Drilling Smarter:

Using Directional Drilling to Reduce Oil and Gas Impacts in the Intermountain West

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FOREWORD

This study was compiled by researching technical and trade publications produced by the oil and gas industry. Conclusions and recommendations of this report rely heavily on the findings and conclusions of the industry experts who authored these studies. We recognize that success stories are more likely to be published than failures, and as a result great pains have been taken to present both the positive aspects and drawbacks of directional drilling, and to present data that reflects industry-wide averages (incorporating both successful and failed projects) wherever these data were available. As a result, a higher proportion of studies outlining the negative aspects of directional drilling are presented here than are found in the petroleum engineering literature, which almost universally provides glowing endorsements of the technical capabilities and economic feasibility of directional drilling. We chose this conservative approach in order to avoid overstating the capabilities of these technologies.

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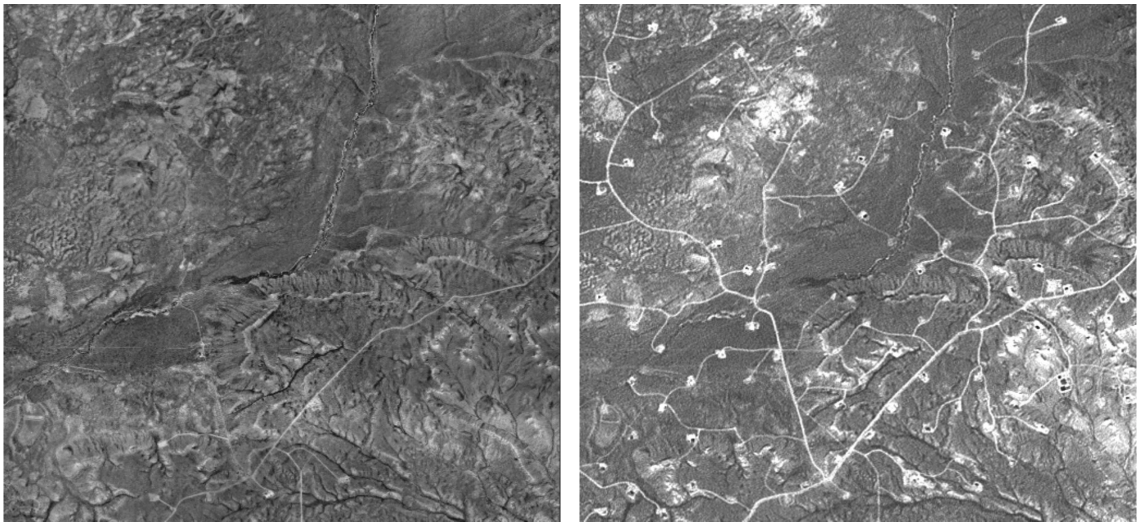
EXECUTIVE SUMMARY

Current practices in oil and gas exploration and development have produced massive environmental impacts across broad stretches of the Intermountain West. However, over the past several decades, the oil and gas industry has developed innovative technologies that can extract energy resources from the ground while reducing the impacts of that drilling on the natural environment. In particular, directional drilling technology has the potential to offer a less damaging alternative to conventional drilling methods in the Rocky Mountain West. Using directional drilling, energy firms can tap deposits of oil and gas at almost any depth from drilling sites up to 6½ miles away from the deposit.

Directional drilling has proven technically and economically feasible in a broad range of geologic settings, including tight gas, heavy oil, and coalbed methane. This method is proven to substantially increase producible reserves of oil and gas. Because the increased productivity of directional drilling compensates for additional costs, directional drilling is often more profitable than vertical drilling.

The Bush Administration's National Energy Policy calls for the use of directional drilling technology to reduce the environmental impacts of oil and gas exploration and development. However, federal agencies rarely even consider directional drilling as an alternative for oil and gas projects involving federal lands and minerals in the Intermountain West, and the oil and gas industry frequently balks when asked to use these technologies. On lands where oil and gas development is deemed appropriate and compatible with other uses in the Rocky Mountain West, federal agencies should consider whether they can reduce the damages from drilling activities through the implementation of directional drilling technologies, and if so, require their use.

Directional drilling does not prevent all environmental impacts of oil and gas exploration and development, and clustering operations lead to an intensification of impacts in the drilling area even while reducing the overall surface area across which those impacts occur. In addition, use of directional drilling technology does not address the numerous other impacts associated with oil and gas development and production, such as chemical spills and air pollution. As a result, some lands — including national wildlife refuges, parks, wilderness areas and monuments; roadless and wilderness-quality lands; and other sensitive lands — contain resources incompatible with oil and gas development and should remain withdrawn from all types of drilling. And appropriate buffers must be established to protect these lands from impacts in adjacent areas. Additionally, other lands such as important wildlife habitat, scenic landscapes, wetlands and other sensitive lands must be protected from the surface impacts of energy development.



Images provided by SkyTruth and the Upper Green River Valley Coalition

Recent full-field development in western Wyoming's Jonah Field as shown by aerial images. The photograph at left shows the landscape in 1994, before full-field development. By 1999 (at right), the landscape had become fragmented by roads and well pads.

AN ENVIRONMENTAL IMPERATIVE

A century of oil and gas development has left a heavy mark on many of our nation's public and private lands, particularly in the West. Oil and gas fields have become a vast spiderweb of pipelines and access roads, pockmarked with well pads, which fragment the landscape. Compressors, trucks, and pumpjacks generate noise, pollutants, and dust. Water and mud "produced" during the course of oil and gas development threatens local surface- and ground-water supplies used for residential and agricultural needs. Indeed, full-field development for oil and gas has often converted pristine wildlands and pastoral rural areas into industrial landscapes. In its conventional form, oil and gas production destroys the wild character of primitive areas, severely diminishes the recreational value of the landscape, creates long-term scarring across scenic viewsheds, and degrades or destroys habitat for native wildlife and fishes. As such, conventional oil and gas development is fundamentally incompatible with most other land uses, both public and private, particularly where dense well spacing is allowed.

The drilling activities associated with oil and gas production are just some of the sources of environmental damage associated with the production of oil and gas. While all of the potential impacts from oil and gas exploration, development and transportation must be considered before this activity is approved on federal lands, it is particularly important to consider alternatives to traditional drilling. The following sections describe a few examples of the impacts of drilling.

Oil and Gas Development Fragments Habitat

The sprawl of oil and gas fields can cause severe habitat fragmentation through the proliferation of roads, pipelines, and well pads across the landscape. The effects of forest fragmentation on bird densities are well-documented (e.g., Hansen and Rotella 2000). But fragmentation also impacts sagebrush bird species (Knick and Rotenberry 1995). In sagebrush habitats, major songbird declines have been found in areas with heavy oil and gas development (Inglefinger 2001). Lyon (2000) found that the construction of roads and wells within 2 miles of sage grouse strutting grounds had negative impacts on nesting. On a population scale, drilling has severe short-term impacts on sage grouse, while associated roads, pumping stations, and associated facilities have permanent negative impacts (Braun 1998, Braun et al. in press). Thus, oil and gas drilling can have serious effects even on relatively small, mobile wildlife.

Wells and Roads Displace Wildlife

Oil and gas development can also have a major impact on big game animals. Powell and Lindsey (2001) found that elk avoid lands within 1.5 kilometers of oilfield roads and well sites in the sagebrush steppes of Wyoming. In mountainous habitats, the construction of a small number of oil or gas wells has caused elk to abandon substantial portions of their traditional winter range (Johnson and Wollrab 1987, Van Dyke and Klein 1996). Drilling in the mountains of western Wyoming displaced elk from their traditional calving range (Johnson and Lockman 1979, Johnson and Wollrab 1987). Migration corridors may in some cases be equally important to large mammals and are susceptible to impacts from oil and gas development (Sawyer et al., in press). A study by Nelleman and Cameron (1998) demonstrated that even where directional drilling is widespread, oil and gas development of the Kuparuk Field of Alaska's North Slope caused caribou of the Central Arctic Herd to abandon their traditional calving grounds and displaced concentrations of calving animals to areas with poorer habitat quality. Because winter ranges and calving areas are crucial to the survival of big game herds, these studies demonstrated the need to completely protect these sensitive habitats from surface development by the oil and gas industry.

A POLICY IMPERATIVE

President George W. Bush made the implementation of lower-impact directional drilling technologies the cornerstone of his energy policy. The President's National Energy Policy contains a section titled, "21st Century Technology: The Key to Environmental Protection and New Energy Production," which states:

> Producing oil and gas from geologically challenging areas while protecting the environment is important to Americans and to the future of our nation's energy security. New technology and management techniques will allow for sophisticated energy production as well as enhanced environmental protection... Smaller, lighter drilling rigs coupled with advances in directional and extended-reach drilling significantly increase protection of the environment...Modular drilling rigs, 'slimhole' drilling, directional drilling, and other advances enable: [...]
>
> - production of oil and gas with increased protection to wetlands and other sensitive environments;
>
> Other examples of advanced technology include: [...]
>
> - highly sophisticated directional drilling that enables wells to be drilled long horizontal distances from the drilling site[.]"

National Energy Policy, May 2001, "Reliable, Affordable, and Environmentally Sound Energy for America's Future: Report of the National Energy Policy Development Group," p. 5.5.

Likewise, the Secretary of the Interior, who is responsible for implementing much of the National Energy Policy, has emphasized the need to begin utilizing directional drilling technology:

> We must also harness 21st Century technology to help our environment. Where we once needed scores of wells to tap underground reserves, today in some areas we can use one hole on the surface to drill for oil in a circle extending seven miles. We can use the resources below ground while we preserve the landscape and habitat above.

Presentation of Gale Norton, Secretary of Interior, to the National Newspaper Association (Washington, DC, March 23, 2001). These policy statements represent an unequivocal commitment on the part of the administration to implement less environmentally damaging directional drilling technologies.

A POLICY FAILURE BY THE BUSH ADMINISTRATION

But despite these commitments, the Bush Administration has failed to live up to its promises to implement technologies to reduce the impacts of oil and gas exploration and drilling on the environment. In fact, rather than pushing for more directional drilling, under the Bush Administration, the Interior Department's Bureau of Land Management (BLM) has actively avoided any effort to consider directional drilling as an alternative when energy production is being considered on public lands in the Intermountain West (see Table 3).

For example, federal agencies under the Bush Administration failed to even consider directional drilling as an alternative for at least six western projects where the public specifically demanded the use of these techniques. The environmental consequences from ignoring the opportunity to reduce damages to these surface lands from drilling are staggering.

In western Wyoming's Vermillion Basin, the BLM refused to analyze a directional alternative to protect roadless lands even after a court order

Table 1. Approval documents for oil and gas developments that have been issued since George W. Bush became President in 2001.

Project	State	Document	Date(s)	Directional Requested?	Directional Analyzed?	Notes
Porcupine Tuit	WY	EA	8/02	Yes	No	Thunder Basin N.G. coalbed methane
Atlantic Rim (3 Pods)	WY	DRs	12/01-8/02	Yes	No	winter range, grouse leks coalbed methane
Hanna Draw	WY	DR	6/02	Yes	No	coalbed methane
Vermillion Basin	WY	DR	8/02	Yes	No[1]	in proposed wilderness
WY Powder River Basin	WY	EIS	1/02	Yes	No	coalbed methane 50,000 wells
Southern Ute	CO	EIS	8/02	Yes	No	700 coalbed methane wells
Raton Basin	CO/NM	EA	9/01	No	No	206 wells
Macum/Klabzuba	MT	EA	5/02	No	No	inside Missouri Breaks NM
Huber Six Well	CO	DR	4/02	No	No	6 wells
Pinon Mesa	NM	DR	4/02	No	No	high-profile recreation area
MT Powder River Basin	MT	EIS	2/02	Yes	Yes[2]	coalbed methane 30,000 wells
Otero Mesa	NM	EIS	10/00	Yes	Yes[3]	includes sensitive wildlife habitats
Farmington	NM	EIS	6/02	No	Yes[4]	10,000 wells

EA=Environmental Assessment (analyzing alternatives); EIS = Environmental Impact Statement (analyzing alternatives); DR = Decision Record (final decision).

1. Despite court ruling requiring the agency to take a harder look at directional drilling.
2. Not selected as the Proposed Action.
3. Proposed alternative under the Clinton administration, but withdrawn from proposed alternative status by the Bush administration.
4. Only 70 of 10,000 wells to be clustered on single well pads.

compelled them to undertake a detailed analysis of directional drilling. Big game habitat, declining sage grouse and prairie dog populations, and important recreational lands are all at risk.

In northern Wyoming's Powder River Basin, the Administration proposed to approve 50,000 new coalbed methane wells, without considering directional drilling as a means to reduce their massive impacts on ranchers and rural landowners who own property above the energy resource. This scale of development, without considering alternatives that could reduce the damage from drilling, could jeopardize the future of 16 species of plants and wildlife, according to the BLM’s own report (BLM 2002a).

On New Mexico’s Otero Mesa, directional drilling was the preferred method for producing energy after an analysis was completed under the Clinton Administration. However, the current the Bush Interior Department reversed course and changed the proposed action to conventional vertical drilling. A largely intact roadless area supporting a suite of rare wildlife and plant species is now at risk.

There is a stark contrast between what the Bush Administration has promised the public and the drilling policy it has been implementing throughout the Rocky Mountain West. If the Bush administration truly supports a responsible energy policy that reduces the environmental damage from oil and gas development, it will stop paying lip service to directional drilling while continuing to conduct business as usual.

WHAT IS DIRECTIONAL DRILLING?

Directional drilling is an advanced technology that allows oil and gas resources to be tapped a long horizontal distance away from the well site. For the purposes of this report, “directional drilling” will encompass all forms of drilling where the endpoint of the well is distant from the drill site, rather than directly beneath it. Under this definition, slant-hole wells, S-turn wells, and horizontal wells are all considered forms of directional drilling. The term “directional drilling” can also be used to describe drilling to lay subsurface pipelines beneath rivers and other sensitive areas; this application of

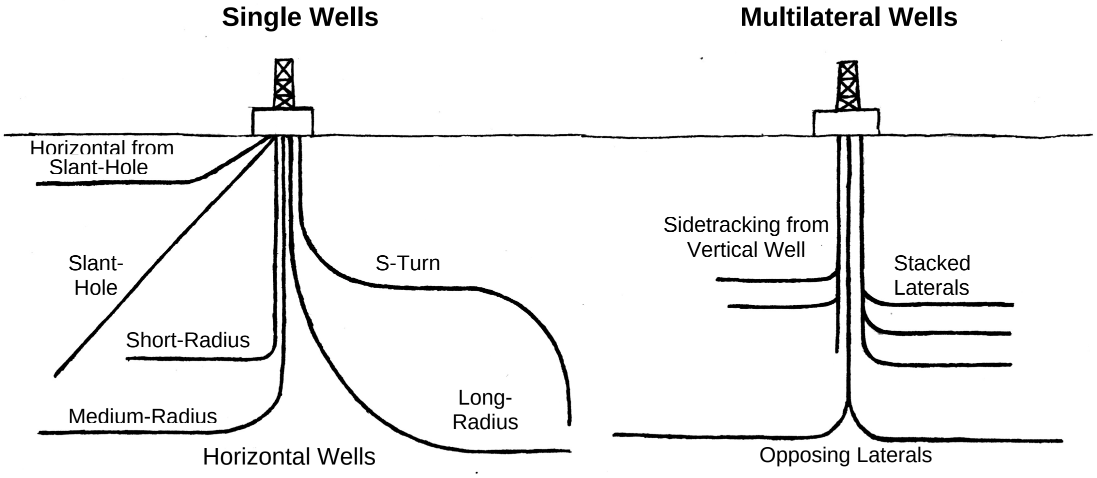


Figure 1. Different types of directional wells.

directional drilling is beyond the scope of this report. A brief synopsis of directional well types follows, and Figure 1 presents a schematic illustration of the various directional well types.

Slant-Hole Wells

Slant-hole wells are drilled at an angle from the vertical, using a tilting drilling rig. Slant-hole wells can be completed without making any bends at all, resulting in the equivalent of a conventional vertical well that is tilted on its axis. Alternately, slant-hole wells can be combined with a horizontal bend that is drilled in much the same way as traditional horizontal wells (see Figure 1), a configuration that is most commonly used for shallow target zones (Smith and Edwards 1992). Slant-holes can also be re-drilled at a later date to add a horizontal section (e.g., Myal and Frohne 1992).

S-Turn Wells

Sometimes known as "deviated wells," S-turn wells start out in a near-vertical orientation, have a long near-horizontal or diagonal section, and finish by approaching the vertical once again. This well type has been used in extended-reach applications. For example, the Sacate Sa-1, an offshore California well, achieved a horizontal distance of over 3½ miles from the well site using this drilling technique (Elks and Masonheimer 2002).

Horizontal Wells

Horizontal wells are defined as wells deviated more than 75 degrees from vertical (Lacy et al. 1992); they often depart from the horizontal in order to track the dip of the target formation. These wells have a characteristic "J" shape, with the horizontal section following the oil- or gas-bearing rock to maximize production.

Short-Radius

Short-radius wells feature a sharp, abrupt turn from the vertical to the horizontal plane. A comprehensive review of short-radius horizontal drilling found that "[r]eservoir management applications, water and gas coning, injection wells, irregular formations and coal degasification [coalbed methane production] are becoming more economically feasible" (Leazer and Marquez 1995). This study found that short radius horizontal wells make it easier to avoid problem formations above the pay zone. And with short-radius wells, submersible pumps can be placed deeper in the wellbore, improving pumping efficiency and extending pump life. The study concluded that "[s]hort radius technology has evolved to the point where it is a common occurrence to drill a 45-ft radius curve into a 10-ft target and achieve displacements in excess of 1,000 ft." These wells are not typically used to drill long horizontal distances from the well site.

Medium Radius

Medium-radius wells make their turn from the vertical to the horizontal at an intermediate rate, and the horizontal length is often longer. By the early 1990s in the United States, medium-radius wells were the most widely used and productive of horizontal wells (USDOE 1993). In 1990, the longest horizontal displacement for a medium-radius horizontal well reached 4,164 feet (Moritis 1990). This drilling style figures prominently in the horizontal successes of the Austin chalk (Sheikholeslami et al. 1991), and also has been used for very shallow applications in coalbed methane drilling (USDOE 1993).

Long Radius

In a long-radius well, the wellbore shifts from the vertical to the horizontal very gradually, with only slight changes in the degree of slope over the course of the bend. Extended-reach, long-radius horizontal wells were being successfully drilled from platforms off the coast of California as early as 1989 (Moritis 1990). Because this type of drilling requires a long transition between vertical and horizontal, it is best suited to deep wells and/or extended-reach drilling that accesses reservoirs far away from the drill site.

Multilateral

Multilateral wells entail drilling two or more horizontal legs from a single vertical well in order to maximize exposure to the oil- or gas-bearing strata. Opposing laterals are most advantageous for deep wells or cases where drilling costs are high, because information gained in drilling the first lateral can be incorporated into the drilling of the second (Meehan 1995). Stacked laterals have been used for steam injection wells in Canadian heavy oil reservoirs (Sarma and Ono 1995), and to access multiple pay zones (Rixse and Johnson 2002). More complex “fishbone” configurations have been drilled in Venezuela’s Orinoco Basin, in which even the laterals have laterals (Moritis 2000).

Chambers (2000) concluded that multilateral drilling was practical for all geologic situations: “There is no depth or specific reservoir type to which multi-lateral use is limited. Multi-laterals are being used for shallow reservoirs (800’ TVD [True Vertical Depth]) to deep (15,000’ TVD) formations, for completions in heavy oil, light oil, and gas.” Meehan (1995) reported that by 1995, multilateral drilling had become “routine” at Union Pacific Resources. Meehan (1995) stated, “State of the art drilling includes as many as four, 4,000+ ft horizontal laterals, horizontal wells at TVDs [True Vertical Depths] greater than 16,000 ft.”

Multilateral drilling has now become an established practice within the oil and gas industry. Chambers (1998) summarized this growing role: “The implementation of multiple lateral wellbores, or multiple horizontal wells exiting a single wellbore, has gained wider acceptance in the oil industry, particularly from a reservoir management point of view. The deeper the junction, the more attractive multilaterals become. The more wells drilled, the cheaper the technology, the more laterals drilled from a well, the less the incremental cost for additional laterals. Open hole branches are very easy to create and fast to implement.”

HISTORY OF DIRECTIONAL DRILLING

Directional drilling is not a new technology. In fact, all types of directional drilling have been around for years, but it is only in the last several decades that these techniques have gained broad acceptance and widespread application. The first horizontal well was drilled near Texon, Texas in 1929 (USDOE 1993). Chambers (1998) noted early horizontal activity dating from 1939. In the early 1940s, horizontal wells were drilled with horizontal distances of 100 to 500 feet (Anon. 1999). China attempted its first horizontal well in 1957 (USDOE 1993). The first coiled-tube and slimhole drilling was also done during this period (USDOE 1999a). The first multilateral well was drilled in the Soviet Union in 1953 (Chambers 1998), and between 1953 and 1980, the Soviet Union drilled 111 multi-branch horizontal wells including exploration wells, production wells, and injector wells (Maurer 1995). Nonetheless, during these early years, directional drilling was comparatively costly and failed to achieve broad acceptance within the industry.

Slant-hole drilling was the first directional technique to achieve widespread use. Between 1982 and 1992, over 1,000 slant or angle wells were drilled, primarily in Canada, Venezuela, and China (Smith and Edwards 1992).

But the big boom came with the widespread use of horizontal drilling. European offshore successes with directional drilling in the North Sea (e.g., Andersen et al. 1988, Jacobsen and Rushworth 1993) led to increasing application of directional technologies to land-based drilling. Horizontal drilling soon took off in North Dakota’s Williston Basin, and as of 1990, some 70 horizontal wells were producing about 7% of North Dakota’s oil from the Bakken Shale formation (Petzet 1990). For northern Alaska’s Prudhoe Bay field, Standing (2000) noted, “Horizontal drilling started experimentally in 1986, and in the 1990s became routine for lengthening wellbores and avoiding gas-oil or water-oil contacts.” Perhaps the largest application of horizontal drilling came in the Austin Chalk deposits in Texas, a formation where production from vertical drilling had been declining. Union Pacific Resources drilled more than 1,100 new horizontal wells and 1,250 horizontal laterals from existing wells in the Austin Chalk between 1987 and 1995 (Meehan 1995). With success in the Texas Austin Chalk, 134 horizontal wells were soon drilled or permitted in the same formation in Louisiana (Maloy 1997). The first directional well in Wyoming was completed in 1987, and as of 1994, 80 producing wells were completed out of 117 attempts (Stewart 1995).

Directional drilling has caught on not only in North America but all around the world. Between 1990 and 1998, Petroleum Development Oman drilled 350 horizontal wells in 33 different Middle Eastern oil and gas fields (Ishak et al 1998). Horizontal wells have been drilled on every continent except Antarctica. Today, horizontal drilling technology is so efficient at extracting oil and gas that it has become the benchmark for the industry: Miller and Steiger (1999) boasted that their array of vertical and directional wells had production that equaled high benchmark projections from horizontal drilling. In the words of Pinney and Rodrigues (1999), “Over the past 20 years, horizontal drilling has progressed from an exotic technology to a standard industry tool.”

DIRECTIONAL CAPABILITIES

Directional drilling in general, and horizontal drilling in particular, are extremely versatile and offer capabilities that make these technologies superior to vertical drilling for the recovery of oil and gas. Deskins et al. (1995) stated that horizontal wells can improve production and increase reserves through (1) intersecting natural fractures that can’t be accessed with vertical wells; (2) delaying the onset of water or gas coning so that more oil is produced; (3) improving production from thin or tight reservoirs; and (4) improving waterflood sweep efficiency (for reservoirs injected with fluids to increase oil or gas production). Zammerilli (1989) compared the effectiveness of three drilling methods for the Devonian Shale of West Virginia and found that “new-lease horizontal drilling is the optimal method [for maximizing production] in West Virginia, and high-angle drilling results in a slight improvement over vertical drilling.” An article in *Journal of Petroleum Technology* summarized the current role of horizontal drilling: “Most experts agree that horizontal wells have become a preferred method of recovering oil and gas from reservoirs in which these fluids occupy strata that are horizontal, or nearly so, because they offer greater contact area with the productive layer than vertical wells. While the cost factor may be as much as two or three times that of a vertical well, the production factor can be enhanced as much as 15 or 20 times, making it very attractive to producers” (Anon. 1999).

Each of the qualities of directional drilling that make it a viable alternative to vertical drilling in the Intermountain West have been thoroughly documented in the published literature, and are discussed in more detail below.

Directional Drilling Increases Production

Directional wells, and horizontal wells in particular, offer substantial increases in production over vertical wells, chiefly because in the words of Hall (1998), “[h]orizontal drilling exposes magnitudes more of the pay zone to the wellbore. Hutzler (2000) summarized the basis for this phenomenon as follows: “Drilling a horizontal, as opposed to a conventional vertical well, enables more of the reservoir to be exposed to the wellbore since most reservoirs are wider than they are deep.” Table 2 displays the results of a number of studies worldwide that directly compared the productivity of horizontal wells with their vertical counterparts.

In one Utah project, for example, 143 laterals were drilled and completed as re-entries from 43 vertical wells. For those 43 wells, 180,000 feet of wellbore penetrated the pay zone, compared with only 26,000 feet for all 379 of the previous vertical wells in the field (Hall 1998). Iverson et al. (1995) found that even without hydraulic fracturing, a horizontal well in Wyoming produced as much gas as a comparable conventional well that used hydraulic fracturing (see Appendix for an explanation of hydraulic fracturing). In Texas, Sheikholeslami et al. (1991) found a linear increase in production with longer horizontal sections: “This relationship and the low cost of drilling incremental medium-radius horizontal lengths show the economic benefit of drilling the longest possible horizontal length.”

But there are limits to the increases that horizontal wells can achieve over conventional vertical wells. Cho and Shah (2002) found that beyond 3,000 feet horizontal distance, wellbore friction and turbulence may reduce gains achieved through a longer exposure to the pay zone, to the point that a maximum output is achieved. These researchers pointed out that

Table 2. Horizontal/directional well production expressed as a percentage of vertical wells from the same field.

Location	Production Increase	Notes	Source
Alaska	200-300%	Prudhoe Bay	Broman and Schmor 1992
California	300%	Elk Hills	Gangle et al. 1991
California	700%	Elk Hills	Gangle and Ezekwe 1995
California	350-900%	Elk Hills	Anon. 1996
Colorado	500-1000%	Piceance Basin	Myal and Frohne 1992
Canada	250-800%	underbalanced, heavy oil	Teichrob 1994
Colombia	400-600%	offshore	Huang et al. 1996
Germany	200-300%	deep gas	Graute et al. 1994
Germany	500%	deep, sour gas	Schuler 1992
North Dakota	200-500%	Bakken shale	Lacy et al. 1992
North Sea	600%	offshore	Reynolds and Seymour 1991
Texas	250-700%	Austin chalk	Sheikholeslami et al. 1991, Lacy 1992
Venezuela	1300%	Orinoco heavy oil	Lacy 1992
West Virginia	700%	hydraulic fractured	Yost and Overbey 1989
West Virginia	400-2500%	Devonian shale	Lacy 1992

friction may be less important if the wellbore is subjected to low pressures. Thus, there may be an upper limit to production increases over vertical wells that can be realized by drilling with horizontal technologies. But in no case does wellbore friction reduce productivity of a horizontal well below that of a vertical well.

Because one might expect directional drilling attempts that produce successfully to be publicized more often than failures, it is useful to examine the overall technical success rate of horizontal wells over a broad area. Deskins et al. (1995) took a comprehensive survey of horizontal wells in North America, and found that horizontal wells enjoyed technical success in 95% of U.S. reservoirs where they were employed, compared to a success rate over 90% for Canadian horizontal wells. These figures were calculated by reservoir rather than by individual well, and the technical success figures are likely to underestimate the true success rate because reservoirs with a handful of failures were given the same weight as reservoirs with thousands of successful wells (Deskins, pers. comm.). Unfortunately, technical success rates for vertical wells were not presented for the sake of comparison.

Directional drilling has been shown to maximize oil and gas production in virtually any oil and gas recovery situation. As early as 1990, Stagg and Reilly proclaimed that “Industry is no longer constrained by the mechanical aspects of horizontal well completions. Equipment and techniques are available, or soon will be available, to meet all completion needs.” These methods are feasible for both exploration and full-field development (French Oil and Gas Industry Association 1990). The effectiveness of horizontal drilling as an exploration tool was noted by Hawkings et al. (1990), who reported that a horizontal well was able to locate high permeability sands where conventional wells had failed. Aguilera et al. (1991) lauded the potential of horizontal drilling in infill situations. According to Thakur (1999), “As a general rule, readers are encouraged to consider horizontal wells as the primary option for a field.” These studies and technical reports by the oil and gas industry illustrate that directional drilling is a versatile and viable alternative and should be considered where oil and gas is proposed for development because of its ability to meet or exceed the production ability of vertical wells.

Directional Drilling Can Tap Distant Resources

Directional drilling can now tap pockets of oil and gas that are miles away from the drilling site. Horizontal drilling can reach subsurface reservoirs up to 29,000 feet away from the drilling site in horizontal distance (Al-Blehed et al. 2000) and, in some cases, even farther. The Exxon-Mobil Sacate Sa-2 well is believed to hold the current North American record for horizontal displacement, reaching a final distance of 21,277 feet (just over 4 miles) from the drilling site; this feat was achieved offshore in over 650 feet of water (Elks and Masonheimer 2002). Elks and Masonheimer went on to state, "Horizontal deviations [for wells in this project] could ultimately exceed 35,000 feet," a distance of over 6½ miles.

In 1997, China's Xijiang 24-3-A14 well achieved a horizontal displacement of 26,452 feet, or over 5 miles (Jiang and Nian 1998). Vighetto et al. (1999) reported on the successful drilling of extended-reach horizontal wells with horizontal displacements of up to 34,728 feet. This example shows the oil and gas industry's current ability to use horizontal drilling to produce from reservoirs more than 6½ miles away from the drilling rig. And according to industry, even greater gains in distance capabilities are likely in the offing. Ron Auflick of K and M Technologies even goes so far as to claim in the press that extended reach drilling rigs will be able to drill nearly 20 miles from the drilling site within the next 10 years (in Schneider 2001).

These industry reports demonstrate the viability of extended-reach drilling technologies to tap oil and gas reserves across great distances. Such long-reach technologies provide the technical capability to extract oil and gas from lands where surface damage from conventional drilling is barred in order to protect the important surface values of sensitive landscapes.

New Steering Technologies Allow for Greater Drilling Accuracy

Advances in modern technology now allow operators to steer the drill bit through the Earth with pinpoint accuracy, unlocking the resources from distant pools of oil and gas. This "geo-steering" is aided by three-dimensional computer programs that allow modeling and visualization of the drill path through the Earth, enabling the operator to guide the drill bit in real-time; this technology has been tested and proven accurate in the Gulf of Mexico, North Sea, and onshore Latin American locations (Sanstrom and Longorio 2002).

The technology that allows this real-time steering of the drill bit is alternately known as "Measurement While Drilling" (MWD) or "Logging While Drilling" (LWD). These technologies gather information at the well bit and instantaneously send it back to the drill engineer, who controls the bit. Corrections can be made immediately if the drill bit strays from the target zone, or to avoid obstacles (Maurer 1995). Barry et al. (1998) reported a case history where Logging-While-Drilling techniques were used to geosteer horizontal wells in real-time along a 40-foot column of oil trapped between an aquifer and a gas cap. The authors of this study noted, "Excellent well performance supports the general validity of the geosteering approach and a static pressure survey in one of the wells verifies the steering accuracy." Geosteering has become so precise that a multilateral well off the coast of Nigeria was successfully completed within a target window of only +/– 2 feet (Aloko et al. 1998).

DIRECTIONAL DRILLING IS EFFECTIVE IN MANY GEOLOGIC SETTINGS

Directional drilling, in its several forms, has proven to be remarkably versatile as an alternative to conventional vertical drilling in recovery of all types of petroleum resources. In the United States, directional drilling has met with economic success in most of the major oil- and gas-bearing rock formations (see Table 3, following page). Aguilera et al. (1991) stated, "Theoretically, all reservoirs can benefit from horizontal wells." Al-Blehed et al. (2000) asserted that horizontal drilling is superior to vertical drilling for a variety of conditions including naturally frac-tured reservoirs, thin reservoirs, heterogeneous reservoirs, vertical permeability homogeneous reservoirs, reefs or isolated sand bodies, and faulted reservoirs. Joshi (1991) asserted that for natural gas production, horizontal wells improve drainage area per well for low-permeability geologic formations and reduced near-wellbore turbulence and increase delivery efficiency for high-permeability formations. Robertson et al. (1992) concluded, "Horizontal wells appear to improve the chances of attaining commercial gas production rates from heterogeneous formations."

Directional drilling offers superior production even when applied to most geologically difficult circumstances. In Germany, an 11,200-foot-deep sour gas well achieved a fivefold production increase over nearby vertical wells. Of this well, Schuler (1992) noted, "The drilling was in a geologically difficult environment with tight target tolerances." In Argentina, horizontal drilling was used to successfully explore a deep, fractured gas reservoir involving hanging wall anticline traps (Blangy 2002). In China's Shixi Field, 5 horizontal wells were drilled into deep volcanic formations with multiple fracture systems and high pore pressure. Of these wells, Xinzhong et al. (1998) observed, "It is very difficult to drill the horizontal well due to the specialty and complexity of its geological configuration, hole construction, and operational requirement. Now 5 horizontal wells with 5000m

MD [Measured Depth, the overall length of the wellbore] have been drilled successfully." On Alaska's North Slope, the Schrader Bluff Pilot Project involved two stacked horizontal wells drilled into heavily faulted sandstone formations with target zones only 25 feet and 28 feet thick, respectively. Using geosteering technology, the paired wells successfully followed the narrow pay formation as it rose and dipped across numerous faults; both wells achieved economic success (Rixse and Johnson 2002).

Horizontal drilling has proven successful in a variety of geological settings, as discussed in numerous industry and government reports summarized on Table 3.

Table 3. U. S. geologic formations where directional projects have successfully produced oil and gas.

Location	Formation	Source
Alabama	Pottsville coal	Swindell 1996
Alaska	Tarn formation	Phillips Petroleum 2002
	West Sak formation	Phillips Petroleum 2002
	Alpine formation	Phillips Petroleum 2002
California	Stevens sand	Gangle and Ezekwe 1995, Anon. 1996
	Veder sand	Chenot et al. 2002
	Monterey chert	Elks and Masonheimer 2002
Colorado	Niobrara sandstone	Petzet 1990, Stright and Robertson 1993
	Codell formation	Swindell 1996
	Mesa Verde sandstone	Myal and Frohne 1992
	Cameo coals	USDOE 1993
Kentucky	Devonian Shale	Bellinger 1991
Louisiana	Austin Chalk	Swindell 1996, Maloy 1997
	Miocene	Swindell 1996
	Cotton Valley	Swindell 1996
	Wilcox sandstone	Lacy et al. 1992
Michigan	Antrim	Swindell 1996
	Dundee limestone	Wood 1997
Montana	Red River	Swindell 1996
	Mission Canyon	Swindell 1996
New Mexico	Fruitland coal	USDOE 1993, Swindell 1996
	Mancos shale	Swindell 1996
North Dakota	Bakken shale	Swindell 1996
	Madison limestone	Swindell 1996
Ohio	Clinton sandstone	McCormac 1996
	Rose Run sandstone	McCormac 1996
Oklahoma	Bartlesville	Swindell 1996
	Mississippi	Swindell 1996
	Viola	Swindell 1996
	Hunton	Swindell 1996
South Dakota	Red River	Swindell 1996
Texas	San Andres dolomite	Leazer and Marquez 1995
	Montoya limestone	Fletcher 2002
	Devonian fm.	Fletcher 2002
	Austin Chalk	Swindell 1996
	Buda	Swindell 1996
	Georgetown	Swindell 1996
	Ellenburger	Swindell 1996
	Wilcox fm.	Doughtie 1994
Utah	Desert Creek dolomite	Leazer and Marquez 1995, Swindell 1996, Chidsey et al. 2002
	Twin Creek	Swindell 1996
	Paradox shale	Morgan 1996
	Ismay limestone	Chidsey et al. 2002
West Virginia	Devonian Shale	Zammerilli 1989, Salamy et al. 1991
Wyoming	Nugget sandstone	Weatherl 1998
	Almond formation	Iverson et al. 1995
	Niobrara sandstone	Swindell 1996
	Minnelusa	Swindell 1996
	Frontier sandstone	Swindell 1996
	Hanna coals	Logan 1988

Shallow Reservoirs

Directional drilling has been employed to successfully access shallow reservoirs in a number of cases. Slant-hole drilling can be paired with horizontal techniques for shallow reservoirs; a well was drilled using this technique near the town of Brooks in southern Alberta, reaching a depth of 1,886 feet and a horizontal displacement of 4,200 feet (Smith and Edwards 1992). In the Black Warrior Basin, Mississippi Valley Gas Company successfully drilled a well 1,805 feet in depth with a horizontal leg of 1,650 feet. The well produced gas from a storage field at 6 times the rate of neighboring vertical wells (Butler and Skeen 1996). Multiple horizontal laterals have been drilled for formations as shallow as 800 feet (Chambers 2000). In Wyoming's Hanna Basin, three medium-radius horizontal wells successfully accessed coalbed methane at a depth of only 363 feet (Logan 1988). Thus, there appears to be no reservoir too shallow for horizontal drilling.

Deep Reservoirs

Directionally drilling has accessed some of the world's deepest oil and gas deposits. As of 1995, the Navasota #1 well was the deepest horizontal well in the Austin Chalk, at 14,172 feet (Pearce et al. 1995). In the Goodwyn gas/conglomerate field in Australia, the GWA-13 well was drilled to 24,620 feet total depth with a horizontal displacement of 9,400 feet (Dolan et al. 1998). Horizontal wells in the Permian Basin of west Texas now exceed depths of 14,000 feet (Fletcher 2002). Schuler and Santos (1996) reported success with hydraulic fracturing on what was then the world's deepest horizontal well (15,687 feet deep). In Alaska's Cook Inlet, the Forest Oil Redoubt #4 well was drilled deeper than 18,872 feet from an offshore rig (Anon. 2002b).

Horizontal and directional technology has proven itself in ultra-deep settings where temperatures and pressures can be intense. In the Middle East, a short-radius sour gas well was successfully drilled to a depth of 14,115 feet in the deep, hot Thamama limestone from an offshore drilling rig (Simpson et al. 1993). Based on drilling deep horizontal wells in Germany, Graute et al. (1994) concluded, "Results of both wells proved that horizontal drilling into these deep reservoirs is technically feasible and economically attractive."

Deep horizontal wells have achieved substantial production successes. A well drilled into the ultra-tight, high pressure, high temperature Roetliegendes sandstone in Germany produced at a rate 3.5-9 times greater than hydraulically fractured vertical wells (Schuler and Santos 1996). According to Krystinik (2001), a horizontal well drilled in Wyoming's Green River Basin reached a depth greater than 15,000 feet in tight-gas sandstone, was drilled at a cost that was reduced to 50% of the industry average, and achieved economic production of greater than 14 million cubic feet of gas per day.

These reports illustrate that use of directional drilling in deep reservoirs is effective and productive. Reaching depths of over 15,000 feet in Wyoming and elsewhere in the world, this technology clearly is versatile enough to be considered in all reservoirs.

Tight Reservoirs

Tight reservoirs are formations of very low permeability, which impedes the flow of oil and gas to the well. Nonetheless, directional wells have proven both feasible and profitable in these geologically challenging settings. Mostafa (1993) reported that horizontal drilling in tight carbonate reservoirs improved production and reduced oil and water coning. Horizontal drilling has proven profitable in the tight chalk reservoirs of the Danish North Sea (Andersen et al. 1988). In the Permian Basin of west Texas, EOG Resources reported successful completions in 14 of 15 horizontal wells of the tight Devonian formation (Fletcher 2002). Directional drilling has been shown to increase rate of gas production and overall recoverable quantity for tight gas sands (e.g., Cassetta 1998).

Kabir et al. (1997) linked horizontal drilling effectiveness in tight carbonate reservoirs with ability to intercept fractures. Because fractures tend to be oriented vertically, wellbores traveling horizontally through a formation have a far greater capability to successfully intercept fractures than vertical wells, which have a rather short passage through the target formation. For tight gas reservoirs that are naturally fractured, horizontal drilling compares favorably with massive hydraulic fracturing and is a sound alternative (van Kruysdijk and Niko 1988). For northwestern Colorado fractured sandstones, Stright and Robertson (1993) stated, "The advantage of a horizontal well over a vertical Niobrara well is higher probability of encountering well-developed fractures, a common problem with vertical Niobrara wells." Hydraulic fracturing can be used in conjunction with horizontal drilling to enhance the productivity of tight reservoirs lacking in natural fractures (Soliman et al. 1996).

Based on these studies, it appears that directional drilling may have a distinct advantage over conventional vertical drilling in tight formations, particularly where fractures are intercepted to release the gas resource.

Heavy Oil

Directional drilling has proven effective in tapping heavy oil deposits in tar sands. Luhowy (1993) reported that "Horizontal wells proved economical for developing, under primary recovery, viscous heavy oil from the unconsolidated McLaren sand channels in Saskatchewan." On Alaska's North Slope, the West Sak heavy oil reservoir is being developed using multilateral horizontal technology (Phillips Petroleum 2002). For heavy oil recovery, Shirif (2000) noted that, "For a given pattern, there is a horizontal well configuration that maximizes the total production rate."

Coalbed Methane

Although vertical drilling currently dominates coalbed methane fields, directional drilling is increasingly being applied to the production of this unconventional resource. According to Moore and Moore (1999), directional drilling is applicable to coalbed methane production, but drilling rig placement may be constrained by rock jointing and fracture patterns. Horizontal wells have been drilled for coalbed methane in Colorado's Piceance Basin using short radius technique, and in Wyoming's Hanna Basin using medium-radius technique (Logan 1988). According to the West Virginia Geological and Economic Survey's coalbed methane database, CDX Gas drilled 13 horizontal wells in West Virginia's Welch Field, which produced 1.5

trillion cubic feet of coalbed methane between 1999 and 2000.

Furthermore, horizontal drilling for coalbed methane appears to be an effective method to increase production. In discussing Penn Virginia Corporation's coalbed methane program, company president A. James Dearlove has stated, "By using horizontal drilling on our coalbed methane and Devonian shale acreage, we expect to significantly accelerate gas production, which should increase the present value of our properties" (quoted in Anon. 2002a). One horizontal well drilled in New Mexico's San Juan Basin produced almost seven times the coalbed methane as the average vertical well in the area (USDOE 1993).

Horizontal methods can also yield substantial increases in coalbed methane producible reserves. In Colorado's San Juan Basin, multilateral drilling by CDX gas is expected to recover 50-75% of available coalbed methane reserves, compared to 10% for conventional methods (McWilliams 2002). According to Wayne Kelley, president of Texas-based Omega Oil Company, multilateral technology using coiled-tube drilling in coalbed methane fields "would replace 220 well pads on the surface with a single well pad" (as quoted in Bleizeffer 2002).

With the dramatic expansion of coalbed methane contemplated for the Intermountain West, directional drilling appears to be a viable alternative to the conventional wells that currently dominate the production of this resource. Conventional methods of coalbed methane production typically entail a high density of roads, well pads, pipelines and transmission lines that can be reduced to some extent by clustered directional drilling. But coalbed methane development also creates the additional problem of disposal of millions of gallons of wastewater, which must be removed from the coal seam before the gas can be extracted. This water is often highly saline or alkaline (e.g., Hulin 2001), and the dumping of such toxic wastewater into streams and groundwater can have disastrous ecological effects. Dumping coalbed methane wastewater onto the surface has unacceptable ecological, economic, and social impacts that are beyond the scope of this report but that should be addressed before this resource is developed.

Thin Reservoirs

Horizontal wells can travel along the pay zone of thin reservoirs for long distances, dramatically improving production over vertical wells that have only a short trip through the pay zone. In Trinidad's Immortelle Field, six "highly successful" horizontal wells were drilled to tap a 48-foot thick oil play (Thakur et al. 1996). In a remote area of Sumatra, a horizontal well was successfully drilled into a 33-foot-deep oil column (Curnutt et al. 1993). Horizontal drilling has been used to produce gas from a pay zone only 10 feet thick in Pleistocene sands in the Gulf of Mexico (Gidman et al. 1995). A dual-lateral horizontal well off the coast of Nigeria was successfully drilled along an 11-foot oil column trapped between a gas cap and an aquifer.

Horizontal drilling yields superior production for thin reservoirs. Production from horizontal drilling into a 130-foot thick oil rim off the coast of East Malaysia has yielded two to eight times the production of vertical wells in the area (van der Harst 1991). In its Pelican Lake project, CS Resources used horizontal wells to target pay zone that was a mere 13-20 feet thick. These horizontal wells achieved productivities that were five to thirty times greater than neighboring vertical wells, with longer horizontals yielding the higher productivities (Sarma and Ono 1995).

Depleted Reservoirs

Due to its higher efficiency in recovering oil and gas, horizontal drilling has proven to be an excellent method to revitalize depleted reservoirs. In Oklahoma's Caddo County, a well with a 4,000-foot horizontal displacement was drilled into a depleted sandstone reservoir, achieving a production of 1,800 barrels of oil per day with very little gas coning—the mixture of gas and oil that reduces production efficiency (Beardmore et al. 1994). In Michigan, horizontal laterals from old wellbores yielded more than a threefold increase in oil production over vertical wells, effectively revitalizing the depleted Niagaran fields (Lanier 1996). A more complete accounting of successes in depleted reservoirs is presented in the section of this report titled "Increasing Producible Reserves."

ECONOMIC ADVANTAGES OF DIRECTIONAL DRILLING

The oil and gas business has always been inherently risky, and profitability is based in large part on market prices of oil and gas products. No drilling method, whether vertical or directional, can insulate a drilling company from the possibility of individual economic failures. Nonetheless, the overwhelming majority of published studies on the subject demonstrate that directional drilling is not only economically feasible but is in fact substantially more profitable than conventional, vertical drilling due to its superior cost-benefit ratio, even though the costs to drill a directional well may be higher in some cases.

Costs of Individual Wells

In 1991, Fritz et al. noted, "If the cost of drilling a horizontal well was equal to that of drilling a vertical well, most reservoirs would be candidates for horizontal drilling." These costs are in fact equalizing. Aalund and Rappold (1993) found that the cost of drilling two horizontal wells in Egypt was 1.4 times the cost of drilling conventional wells, and made the following prediction: "As horizontal drilling becomes more common, the cost of horizontal wells will decrease to near that of vertical wells in the Middle East." Under Elf Aquitaine's drilling program, horizontal well costs averaged 1.5 times the cost of vertical wells (Thakur 1999). On the basis of cost per foot of drilled wellbore, directional drilling is only slightly more expensive than vertical drilling. According to Sarma and Ono (1995), "The 1993 Joint Association Survey of drilling costs on 845 horizontal wells indicated that at $80.76/ft, a horizontal well was only 8% more expensive to drill per foot than a vertical well." Hawkings et al. (1990) reported that a horizontal gas well in the Roetliegendes Field in Germany cost roughly the same to complete as a fracture-stimulated conventional well. Thus, compared to vertical wells, the costs for drilling a directional well can be higher than, or sometimes equal to, costs for drilling a vertical well. But horizontal wells often yield much higher oil and gas production than vertical well, offsetting cost increases (see following section).

For each new formation, there is a learning curve that progressively drives down the cost of horizontal drilling as more wells are completed. Lacy et al. (1992) summarized this effect as follows: "As drilling experience is gained in a certain area, horizontal well costs decrease. The first well usually costs two or three times more than a vertical well. The second well usually costs much less than the first one. After drilling a few wells, the horizontal/vertical well cost ratio is about 1.5. Therefore, a multi-horizontal well program has a better chance for economic success."

Technological advances are bringing down the cost of horizontal drilling. Slant-hole and coiled-tube drilling can be used to bring down the costs of horizontal drilling. According to Smith and Edwards (1992), "Slant hole drilling technology can result in considerable savings over conventionally drilled deviated holes because mud motors and deviation control with measurement while drilling tools are usually unnecessary." Slimhole and coiled-tube drilling offers further economic advantages in drilling horizontal laterals from existing boreholes. McCarty et al. (2002) reported that for 64 sidetracks drilled in 2002 on the North Slope with coiled-tube methods, costs averaged less than one-half that of conventional rotary sidetracks. This study concluded that "CTD [coiled-tube drilling] has matured into a highly efficient and economical means of sidetracking wells on the North Slope." According to the U.S. Department of Energy, "a typical 10,000-foot well drilled in southwest Wyoming costs about $700,000, but with coiled tubing and slimhole, the same well would cost $200,000 less" (USDOE 1999a).

Multilateral horizontal wells take the economic savings to an even higher level. According to Maurer (1995), "Multibranch horizontal wells can reduce horizontal drilling costs by 20 to 30% and the size and number of offshore platforms by 50%." In the same study, Maurer noted that "Unocal stated that its B-34 trilateral well [in the Dos Quadras offshore field] cost $2 million compared to $3 million for three conventional horizontal wells ($1 million each)." Just as with single horizontal wells, there is a learning curve associated with multilateral wells (Chambers 1998). Moritis (2000) found that for multilateral wells in Venezuela, the cost of drilling a single lateral leg decreased from $1 million to $700,000 during the course of the project, while the cost of drilling complex "fishbone" configurations decreased from $1.7 million per well to $1.2 million. For drilling horizontal laterals from existing wellbores, Lanier (1996) reported that costs decreased from $600,000 to $350,000 per well during the course of the 20-well program.

Higher Cost-Benefit Ratio of Directional Wells

It is important to recognize that well cost alone provides a poor comparison between conventional and horizontal technologies; it tells only half the story. For a true economic comparison, the difference in cost must be measured against difference in productivity. For the Seidenburg Z-17 well, a deep well in a German sour gas field, drilling and production costs were 1.2 times greater for a horizontal well, but production exceeded that of vertical wells by a factor of 4.5 (Niggeman and Ehlers 1991). In a continent-wide survey of horizontal wells in 1995, Deskins et al. found that while U.S. horizontal wells were twice as expensive on average than vertical wells, their output of oil or gas averaged 3.2 times as much as vertical wells. With over three times the product for only twice the cost, it is easy to see that horizontal wells were in fact more economical on average than vertical wells. In the same study, Canadian horizontal wells produced 4.1 times as much product on average as vertical wells with only 2.2 times the investment, an even higher economic advantage for horizontal wells than in the U.S. For the Devonian shales of the Appalachian Basin, Salamy et al. (1991) stated, "Recent drilling and completion operations have demonstrated the technical and economic successes of horizontal wells over vertical wells." Thus, while costs are slightly higher to drill directional wells, the higher costs of individual wells are more than offset by dramatically increased production.

Economic Success of Individual Wells

As is the case with vertical wells, there are no guarantees that individual directional wells will turn a profit. For 20 horizontal wells in Colombia, Saavedra and Joshi (2002) reported that costs were 1.5-2.5 times the cost of comparable vertical wells. Of these wells, two of the four completed in carbonate formations became economic successes, while 88% of the horizontal wells drilled in sandstone achieved economic success. In a survey of horizontal drilling in U.S. fields (Deskins et al. 1995), economic success rates averaged 54% (59% for clastics, 45% for carbonates). Canadian economic success rates were 59% for light-oil clastics, 79% for carbonates, and 92% for heavy oil reservoirs. Once again, this survey likely underestimated economic success rates for individual wells by calculating economic success by reservoir rather than by individual well: Reservoirs with initial horizontal failures do not inspire repeat attempts, and this survey gave reservoirs with a few failed wells the same weighting as reservoirs with thousands of successful wells (Deskins, pers. comm.). No economic success data were provided for vertical wells over the same period for comparison purposes, and it is unknown how the market prices of the day may have influenced the profitability ratings of wells in this study.

It is useful to consider the factors behind the minority of horizontal wells that do not prove profitable. For Canadian horizontal wells that failed to achieve economic success, Sarma and Ono (1995) summarized the primary factors: (1) The wellbore missed the target zone or improperly placed within target zone; (2) Vertical permeability was low. Deviated wells with multiple laterals were found to be favorable for this situation; (3) In a fractured reservoir, the well failed to intersect fractures as anticipated; (4) Formation damage or excessive well undulation made cleaning difficult; (5) The well traversed unexpected variations in rock formations, leading to water coning; (6) The presence of flow barriers such as shale streaks inhibited production (but flow barriers can also augment production by inhibiting coning); (7) Feasibility studies were poor (e.g., based solely on simulations). Some of these problems can be overcome through improved planning and performance, while others are inherent and would likely affect vertical wells in much the same way.

Profitability for Large-Scale Projects

To evaluate a fundamental shift from vertical drilling to directional drilling, it is best to evaluate the economic advantages of implementing directional drilling on a large scale. Because each directional well drains a greater reservoir volume than a corresponding vertical well, fewer wells are required to drain a reservoir, reducing up-front project costs (Fritz et al. 1991). The technology continues to improve and efficiencies in using this technology will also likely increase. Al-Blehed et al. (2000) stated that their use of horizontal wells reduced drilling, flowline, and facilities costs by 20-25% over vertical drilling. Turaiki and Raza (1998) reviewed the track record of horizontal drilling in Saudi Arabia. They reached the conclusion that "Implementation of [3-D seismic, horizontal drilling, and multi-lateral drilling] has had a pronounced effect on reducing capital and operating costs. Development planning has become more cost-effective, oil production rate declines are being arrested, plateau oil rates are being sustained over longer duration, and oil recoveries are being improved."

These improved efficiencies in oil and gas recovery have translated into real economic successes when directional drilling technologies are applied on a large scale. Meehan (1995) evaluated Union Pacific Resources' horizontal drilling program in the Austin Chalk: "UPRC's first 1,000 horizontal wells have been an economic success," he reported, returning 19%

over their expenses. As of 1993, horizontal drilling was reducing total drilling, flowline, and facilities costs in the Middle East by 20-25% while improving well capacity by 150-400% (Aalund and Rappold 1993). Fritz et al. (1991) compared the costs of older-technology directional drilling with vertical drilling and found that oil production costs per barrel were lower for directional drilling in the Austin Chalk, but higher in the Williston Basin of North Dakota. According to Maloy (1992), "Horizontal drilling in Giddings field Austin Chalk has significantly improved well recoveries and more than offset drilling costs."

According to Harrison et al. (1994), techniques to control production unique to horizontal drilling make production from certain types of sandstone reservoirs profitable, which would be unprofitable with vertical drilling. Baker et al. (1984) performed an economic analysis on coalbed methane recovery via directional drilling and found it to be economically feasible. Based on BP's horizontal drilling experiences in the Gulf of Mexico, Badgett et al. (1994) stated that "[t]he wells have provided access to reserves isolated by depositional features within the reservoir at a cost equal to or less than that of conventional drilling." According to Sarma and Ono (1995), "Most IOR [improved oil recovery] with horizontal wells has been successful, both in terms of oil productivity and economics. In most cases, project cost has been realized within months of production."

When horizontal drilling is applied broadly, the increases in oil and gas production more than compensate for higher costs per well. According to studies, directional drilling appears to yield economic advantages on a large scale. Even in individual cases where directional costs are higher, the overall cost-benefit of directional drilling appears to favor this technology over conventional vertical drilling.

INCREASING PRODUCIBLE RESERVES

Numerous reports have also found that directional drilling is also more effective at removing oil and gas from geologic formations than conventional vertical wells. Thakur (1999) reported that because horizontal drilling is a more efficient extraction method, it increases the recoverable reserves for a given reservoir.

There are numerous cases where horizontal or other directional drilling has rejuvenated oil and gas reservoirs that previously were dormant. The Anglia gas field of the western North Sea was unproductive with vertical drilling, even with well stimulation and fracturing technologies. But "at a small cost premium, the [horizontal drilling] method enabled a marginal field to be developed successfully" (Guyatt and Allen 1996). The Tyra Field of the Danish North Sea, which originally produced only gas, became a productive oil field due entirely to the success of horizontal drilling (Nykjaer 1994). In northern Alberta, horizontal wells are being used to tap "attic oil" missed by previously existing vertical wells (Morrissey 1996). In Canada, declining or shut-in fields such as the South Bodo, Edam West Sparky, Midale Bed Unit 5, Weyburn, and Cummings-Dina pools returned to strong production through horizontal drilling (Sarma and Ono 1995). In south Texas, the Pearsall Field had been abandoned as uneconomic until it was rejuvenated through horizontal drilling (Lichtenburger 1990). Based on initial successes, horizontal drilling is expected to yield an additional 80 million barrels of oil from the moribund Crystal Field in Michigan (Wood 1997).

Directional drilling can profitably tap new fields that are unprofitable to develop with conventional vertical methods. Jacobsen and Rushworth (1993) evaluated horizontal drilling in the Troll field of the Norwegian North Sea. They summarized their findings as follows: "Under the large gas accumulation of the Troll field lies a significant quantity of oil. However, this oil is contained in thin layers distributed over a wide area and therefore cannot be developed using conventional wells. In 1988 Norsk Hydro re-evaluated possible development schemes for the oil resource, and concluded that the application of horizontal well technology could provide an economically viable means of developing the resource." Following successful test wells, full-scale development followed. A five trillion cubic foot sweet gas play in northeastern British Columbia was rendered feasible by horizontal drilling; *Oil and Gas Journal* reported that "En Cana said Greater Sierra would be uneconomic without two technologies: horizontal drilling and underbalanced circulation" (Anon. 2002c).

Finally, horizontal drilling maximizes the amount of oil in place that can be extracted from underground reservoirs. Hawkings et al. (1990) reported that horizontal drilling would double the producible reserves from the Rotliegendes Field in Germany. According to Maloy (1992), horizontal drilling in the Austin Chalk "has conceivably increased recoverable reserves by 400 million BOE [barrels of oil equivalent, a measure allowing comparison of gas and oil production].” In the Elk Hills field in California, Gangle and Ezekwe (1995) concluded, “The horizontal wells produce at higher rates, lower drawdowns, and lower gas-oil ratio which will extend the life of the project and result in higher recovery.” Horizontal drilling has increased the recovery potential for this tilted reservoir to over 70% of the oil in place, an increase of 10 million barrels of producible oil per horizontal well (Gangle et al. 1991). For the Paradox formation of Utah, Arizona, and Colorado, Chidsey et al. (2002) reported, “Proper geological evaluation of the reservoirs may increase production by 20 to 50% by the application of horizontal, possibly multilateral drilling projects.” Deskins et al. (1995) predicted that horizontal drilling would increase U.S. producible reserves by 38%.

Directional Drilling Exploratory Wells

Based on industry reports, directional drilling is feasible for both exploration and full field development (French Oil and Gas Industry Association 1990). The effectiveness of horizontal drilling in particular as an exploration tool was noted by Hawkings et al (1990) who reported that a horizontal well was able to locate high permeability sands where conventional wells had failed.

THE POTENTIAL TO REDUCE IMPACTS THROUGH DIRECTIONAL DRILLING

Directional drilling, coupled with new well spacing patterns, can reform the way that the oil and gas industry does business. This is particularly important on public lands and on private lands overlaying federal minerals in the Rocky Mountain West, which must be managed for multiple uses. These tools have great potential to reduce damages from exploration wells, infill projects, and new full-field development. As a result, directional drilling technology should be considered in all pending and future oil and gas projects, and if found to be more environmentally beneficial, it should be implemented.

However, directional drilling is by no means an environmental panacea. When properly employed, these techniques can reduce the quantity of roads, well pads, pipelines, and overall surface impacts, and also concentrate human activity and vehicle traffic in a smaller area. But directional techniques do not eliminate these impacts, nor do they necessarily reduce other environmental impacts such as noise, some types of air pollution, chemical spills, and in the case of coalbed methane, toxic wastewater. In order to truly minimize the environmental impacts when producing oil or gas, additional measures beyond the scope of this report will be required. In addition, directional drilling does not eliminate all impacts of oil and gas development, and in some cases merely shifts the impacts to other lands.

Consequently, directional drilling is not suitable for use in all instances. There are a number of sensitive lands and habitats that are fundamentally incompatible with industrial use, where oil and gas development of any kind is inappropriate. These lands include national wildlife refuges, parks, monuments, and wilderness areas; roadless and wilderness-quality lands; and other sensitive areas; as well as appropriate buffers around these lands.

Other sensitive lands, such as important wildlife habitat, areas of high archaeological and cultural interest, floodplains, and lands of critical importance to endangered and threatened species and other rare plants and wildlife, should be withdrawn from all surface developments to protect these sensitive lands from the surface impacts associated with energy development. Directional drilling has potential as a tool to access subsurface energy resources while protecting important surface values that would be damaged through conventional vertical drilling operations. It is directional drilling that allows for oil and gas to be extracted from federal lands with a “no surface occupancy” lease requirement.

However, environmental benefits can only be maximized if all surface activities, including exploration, are eliminated. The following paragraphs outline some of the potential environmental damage-reduction benefits of this technology.

Directional Drilling Requires Fewer Wells in Existing Fields

Because each horizontal well drains a much larger area than a vertical well does, fewer horizontal wells (and their associated roads, wellpads, pipelines, and in some cases, powerlines) are needed to drain a given oil or gas field. Maurer (1995) reported that Petro-Hunt used a single multibranch horizontal well to drain an entire lease; this dual wellbore produced at a rate that was 1.5 times greater than single-bore horizontal wells. For offshore drilling, Huang et al. (1996) reported, “In this application, the horizontal well can replace at least four vertical wells.” According to Al-Blehed et al.

(2000), horizontal drilling has decreased the number of wells required to drain Middle Eastern reservoirs by 30%.

Because fewer directional wells are required to drain a subsurface reservoir, well spacing is greater for directional wells (Fritz et al. 1991). Joshi (1991) stated that "to achieve larger producible reserves, horizontal wells will have to be drilled with a larger well spacing than vertical wells." In one full-field horizontal drilling scenario, Stright and Robertson (1993) noted "It is also concluded that horizontal well spacing in the fractured Niobrara should be greater than 640 acres." Indeed, horizontal wells that are spaced close together compete to draw the same oil or gas, reducing production efficiencies. In the Austin Chalk, Meehan (1995) found that "[i]nterference between [horizontal] wells more than 8,000 feet apart was not uncommon." Thus, it would be foolish from a technical perspective to implement a directional drilling program with an ultra-dense (20- to 80-acre) well spacing pattern.

In existing oil and gas fields, horizontal and multilateral drilling allows additional production to occur without an increase in well density, by drilling from existing wells or well pads. The U.S. Department of Energy agrees, stating that "new techniques for sidetrack drilling (drilling a lateral extending from an existing wellbore) and deeper drilling from existing wells can allow some of these resources to be developed without drilling new wells or disturbing previously undisturbed areas" (USDOE 1999a). Horizontal infill drilling can utilize existing wellpads to produce additional resources with few added impacts.

Directional Drilling Extends the Reach of Drilling Operations

Extended-reach drilling is both practical and economical. Based on experience in offshore California fields, Elks and Masonheimer (2002) concluded that "[a]lmost any rig can drill ERD [extended-reach drilling] wells, when the wells are designed and engineered within the rig's limitations." In 1994, emerging technological advances allowed extended-reach wells in Australia's Bass Strait field to be drilled "more economically and consistently" (Santostefano and Krepp 1994). The literature abounds with examples of technically and economically feasible "extended reach," or long-distance directional drilling, in a variety of settings, as summarized in this report. Such extended-reach drilling provides the possibility for extracting energy resources from under sensitive lands needing protection from surface disturbances. However, to date there are only a few examples where this has taken place. According to Deskins (1995), only 7% of the horizontal wells in a nationwide survey were drilled to avoid surface restrictions above the target formation. In Brazil, PetroBras has employed horizontal drilling in the Amazon to reduce the need to clear rainforest (Knott 1994). In this case, equipment was brought in by barge, and crews were helicoptered in, eliminating the construction of access roads to the wellpad. Slimhole drilling was used to access natural gas beneath the city of Howell, Michigan (Gredell and Benson 1995). In Texas, horizontal drilling was employed to access a large gas deposit beneath Falcon Reservoir, which was protected from surface drilling for ecological reasons (Doughtie 1994). These cases show that where surface resources require protection through lease stipulations or other measures, companies with a vested interest in a specific area may still be able to access the resource through directional drilling although this will displace impacts to other areas.

Cluster Drilling Reduces Surface Damage

Extended-reach drilling can be paired with cluster development to reduce the surface footprint associated with oil and gas drilling operations Slant and conventional directional drilling was used to drill 23 shallow wells (ranging from 1,716 feet to 1,860 feet deep) from a single pad near Wolf Lake in northeastern Alberta (Smith and Edwards 1992). In Venezuela's Orinoco Basin, Petrozuata has drilled up to 12 wells from a single pad (Moritis 2000). The Tabasco satellite field in the North Slope's Kuparuk area has been produced entirely from 9 wells drilled from a single pad (Phillips Petroleum 2002). Foregoing sentence reinstated. Elsewhere on Alaska's North Slope, a 25,000-acre reservoir was drained with 36 wells on two drilling pads (Redman 2002). The surface disturbance from the well pads, roads, and airstrip constructed during this project totaled 97 acres, compared to a total of 128 vertical well pads and 1,925 acres of surface disturbance for a comparable 25,000-acre part of Wyoming's Moxa Arch field (data from BLM 1995). But it is important to note that such cluster drilling has been shown to cause caribou to abandon the critically important calving grounds (Nelleman and Cameron 1998).

Cluster drilling from a single well pad not only reduces the overall footprint of oil and gas development on the landscape by concentrating the activity and impacts of many wells at a few widely dispersed sites but also minimizes the capital investments of drilling companies (French Oil and Gas Industry Association 1990), and reduces costs for an expensive and ecologically damaging network of improved roadways. “By minimizing the number of production wells and usage of cluster locations,” noted Graute et al. (1994), “a reduction of field investment and operating costs should be attained.…” British Petroleum (2002) also has acknowledged the economic advantages of cluster development, stating that “limiting the size and number of new facilities also allows petroleum operations to be conducted more efficiently.” Hub and cluster development is currently being used to develop the Tchibouela-Est field in Congo; this full-field production method is expected to improve production at reduced capital outlays (Energy Information Administration 2002).

By implementing cluster development in conjunction with directional drilling technology, there is the potential to simultaneously reduce environmental damages associated with full-field development using traditional vertical wells, as well as reduce industry costs. This provides an additional incentive for considering directional drilling, coupled with cluster development, when developing mineral resources in the Intermountain West.

CONCLUSIONS

This report demonstrates that directional drilling is a proven, feasible method to extract oil and gas resources in a variety of geologic settings throughout the Intermountain West and elsewhere across the globe. It is frequently economically superior to vertical drilling when the cost of drilling and the benefit from increased production associated with directional wells is taken into account

Where directional drilling is undertaken in a localized area by clustering wells, the surface disturbance associated with the drilling activity can be reduced, compared to vertical drilling. Directional wells generally need wider spacing within an area as well, which spreads out the amount of surface disturbance and may reduce the damage to any particular area. Thus, in a full-field development scenario, cluster drilling incurs a much more compact impact on the landscape when compared to the sprawl of roads, pipelines, and wellsites inherent to conventional vertical drilling. Directional drilling also enables oil and gas to be extracted from beneath lands where “No Surface Occupancy” restrictions have been place to protect sensitive resources valued by the public.

Directional drilling will not prevent all environmental impacts of oil and gas exploration and development. While clustering operations reduce the overall amount of land disturbance, they do intensify impacts in localized drilling areas. Directional drilling technologies also will not address other impacts associated with oil and gas development, such as air pollution and chemical spills. As a result, lands that contain resources incompatible with oil and gas development should remain withdrawn from all types of drilling, with buffers established to protect these lands. Still other sensitive lands must be protected from the surface impacts of energy development.

Given the availability and utility of this technology, it should be considered as an alternative wherever the federal government is examining oil and gas development of publicly owned minerals in the Intermountain West. When found to be the more environmentally protective alternative, this technology should be required in the development of federal mineral resources.

Although the Bush Administration has lauded directional drilling for its potential to reduce environmental impacts, so far it has failed to implement or even study the widespread use of directional drilling technology. Directional drilling should be factored into every decision about oil and gas activity affecting the minerals owned and managed by the federal government in the West. It could be a replacement for vertical drilling in a variety of circumstances, from exploration wells to infill projects to full-scale development of new fields.

APPENDIX A

Other Means to Reduce Surface Impacts

Pitless Drilling

One method that is universally applicable to reduce drilling impacts is “pitless drilling,” entailing closed-loop systems that recycle drilling mud rather than dumping it into open pits. In addition to the elimination of toxic waste pits on the surface, this method reduces wellfield truck traffic by up to 75%, reduces water consumption by 80%, and is actually 8% less costly than constructing and maintaining a reserve pit (Longwell and Hertzler 1997). This method has proven successful in Alaska (Phillips Petroleum 2002) and Colorado (Longwell and Hertzler 1997), and is planned for the Sakhalin I project in Russia (Sumrow 2002). Due to its environmental advantage, pitless drilling should be mandated as a standard requirement for drilling operations.

The Need to Reduce the Impact of Seismic Exploration

Seismic oil and gas exploration can also have serious environmental impacts. There are two main methods: vibroseis, which relies on heavy equipment to send vibrations through the Earth, and shot-hole method, which required setting off underground explosive charges. The resulting shock waves are recorded by geophones to produce an underground map of oil and gas deposits. Desert soils, particularly those with biological soil crusts, are acutely susceptible to compaction and destruction when subjected to off-road vehicle driving of the type that accompanies heavy-impact types of seismic exploration; these soils and crusts can take 50-200 years to recover (Belnap 1995). Menkens and Anderson (1985) reported that prairie dog colonies subjected to vibroseis-method explor-

Photos by Scott Groene, Greater Yellowstone Coalition

Top: 26-ton vibroseis trucks used for heavy-impact seismic exploration.
Bottom: The aftermath of vibroseis truck use.

ation showed population declines while neighboring colonies experienced population increases. Seismic exploration projects can also have impacts on big game, particularly in sensitive habitats. Both shot-hole and vibroseis methods have been shown to disturb and displace elk on winter ranges (Ward 1986). Seismic exploration can also cause elk to abandon preferred calving habitats (Gillin 1989). Shot-hole seismic projects, while less damaging to the land, may also have negative impacts on wildlife. Explosions from shot-hole seismic testing may injure or kill fish when the shots are placed too close to aquatic habitats (Yukon Fish and Wildlife Management Board 2002). When performed in the winter, seismic shots can disturb and cause stress to hibernating bears (Reynolds et al. 1983). For these reasons, seismic exploration projects also deserve special planning to minimize their impacts on lands and wildlife.

The most prevalent method, 3-D seismic exploration, can be accomplished through two distinct techniques. In both types of seismic work, strings of receivers called "geophones" are strung out along set patterns across the landscape to pick up vibration signals from artificial sources. "Vibroseis" techniques employ 56,000-pound trucks that lower a 6,000-pound vibrating pad to create the vibration. "Shot-hole" methods employ drilling shallow holes and setting off explosive charges to set up the vibration signals. When properly conducted, this method can be a lower-impact alternative to vibroseis.

The vibroseis truck method is very heavy handed, requiring extensive off-road driving by massive machinery, which crushes vegetation and destroys fragile soils. According to the U.S. Bureau of Land Management, "Thumper trucks are obsolete technology that generate a greater shock wave through the ground and have the potential for greater impact to undiscovered cultural sites (due to the fact that they operated by dropping a 6,000 pound weight)" (BLM 2002b). Nonetheless, vibroseis trucks continue to be widely used throughout the American West.

The shot-hole method is much lighter on the land, particularly if it is performed without off-road vehicle travel. For environmentally sensitive areas, geophone cables can be laid by hand, and heliportable drills can be airlifted in to shot-hole sites (BLM 2001). This eliminates the need for damaging off-road truck and buggy traffic. Advances in shot-hole technology now allow 3-D seismic exploration to be conducted even in cities (Hansen 1993). Hansen later pointed out that exploration companies have a high degree of flexibility in locating shot points, increasing their ability to reduce impacts with this method (Hansen 1996). As in the case of drilling, some lands are so sensitive to disturbance that they are inappropriate for any type of seismic exploration.

APPENDIX B

Emerging Technologies Compatible with Directional Drilling

Virtually every technological advance developed for vertical drilling has also been successfully applied to directional drilling. For directional wells, these technological advances further improve the technical capabilities, increase oil and gas recovery, and lower drilling and production costs. As more advances are made in drilling technology, these methods will be able to access oil and gas from deeper reservoirs, farther from the drilling pad, and at lower costs per barrel produced than ever before.

Hydraulic Fracturing

Hydraulic fracturing has been successfully implemented with horizontal wells on any number of occasions (Yost and Overbey 1989, Salamy et al. 1991, Iverson et al. 1995, Soliman et al. 1996). Multiple hydraulic fractures have been successfully employed with very deep horizontal wells (Schuler and Santos 1996). Guo and Evans (1993) developed algorithms to predict production for horizontal wells with any combination of fracturing and oil or gas viscosity. Thus, for low-permeability (tight) reservoirs, the option of hydraulic fracturing is available to companies employing directional drilling technologies.

It is important to note that hydraulic fracturing is a controversial technique for gas extraction. Fracturing can have dramatic impacts on water supplies and nearby dwellings. These impacts, while outside the scope of this report, must be carefully considered before undertaking this approach.

Steam Injection

Steam injection can be used to improve heavy oil recovery from unconsolidated sand formations. Horizontal wells have been effectively employed in conjunction with steam injection from vertical wells (Chenot et al. 2002) and with paired horizontal injector wells (Sarma and Ono 1995). O'Rourke et al. (1997) found horizontal drilling of paired wells to be effective in gas production using steam injection techniques.

Underbalanced Drilling

In underbalanced drilling, drilling mud is infused with gas to make it lower-pressure than the producing formation. This prevents the drilling mud from being forced out from the wellbore into the reservoir formation, impairing the flow of gas into the wellbore (Teichrob 1994, Pinney and Rodrigues 1999). Brookey (1998) recently developed new drilling fluids using long-lasting "micro-bubbles," enabling balanced and underbalanced drilling fluids to be created at a fraction of the cost of injecting air or gas into drilling mud. Underbalanced drilling is particularly effective in producing oil and gas from low-pressure formations using horizontal drilling.

Well Casings

Originally, most horizontal wells were drilled as "open hole" completions, with no liner or casing of any type. Later, a number of different well casing types were developed for use with directional wells. Gomez et al. (2002) provide a useful synopsis of horizontal well casing types. According to this study, horizontal wellbores are most commonly completed in "open hole" fashion, or with slotted liners in unstable formations where wellbore collapse is a potential problem. Slotted-liner completions can be gravel packed to reduce sand production, which lowers efficiency. Gels can be used to isolate problem zones, even with slotted liners (Gomez et al. 2002). At the beginning of the 1990s, cased horizontal wells in Alaska were being completed with either cemented or slotted liners (Stagg and Reilly 1990). These researchers noted that cement casings were being used to isolate problematic rock formations outside the pay zone. Thus, many different well casing options are available to drillers of horizontal wells.

Coiled Tube and Slimhole Drilling

Coiled-tube drilling replaces the segmented drill pipe of conventional drilling with flexible tubing. The coiled tubing is run under compression in order to maintain the necessary pressure on the drill bit (Faure et al. 1994a). According to Faure et al. (1994b), coiled tubing allows re-drilling old wells and performing horizontal re-entries, even in offshore situations where there is no derrick in place. Graham et al. (1999) extolled the advantages of coiled-tube drilling for drilling horizontal lateral sections from existing vertical wellbores: "Due to economic, environmental, and surface logistics concerns, re-entry drilling from existing wellbores is often an extremely viable solution to horizontal development in existing reservoirs. By utilizing an existing wellbore, many of the costs can be avoided and often troublesome formations are already secured behind casing."

Coiled-tube methods have been paired with underbalanced drilling to achieve significant production improvements over vertical wells in a deep chalk reservoir in the Gorm Field of the Danish North Sea (Wodka et al. 1995) and also in the deep Elkton formation (McGregor et al. 1997). In addition, coiled-tube methods require a smaller wellpad and produce less toxic waste (Faure et al. 1994a) and are quieter than conventional drilling (USDOE 1999a).

Slimhole drilling, often accomplished through coiled-tube technology, entails the drilling of smaller-diameter wellbores, often from an existing vertical well. The new generation of smaller-diameter drilling bits developed for slimhole drilling are more durable, have increased penetration rates, and develop more power (McDonald et al. 1996). Slimhole drilling can also reduce wellpad footprint. According to the U.S. Department of Energy, "Operational footprints are also reduced, since equipment for slimhole drilling is smaller than that used in conventional operations. The area cleared for drilling locations and site access can be as little as 9,000 square feet with mud holding pits, as much as 75 percent less than that required for conventional drilling operations" (USDOE 1999a). Like coiled-tube drilling, slimhole drilling is quieter than conventional methods, reducing disturbance to local people or wildlife (USDOE 1999a).

A technique known as "microdrilling" is currently under development with the U.S. Department of Energy. This technique uses coiled-tube drilling from a trailer that can be pulled by a pickup truck, and can drill new wells up to 500 feet deep with no site preparation. According to the U.S. Department of Energy (1999b), "When developed for deep drilling, the technology will replace traditional methods that use massive amounts of equipment, material, and manpower, all of which are extremely expensive." This technique may allow drilling to occur without additional well pad construction.

Waterfloods and Miscible Floods

Oil and gas producers may use waterfloods and miscible floods to increase reservoir production; these methods entail the injection of water or solvent to raise reservoir pressure and force oil or gas out through producing wells. These methods are typically employed in a coordinated fashion over entire reservoirs to maximize the production of oil or gas. Horizontal wells enhance the effectiveness of waterfloods through maximizing the "sweep efficiency," or ability to force more oil out of the reservoir (Aalund and Rappold 1993, Deskins et al. 1995).

Cases abound regarding the successful pairing of horizontal drilling with waterfloods and miscible flood. The combination of waterfloods and horizontal drilling has achieved success in Utah (Hall 1998). With miscible floods, horizontal wells in Canada's Rainbow Keg River G Pool achieved 3.5 times the hydrocarbon production of the best vertical well in the pool (Sarma and Ono 1995). In addition, the drilling of horizontal wells actually improved the productivity of offset vertical wells for miscible floods in the Rainbow Keg River E Pool (Fong et al. 1996). The cost of these horizontal wells in this pool as well as similar miscible flood horizontal projects in the Brazeau River field were recovered within the first year of production (Sarma and Ono 1995). Miscible floods have also been effectively employed in conjunction with cluster drilling on Alaska's North Slope (Redman 2002).

Rotary Steerable Drill Bits

Rotary steerable drill bits can change direction on a dime and offer faster drilling through the rock than older directional systems. In the Norwegian North Sea, a rotary steerable system drilled through 8,586 feet of horizontal reservoir section in only 8.9 days, saving the rig operator $1 million in rig time (Gaddy 1999). Similarly, rotary drilling systems saved 100 days of rig time (and the associated costs) in Norway's North Sea Jotun Field (Grini et al. 2002). Grini et al. noted that "Rotary-steerable systems provided greater directional-steering accuracy and drilling efficiency in extended-reach drilling applications." Most importantly, rotary steerable technology holds the promise of increasing extended reach distances by 25% over current achievements (Sumrow 2002).

But there are limitations to rotary-steerable technology. Chenot et al. (2002) reported that unconsolidated sands were poor candidates for rotary steerable drilling after a well failed in this formation where a conventional horizontal well was successful. Rotary-steerable systems remain an expensive option at the current time. Sumrow (2002) noted, "Anecdotally, only about 15% of the rigs in the North Sea can afford to run rotary steerable systems, limiting rotary steerable technology to only the more expensive wells." But if rotary-steerable technologies follow the trends of other advances in petroleum engineering, costs may soon decrease to the point where this technology is economically feasible for a broad range of applications.

Other Emerging Technologies

A host of other technologies have arisen to increase the productivity or economic efficiency of directional drilling. Ali et al. (1996) developed an acid foam treatment to repair "skin damage" problems for open-hole wells in unconsolidated sands. Miller and Geehan (1998) also found that acid stimulation improved production in under-producing horizontal wells in carbonate formations. A plunger lift has been developed specifically for use in removing liquids from horizontal wellbores (Pullin and Porter 2001). Mathematical algorithms to predict bit walk in diagonal, directional, and horizontal wells have been developed to achieve even greater accuracy in drilling (Liu and Zaihong 2002). All of these technologies improve the performance of directional wells and increase their cost effectiveness.

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