed using the Texas Eastern Drilling Systems, Inc. (Teds) technology for short-radius horizontal wells. Sixteen were drilled, of which 13 had delivered production of 358,817 barrels of oil through 1987 or, in a period of 6 years, 2½ times the amount delivered by the 5 conventional wells during 16 years. Virtually all of the horizontal production came from 10 of the wells, in which 29 of 39 laterals drilled into different members of the Moenkopi Formation were productive. Vertical fractures encountered by the laterals were found to range from ½ to 1½ inch in width at interval spacings of from 100 to 200 feet. It is believed that the production curves from the Grassy Trail Creek Field wells showed the influence of two different producing mechanisms. The first was hyperbolic decline resulting from rapid gas expansion in those fractures which were in direct contact with the borehole, while the second was exponential decline resulting from the gravity drainage of fluid entering fractures from the rock matrix at some distance from the borehole.⁵⁴

⁵⁴Gary C. Mitchell, Fred E. Rugg, and John C. Byers, "The Moenkopi: horizontal drilling objective in East Central Utah," *Oil & Gas Journal*, (September 25, 1989), pp. 120-124.

3. New Developments

Expected Growth of Horizontal Drilling

Virtually all relevant trade journals have carried articles over the past 5 years expressing considerable optimism as to the business growth prospects of horizontal drilling. So far, these predictions appear to be valid. A close student of the subject, David Yard, estimated in January 1990 that horizontal completions would escalate by 230 percent annually, and that more than 2,000 successful completions could be expected in 1992. He also expected lifting costs to fall into the \$4- to \$6-per-barrel range.⁵⁵

Coiled Tubing and Horizontal Drilling

Initially tested for petroleum industry applications in the 1960's,⁵⁶ coiled tubing technology has been used for some time to perform conventional well workovers (maintenance and remedial work). Its use to do initial drilling and completion work, particularly in horizontal holes, is a phenomenon of the late 1980's and the present. Unlike standard drill pipe, which comes in 30-foot lengths equipped with threaded connectors at each end, and is stored in 3-section, 90-foot-long joints on the drilling or workover rig's pipe rack, coiled tubing is a continuous length of pipe that is stored wrapped around a large reel, in much the same fashion as thick electrical cable is stored and shipped. In operation, the tubing is straightened off the storage reel and led over a curved guide to and through a motorized injector head mounted atop the well control equipment stack, and thence through the control stack into the well. Tools are attached to the downhole end; wire cables can also be passed, and fluids circulated, through the tubing.

The tubing's wall thickness, on the order of 0.05 to 0.2 inches, is considerably less than that of drill pipe, which ranges from about 0.2 inches to about 0.5 inches. Its diameter is also less, on the order of $\frac{3}{4}$ to $2\frac{3}{8}$ inches, whereas drill pipe ranges from about $2\frac{3}{8}$ inches to about $5\frac{1}{2}$ inches in diameter. The smaller dimensionality, as well as the use of different alloys, renders the tubing much more flexible than standard drill pipe, at the expense of increased fragility and decreased load handling capabilities in both compression and tension. In horizontal use, the sliding friction increases as the horizontal displacement increases, adding to the load in both compression and tension. As noted by Spreux, "The weak link in the system is its relative fragility, rendering it incapable of pushing heavy tools over great distances."⁵⁷ Particularly to be avoided are the development of local ovalities ("out of round" spots) and the placement of excessive axial tension on the pipe, which can produce "necking" (a local reduction of diameter), both of which reduce its collapse strength. At the opposite extreme, excessive compression, the combined result of the downward force applied by the injector head and the upward force caused by frictional drag of the downhole tools, will cause buckling of the tubing, which can ultimately deform into a helix that is in contact with the wellbore along the entire length of the tubing. At that point, friction becomes so great that no further downhole progress can be made. Thus, tighter controls on operating conditions and handling methods are required in coiled tubing applications than are normally applied when using conventional drill strings.

⁵⁵"Reservoir Engineering is Key to Horizontal Drilling," *Petroleum Engineer International*, (March 1990), p. 49.

⁵⁶Alexander Sas-Jaworsky, II, "Coiled tubing...operations and services, Part 1-The evolution of coiled tubing equipment," *World Oil*, (November 1991), pp. 41-44, 46-47.

⁵⁷A.M. Spreux, A. Louis, and M. Rocca, "Logging Horizontal Wells: Field Practice for Various Techniques," *Journal of Petroleum Technology*, (October 1988), pp. 1352-1354.

To relieve compression problems in the use of coiled tubing to push tools in horizontal well maintenance operations, Statoil and others⁵⁸ are combining two variants of the pumpdown technology of conventional wireline operations with coiled tubing use: coiled-tubing assisted pumpdown (CTP) and pump-assisted coiled tubing. In coiled-tubing assisted pumpdown, an independent (not connected to the surface) coiled tubing segment is run into the well using pump locomotives at either segment end. The lower end locomotive is "floating" so that the tubing can be pushed through it even farther into the well. A hollow locomotive at the upper end is used to drive the entire assembly back up the well. In the pump-assisted coiled tubing approach, the tubing runs in the conventional manner all the way from the surface, where the tubing is telescoped through a seal adapter. The fluid displaced by the telescoping coiled tubing goes either into the external annulus or into the formation. A clear advantage of this approach is that logging tool cable can also be run.

Offsetting the consequences of the relative frailty of coiled tubing is the fact that a coiled tubing unit is often less expensive to operate than a conventional drilling rig, for a number of reasons. A coiled tubing unit is quicker to rig up on-site. "Run in" and "pull out" rates can exceed 170 feet per minute, so when numerous "trips" (removals and reinsertions of the drill string from the hole) are required to replace downhole motors or tools, or to retrieve cut core, use of a coiled tubing unit significantly reduces total on-site time and, therefore, cost. Another favorable factor is that fluid circulation can be maintained at all times since there is no need to break apart joints of pipe when "tripping." A bonus, from both cost and environmental viewpoints, is that a coiled tubing unit typically has a reduced "footprint" (disturbed drill site area) and is less noisy relative to a conventional drilling rig. Finally, operations performed by the use of coiled tubing technology are often less damaging to the potential producing formation than if performed using conventional drilling and completion methods.⁵⁹

Application of coiled tubing technology in the drilling, completion, and servicing of horizontal wells has been growing both absolutely and with respect to the range of jobs performed. The lower costs and reduced environmental impacts of coiled tubing technology have contributed to this growth. Directional drilling of wells with HD's of over 1,500 feet has been accomplished using coiled tubing. Drill-out of blockages in existing wells using positive displacement mud motors mounted to coiled tubing have also worked, with the advantage that horizontal wells can be entered via coiled tubing without the prior removal of production tubing or liners.⁶⁰ Coiled tubing is also used in horizontal wells to insert and manipulate flow control equipment that regulates reservoir drainage, as well as in the traditional well workover application, the precision placement downhole of various fluid treatments such as cement slurries and acid gels. The success of coiled tubing in this use is based on its ability to be pushed into a horizontal well bore (as compared to a conventional wireline) to a precise position, its ability to work in flowing wells, and its ability to operate hydraulically actuated tools.⁶¹

Over time, it is to be expected that lighter but nevertheless robust tools will be developed, extending the capabilities of the technology. In both horizontal and conventional applications, particularly the former, its use is expected to continue to grow rapidly.

⁵⁸Roger J. Tailby, "Pumpdown assistance extends coiled tubing reach," *World Oil*, (July 1992), pp. 55-61.

⁵⁹Vance Norton, Fred Edens, Glenn Coker, and George King, "Large diameter coiled tubing completions decrease risk of formation damage," *Oil & Gas Journal*, (July 20, 1992), pp. 111-113.

⁶⁰M. Wasson, F. Pittard, and L. Robb, "Horizontal Workover With Coiled Tubing and Motors," *Petroleum Engineer International* (June 1991), pp. 40, 42.

⁶¹Cameron White and Mark Hopman, "Controlling flow in horizontal wells," *World Oil*, (November 1991), pp. 73-80.

Slim Hole Horizontal Drilling

A recent trend that undoubtedly will be adapted to both deviated and horizontal applications over the next few years is increased use of what is called "slim hole" drilling. Most conventional oil and gas wells have been, and continue to be, drilled at a successively smaller series of diameters as depth increases, such that the bottom hole segment is on the order of 6 inches or larger, and the higher segments telescope upward in diameter between the bottom hole and final surface diameters. The surface casing segment may be as much as 24 inches in diameter. Slim hole drilling, long practiced in the mining industry to do exploration work and obtain rock samples, simply reduces the diameter of each segment substantially.

The use of slim hole drilling in the oil and gas industry has been made possible by the development of materials and technologies that allow drilling, completion, and production operations within the bounds of the smaller involved diameters. As more instruments and tools are designed and built to accommodate the smaller diameters of slim holes, there will occur a perfectly natural extension of slim hole drilling to deviated and horizontal drilling operations, due to its principal advantage: reduced cost.

For example, steel is priced by the ton and 1,000 feet of casing for 12¼ inch hole weighs 59 tons while the equivalent length of 8½ inch hole casing weighs only 29 tons.⁶² Lower costs similarly result for many other items such as drill pipe, drill bits, fuel costs, mud chemicals, cement, and cuttings cleaning and disposal. Beyond that, the overall size of the necessary drilling rig, its hook (lifting) capacity, and its footprint can all be lowered by scaling down the hole diameter, although typically there is a loss of torque transmission capability as diameter is reduced, requiring compensatory use of higher rotation rates than are commonly used in conventional drilling. Finally, time to TD is usually reduced, as a smaller diameter hole is usually much quicker to drill, all other factors being the same.

The Drilling of Multiple Laterals

Yet another trend is increased frequency of the drilling of multiple laterals from the initial vertical section of a hole. There are many instances in which two horizontal laterals have been successfully drilled and completed, running in opposite directions from the kickoff point. There are also instances (one was cited earlier) in which several short, short-radius laterals have been drilled in fan or radial patterns from a single initial vertical hole section. It would appear that, particularly in inhomogeneous reservoir situations, expansion to the drilling of multiple laterals with longer lengths, larger radii, and larger diameters is not chronologically far off.

A "Fire and Forget" Drilling System

Several firms are now developing directional drilling control systems that are supervised by either surface-located or on-board computers.⁶³ The computer continuously monitors MWD sensors for downhole conditions, operating parameters, and hole azimuth and inclination. It then feeds back continuous steering adjustments to the downhole assembly. The results, in tests to date, have been smoothly transient holes

⁶²"Smaller Top Hole Equates to Lower Drilling Costs," *Petroleum Engineer International*, (September 1992), p. 17.

⁶³An example is the Automated Guidance System (AGS) under development by Cambridge Radiation Technology, Ltd. (United Kingdom). "Intelligent Tool Automates Directional Drilling," *Petroleum Engineer International*, (September 1992), p. 13.

conforming much more closely to original engineering plans than would have been achieved by the use of standard, human-applied incremental adjustment techniques.

Ultimately, full development of such systems may well result in the drilling of deviated and horizontal wells in a "fire and forget" mode, wherein the hole design is loaded into the computer, the drilling process is initiated, and human intervention (other than to perform "maintenance work" such as bit changes and the like) is thereafter unneeded until TD is reached at exactly the intended location. Such a system should provide several economic advantages such as less necessity for tripping, higher penetration rates, and lower personnel costs.

Gas Research Wells

As noted early on, most domestic horizontal wells have thus far been drilled in search of, or to produce, crude oil. There is no physical reason why they should not also be targeted for natural gas. To promote their wider use in this application, two horizontal wells, partially funded by the Department of Energy through its Morgantown Energy Technology Center (METC), have been drilled for research and demonstration purposes in West Virginia and Colorado, as part of a program to develop methods to increase production from impermeable (tight) formations. The West Virginia well, the Recovery Efficiency Test well, was completed for Devonian shale gas in December 1986. It was the first horizontal well that used air as the bit cooling and chip removal medium. The pay zone of this well was the Upper Devonian Huron Shale; productive thickness of the lowest section of the Huron in this area is 40 to 60 feet.⁶⁴ The well was drilled in a direction orthogonal to the primary natural fracture orientation to improve the efficiency of natural gas extraction from the shale.⁶⁵

⁶⁴J.R. Duda, S.P. Salamy, Khashayar Aminian, and Samuel Ameri, "Pressure Analysis of an Unstimulated Horizontal Well With Type Curves," *Journal of Petroleum Technology*, (August 1991), p. 988.

⁶⁵J.R. Duda, S.P. Salamy, Khashayar Aminian, and Samuel Ameri, " Pressure Analysis of an Unstimulated Horizontal Well With Type Curves," *Journal of Petroleum Technology*, (August 1991), p. 988.

4. Summary

The technology of horizontal drilling has solidly moved into the arsenal of the oil industry over the past 10 to 12 years. A particular synergism of developments among equipment, techniques, and economically-driven efficiency requirements has caused widespread consideration and testing of this technology. In many basins and reservoirs, properly applied horizontal drilling technology has demonstrated an incremental advantage over vertical wells.