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Cost/Benefits of Horizontal Wells

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Abstract

This is a summary of state of the art horizontal well technology and a review of the economic benefits of horizontal wells. The paper describes various reservoir applications of horizontal wells from primary recovery to EOR applications. The paper includes field examples of different applications. .

Although horizontal wells have been drilled as early as 1927, the major thrust of drilling horizontal wells started in 1980. Initial wells were short length wells (about 250 ft. long wells). In 1985, the first medium radius horizontal well was drilled using a down-hole mud motor. Since then, using horizontal wells has become a common practice. Today, the medium radius drilling technique is the most commonly used drilling method.

In the U.S., the majority of applications are in low permeability, naturally fractured, carbonate reservoirs. However, in California, Alaska and Gulf of Mexico most of the wells are drilled in clastic reservoirs. Similarly, outside the U.S., most of the horizontal wells are drilled in clastic reservoirs.

Horizontal wells have been used to produce thin zones, fractured reservoirs, formations with water and gas coning problems, waterflooding, heavy oil reservoirs, gas reservoirs, and in EOR methods such as thermal and CO_2 flooding. The paper includes field examples with cost benefit analysis for various applications.

Introduction

Some of the early horizontal well efforts date back to 1930. After World War II, with the advent of jet perforation, major industry efforts were focused on casing the drilled hole and perforating in the desired zones. The field implementation of this perforation technique was a great success and at least for a while horizontal drilling took a back seat.

In the late 70's and early 80's, with oil prices around $35 a barrel, interest in horizontal wells was reignited. The purpose of the horizontal wells was to enhance well productivity, reduce water and gas coning, intersect natural fractures and to improve well economics. [1]

In the early 80's, Elf Aquitaine, a French company, introduced horizontal wells to the oil industry to produce a heavy oil carbonate reservoir in the Rospo Mare Field, offshore Italy, in the Adriatic Sea. At the same time, in the U.S., several companies were using horizontal wells to reduce gas coning in the Abo Reef in New Mexico. They were also using horizontal wells to intersect fractures in the fractured carbonate reservoirs in Oklahoma, Kansas and Texas.[2]

The drilling technique used by Elf Aquaitain was very different from that used in the U.S. The Elf technology involved drilling long radius (1000 ft. turn radius, see Fig. 1) and long length (a few thousand ft.) wells.[3] They were also using down-hole motors to turn the bit and drill wells. To date, this long radius drilling technology remains suitable to develop offshore fields around the world. In the U.S., initial efforts were with the "short radius" drilling technique where turn radius was around 30 ft. The wells were drilled using stabilizers, knuckle joint and flexible collars. A mushroom type, helical collar joint was used to provide necessary flexibility to the drill pipe to turn from the vertical to the horizontal direction in a short distance. Well completion was either open-hole or with a slotted liner. The typical well length was 100 to 300 ft. The major disadvantage of this drilling technology was its limited completion options and high cost of drilling. In the mid-eighties, the cost of drilling the 30 ft. radius well was of the order of $2000 to $3000 per ft. To minimize this drilling cost, and to drill long length wells, a medium radius drilling technology was developed.

The first medium radius horizontal well was drilled in 1985.[4] Turn radius for the medium radius wells was about 300 ft. to 600 ft. and it utilized down-hole motors. To date, medium radius technology remains the most common method to drill horizontal wells. This drilling method provides various completion as well as artificial lift options. It is quite common to see well lengths varying from 1000 ft. to 5000 ft.

Short radius technology has also evolved over time and there has been significant cost reduction. This, however, remains a niche market mostly in low productivity wells in the U.S. and parts of China. In the U.S., small independents with marginal wells (production rate less than 10 BOPD) use low cost, short radius technology to enhance well production.

Recent Developments

In the last few years, several technical advances have been made. Some of these advances include LWD and MWD (logging while drilling) and geo-steering. Technologies are available to drill and complete multi-lateral wells, drill with coiled tubing, drill under-balance, and use rotary steerable assembly to drill straight holes. For completion, one can cement and stimulate horizontal wells in low permeability formations and gravel pack long horizontal wells in high permeability formations. These new technologies are briefly described below.

Technologies have been developed to drill *multi-lateral wells*. These wells have various shapes and offer the possibility of different types of completions to isolate and control production from different branches of multi-laterals (see Figure 2). Nevertheless, through the year 2002, the large scale multi-lateral applications are seen in heavy oil reservoirs (where wells are completed with slotted liners) and in carbonate reservoirs using open hole completions. A large scale of applications of multi-laterals is found in the heavy oil reservoirs in Canada and Venezuela and in the carbonate reservoirs in the Middle East.[5,6]

Another development is *under balance drilling* of horizontal wells to minimize formation damage, especially in low permeability formations.[7] The technique has been very popular in Canada. In addition to low permeability formations, under-balance drilling is also important in depleted gas reservoirs where current reservoir pressure is significantly less than the hydrostatic pressure. If one uses liquid drilling fluids, it would result in an excessive mud loss, resulting in reduced well productivity and possibly a non-commercial well. Under-balance drilling allows us to drill and complete horizontal wells in depleted gas reservoirs.[8] Typically, horizontal well productivity is two to five times larger than the vertical well productivity. Thus, for the given economic gas rate limit, horizontal wells could be produced with up to 1/2 to 1/3 reservoir pressure as compared to the reservoir pressure required for economic production from a vertical well. This results in a large enhancement of producible reserves from discovered, depleted gas fields. Horizontal wells are drilled in the depleted gas reservoirs in Texas, Oklahoma and also in Canada.

Typically, drilling a re-entry well is less expensive than drilling a grass roots horizontal well from the surface. The re-entry well costs could be further reduced by using the C*oiled tubing drilling* technique. This is especially important in Alaska where drilling costs are high.[9]

Significant advances have also been made in drilling technology to drill straight horizontal holes. The straight horizontal holes are necessary to obtain reliable gravel pack completions and to eliminate acid accumulation in the low spots along the length of the horizontal well. The corrosive acid effects can significantly reduce liner life in offshore, expensive, high production rate wells in deep waters. Progressively, *steerable rotary assembly* is used to drill horizontal wells, especially in deep water reservoirs to achieve fairly straight drilled holes.[10]

Most of the horizontal wells drilled in North America are completed as open hole or with slotted liners. The stimulation of horizontal wells is found to be necessary in many low permeability formations. *Stimulation techniques* are available for open hole horizontal wells using liquid fracs (either water fracs or acid fracs). In a few cases in onshore U.S., horizontal wells are cemented and fracture stimulated in the low permeability formations, such as Devonian formation in West Texas [11] (12000 ft deep, k=0.05 md), Diatomite [12] formation in Belridge Field in California, and Kuparek Field in Alaska.[13]

Open-hole gravel packing has also been an important development, especially for deep water reservoirs, which are typically high permeability, unconsolidated reservoirs.[14] Open hole gravel packing is used quite commonly in horizontal wells in the Gulf of Mexico. [15]

Cost/Benefits Of Horizontal Wells

Disadvantages of horizontal wells are:

1. High cost as compared to a vertical well. In the U.S., a new horizontal well drilled from the surface, costs 1.5 to 2.5 times more than a vertical well. A re-entry horizontal well costs about 0.4 to 1.3 times a vertical well cost.
2. Generally only one zone at a time can be produced using a horizontal well. If the reservoir has multiple pay-zones, especially with large differences in vertical depth, or large differences in permeabilities, it is not easy to drain all the layers using a single horizontal well.
3. The overall current commercial success rate of horizontal wells in the U.S. appears to be 65%. (This success ratio improves as more horizontal wells are drilled in the given formation in a particular area.) This means, initially it is probable that only 2 out of 3 drilled wells will be com

mercially successful. This creates extra initial risk for the project.

Benefits of horizontal wells are:

1. Higher rates and reserves as compared to vertical wells. This results in less finding cost and less operating cost per barrel of oil produced. In the U.S., as shown in the example in this paper, in places where vertical well operating costs are $7 to $9 per barrel of oil, the horizontal well operating costs are $3 to $4 per barrel.
2. For many horizontal well projects, the finding (developing) cost, defined as well cost divided by well reserves, is about $3 to $4/bbl. This is about 25% to 50% lower than the cost of buying proved producing reserves.
3. To produce the same amount of oil, one needs fewer horizontal wells as compared to vertical wells. This results in reduced need for surface pipelines, locations, etc.

Reservoir Applications

Horizontal wells have been employed in a variety of reservoir applications. Eight different types of applications are listed in Table 1. As shown in the table, horizontal wells have been used in thin zones, naturally fractured reservoirs, reservoirs with water and gas coning problems, low permeability reservoirs, gas reservoirs, heavy oil reservoirs, waterflooding and EOR applications.

Table 1 also includes a brief list of applications and reservoir properties. The recent trend indicates horizontal well applications in waterflooding and gas reservoirs in addition to exploiting naturally fractured reservoirs.

It is interesting to note that in the U.S., the largest number of horizontal wells are drilled in Austin Chalk and Buda formations in Texas.[16] These are low permeability, naturally fractured reservoirs. The objective of these wells is to intersect fractures. In addition to Texas, one can find horizontal wells used in carbonate formations in a few fields in the North Sea, Canada, in the Middle East, offshore India and a few other Asian countries. However, use of horizontal wells in clastic reservoirs is found around the world. This includes offshore Gulf of Mexico and California in the U.S., Canada, South America, North Sea, Russia, China, Nigeria, Malaysia and Indonesia.

The majority of the U.S. wells are in carbonates while the rest of the world applications are in clastic reservoirs. As noted earlier, in the U.S. most wells were drilled to intersect fractures. In contrast, internationally, most wells are drilled to minimize water and gas coning. In general, the horizontal wells drilled internationally, are in much higher quality reservoirs (in terms of porosity and permeability), than those drilled in the U.S.

Figure 3 shows the formations in the U.S. where a large number of horizontal wells have been drilled. (Here each multi-lateral branch originating from the main vertical wellbore is considered as a separate horizontal well.) As of December 2002, about 17,267 horizontal wells have been drilled in the U.S. Figure 2 shows that the Austin chalk formation in Texas has 7,428 wells, representing 45% of the U.S. horizontal wells. This is followed by the Red River formation in North Dakota. In California, a large number of horizontal wells are in the Tulare Sand reservoir.

Although there are several noteworthy projects around the world, the next sections include discussion of a few projects to indicate different applications of horizontal wells. Only North American projects are included.

Heavy Oil Production

In Canada, there are several projects where closely spaced long horizontal wells are drilled to produce heavy oil. These projects include those at Senlac, Cactus Lake in Saskatchewan and Pelican Lake in Alberta. The typical well length is 3000 ft. to 6000 ft. Due to shallow depth and fairly homogenous sandstone rock, drilling operations are fairly fast and inexpensive. A typical cost for a 2000 to 3000 long completed well at 1500 ft. depth is Can$275,000 to $350,000 (US$185,000 to $235,000). The wells are typically completed with slotted liners. The slot sizes are designed to minimize sand entry into the wellbore.

In general, these reservoirs are difficult to produce economically due to thin oil zones (2 to 5 meters thick) resulting in very low production rates from vertical wells. Moreover, in some cases, bottom water zone is also present. This bottom water zone makes thermal oil recovery difficult as steam tends to enter the bottom water zone preferentially.

For example, in Pelican Lake (13 to 15^{o} API oil) which has close to 2.3 billion barrels of heavy oil in place, about 450 horizontal wells are expected to produce about 5% of original oil in place.[17, 18] This gives an average of 250,000 barrels of cumulative oil production per well with drilling cost of about US$230,000. Thus, the well cost is only US$1 per barrel of reserve.

With such a low oil primary recovery and with large numbers of wellbores in place, it is possible to implement a waterflood between horizontal injectors and producers. A pilot test in three well pairs has been commercially successful. Even a one percent improvement in recovery using waterflood would result in about 20 million barrels of additional oil production. The only possible problem could be availability of a large volume of injection water.

Low Permeability Oil Reservoir

Another example is Mission Canyon Nesson formation in North Dakota. This is a thin limestone reservoir of Mississippian age. The formation depth is 9700 ft. with 10 to 30 ft. pay-zone thickness. The porosity varies from 5.7 to 12.9%.

In this reservoir with producing vertical wells, horizontal wells are drilled to increase production rates and reserves per well and also to reduce operating cost per barrel.

In Poe Field in McKenzie County, N.D., four horizontal wells were drilled. The reservoir permeability varies from 0.2 to 0.9 md. Originally, the field was developed using vertical wells. The production rate from vertical wells is limited due to small pay-zone thickness. A vertical well cost (drilled and completed) is about $650,000. A vertical well produces about 20 to 40 BOPD and rates drop to 10 BOPD, making it economically unviable, especially when oil prices are lower than $20 per barrel.

In this field, pressure transient tests were conducted in the vertical wells to estimate reservoir pressure and permeability. The initial hydrostatic pressure, based upon the depth, was estimated to be 4400 psi. The vertical wells are producing over 10 years with production rates ranging from 10 to 30 BOPD. The build-up test showed reservoir pressure to be about 3600 psi. It was decided to drill a 2500 to 3000 ft. long horizontal well with a build radius of 600 ft. Initially, a jet pump was to be located in the vertical section. Thus, it is estimated that the bottom-hole well flowing pressure would be maintained to as low as 600 psi. The estimated stabilized rates of the horizontal well were expected to be 60 to 100 BOPD with estimated reserves of 250,000 to 400,000 STB/per well. Due to prior drainage by a vertical well, re-entry wells are expected to have smaller reserves than the grass root horizontal wells. In the field, wherever possible, re-entry horizontal wells were drilled. Additionally, new horizontal wells from the surface (grass root wells) were also drilled. The cost of a re-entry horizontal well is about $670,000 while the cost of a horizontal grass root well is $1.2 million. The estimated reserve finding (developing) cost is $3 to $3.50/bbl with an economic pay-out of 2 to 3 years[19]. With a water disposal well nearby the operating cost is about $4/bbl of oil, making horizontal wells economically viable even if the oil price decreases to $10/bbl.

The performance of a typical horizontal is shown in Figs. 4 and 5. One dual lateral was also drilled, near the edge of the field. One of the laterals found limited pay-zone while the other lateral found very small pay-zone. This resulted in a limited production from the open hole dual lateral well.

Marginal Oil Wells

As noted earlier, a few small independents that have marginal oil wells have also used horizontal wells to enhance production rates. The marginal oil well is defined as a well with a production of less than 10 BOPD. In many marginal wells, short radius technology is used to minimize horizontal well cost.

One such example is in Tulsa County, Oklahoma. A small company bought the tools from AMOCO to drill short radius wells.[20] The horizontal wells are drilled in the Tucker formation. The Tucker formation is about 1300 ft. deep sandstone reservoir, with permeability of about 400 md and porosity of about 28%. Oil pay-zone is typically 30 ft thick with 50 ft thick bottom water zone. A vertical well produces about 4 BOPD and about 50 BWPD (barrels of water per day). The main operating cost is a pumping cost. A water disposal well is available nearby where water could be disposed at a few cents per barrel.

Three horizontal wells have been drilled from the surface in the field. These short radius wells, (about 400 ft to 800 ft long) are drilled at a cost of about $120,000 per well.[21] In these 70 ft radius laterals, the horizontal section is left open hole. A horizontal well produces about 10 to 14 barrels of oil per day. The water production rate varies from well to well and it ranges from 0 to 280 BWPD. Assuming $15 profit before taxes, the well pay-out is less than 2.5 years. The monthly operating cost for horizontal and vertical wells is about the same, about $1000/month. Thus, operating cost for a vertical well is $8.30 per barrel as compared to $3.33 per barrel for a horizontal well.

Water Coning In Carbonate Reservoir

In Marion County, Illinois, several horizontal wells have been drilled to produce oil from a fractured Geneva dolomite formation. The formation represents a part of the Silurian Reef Structure. [22, 23]

The field was discovered by seismic program under the State Park. Due to environmental constraints, the wells were drilled from "off the park'" sites to reach the formations under the park.

The Geneva dolomite has two main zones, the upper low permeability (approximately 10 md) "A" one and the bottom high permeability (approximately 3000 md) vuggy, fractured "B" zone. A fairly good aquifer support is experienced in the "B" zone. The porosities of A and B zones are 12.5% and 20%, respectively. The oil column thickness in A and B zones is 20 and 25 ft., respectively. The A and B zones are separated by very thin shale and are in hydraulic communication with each other. Two horizontal wells are drilled in each zone. The lengths of the horizontal wells in the 'A' zone vary from 50 to 500 ft. while the well lengths in the 'B' zone vary from 150 to 450 ft.

Expected recovery from four horizontal wells is about 3 million barrels. The cost of drilling a horizontal well is about $1.2 million. This represents $1.60 per barrel finding (developing) cost and $0.25 per barrel operating cost.

The horizontal wells initially flow with a rate varying from 600 BOPD to as high as 2000 BOPD. Initially, very little water is produced. After a while wells typically require pumps to produce. One of the wells is flowing after about 1 ½ years of production and cumulative oil recovery of 750,000 STB.

Project Economics

The field histories noted in the preceding section demonstrates the utility of horizontal wells in reducing hydrocarbon finding cost and also reducing operating cost. It is also important to note that the projects described in this paper have multiple horizontal wells. This indicates that for a commercially successful application, having a multiple well project certainly helps. [24,25] The past field histories also indicate some successes but also some failures. The failure could be due to reservoir/geological reasons or due to mechanical problems. Also, initially, only 2 of the 3 wells drilled may be commercially successful. So it is important to evaluate the overall impact of all the successful and uneconomical wells on the project economics.

In Michigan, several horizontal wells have been drilled in the Northern Silurian Niagaran Pinnacle Reef Trend. [26] The wells were drilled in various reservoir applications, however, mainly in thin oil columns with gas caps. Some horizontal wells were commercially successful while some were commercial failures. An example of the economics of a multi-well project is shown in Table 2. The Table clearly indicates the commercial success of horizontal wells.

The Table shows that out of 25 horizontal wells drilled, only 5 wells are successful, 11 are uneconomic wells and 4 wells are dry holes. Even then, the project is commercially attractive. This demonstrates the usefulness of multi-well horizontal well projects to minimize project risk and maximize economic benefits.

Conclusions

1. Horizontal well technology is a proven technology.
2. Horizontal wells have been used in a variety of primary, waterflooding and EOR projects.
3. In North America, horizontal wells are utilized to reduce hydrocarbon finding cost and operating cost.

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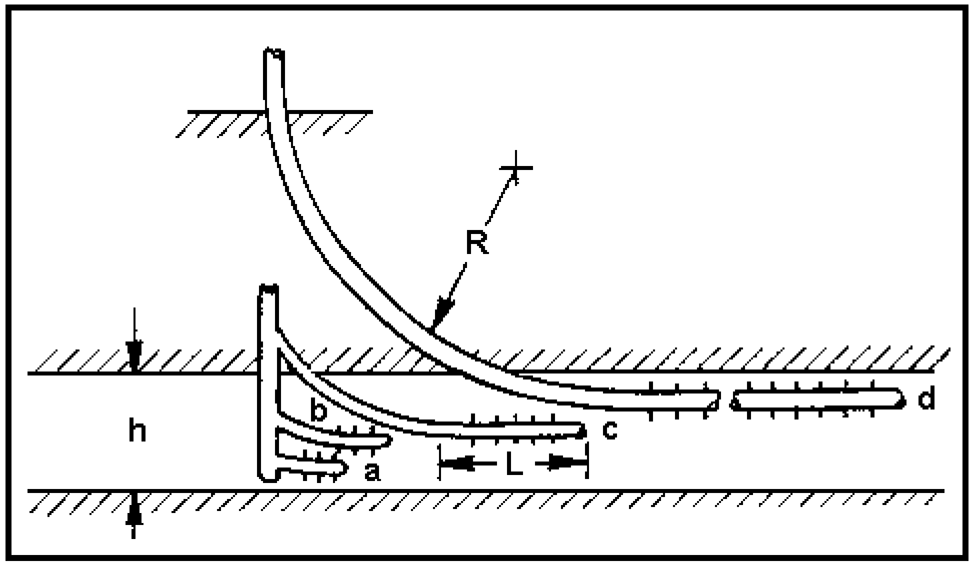

a) Ultra short radius	R = 1-2 ft	L = 100-200 ft
b) Short radius	R = 20-70 ft	L = 100-800 ft
c) Intermediate Short radius	R = 120-150 ft	L = 1000 ft
d) Medium radius	R = 300 - 800 ft	L = 1000-4000 ft
e) Long radius	R > 1000 ft	L = 1000-4000 ft

Figure 1: A Schematic of Different Drilling Techniques

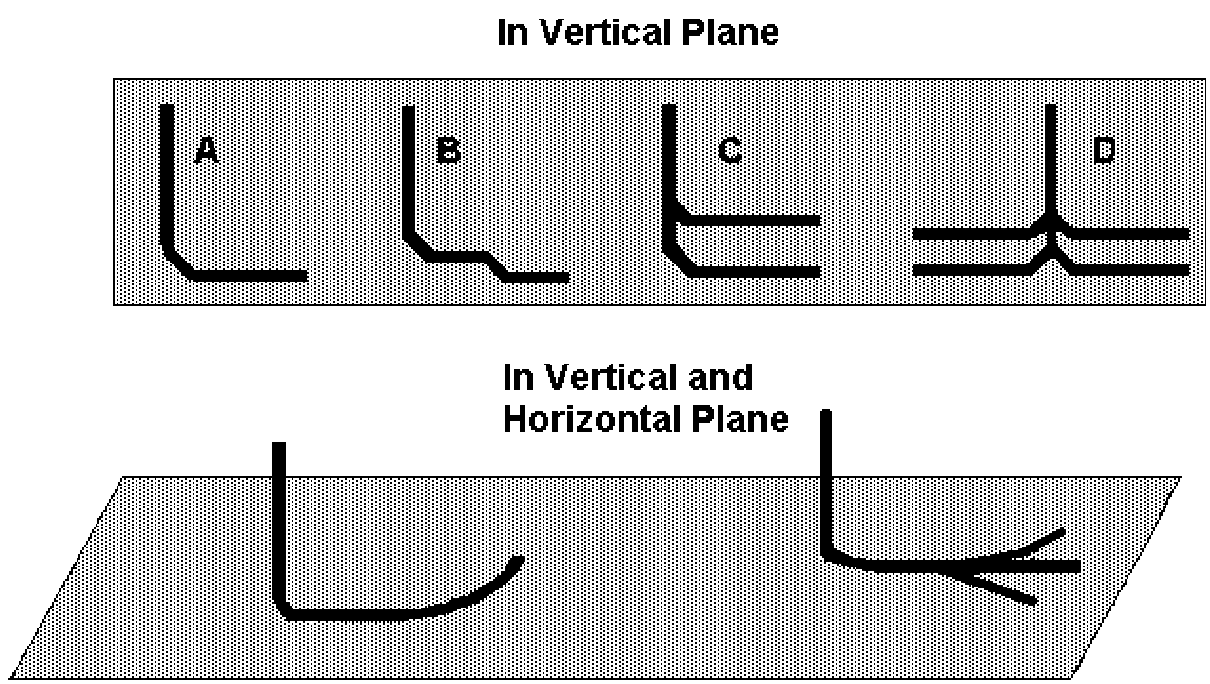

Figure 2: Different Multilateral Well Configurations

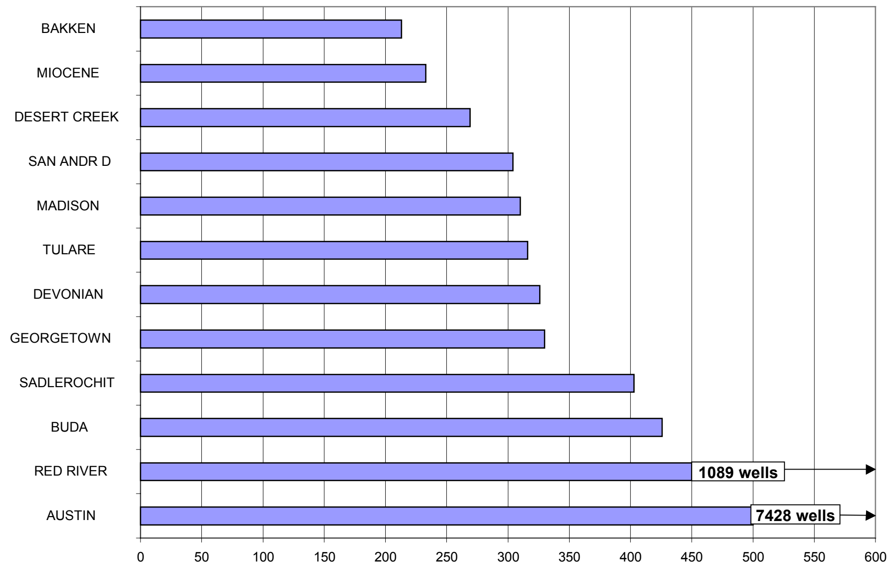

Figure 3: Number of Horizontal Wells as of Decem-

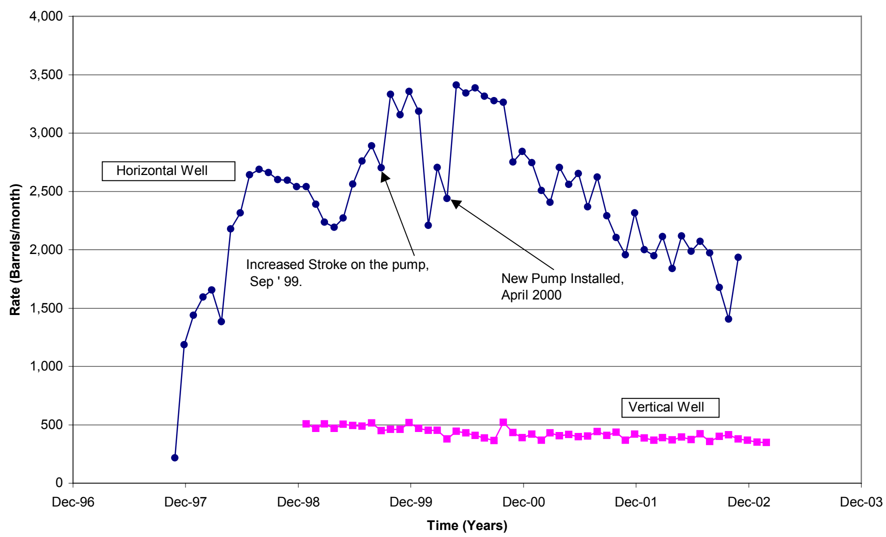

Figure 4: A Comparison of Monthly Production Rates for Horizontal and Vertical Wells

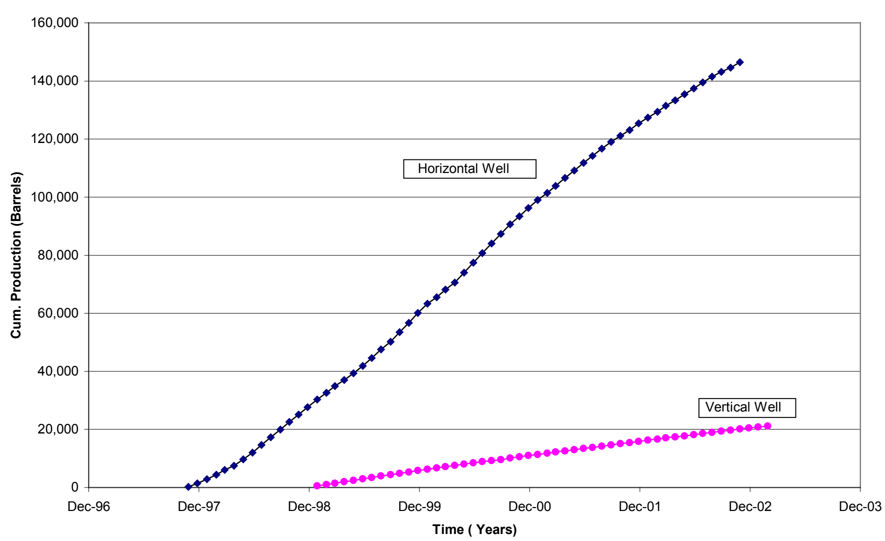

Figure 5: A Comparison of Cumulative Production Over Time for Horizontal and Vertical Wells

Table 1: Typical Horizontal Well Applications in North America

RESERVOIR APPLICATION	RESERVOIR	PAYZONE THICKNESS	POROSITY	HORIZONTAL PERMEABILITY
Thin Reservoirs	Bakken Shale, ND	10 to 30 ft	1.5 to 12.9 %	<1md
Naturally Frac.	Austin Chalk, TX	25 to 70 ft	3 to 12 %	< 1 md
Reservoirs	Bakken Shale, ND	10 to 30 ft	1.5 to 12.9 %	<1md
	Marmaton, TX, OK			
	Niobrara, WY		< 10%	< 0.1md
Reservoirs with	Prudhoe Bay, Alaska	100 to 200 ft	22%	200 md
gas and water	Elk Hills, CA	1500 ft (Orig)	23%	8 to 80 md
coning		275 ft (Current)		
	Smackover Formation, AR	20 to 40 ft	25%	0.2 to 800 md
	Benton Sound Blk, Gulf of Mexico	20 ft	34-37%	3 to 7 darcies
	West Delta Block, Gulf of Mexico	25ft Oil Col	30%	800 md
	Yates Field, TX	50 ft	30-35 %	10-1000
	Empire Abo Unit, NM (Reef)	90 ft	8.60%	25 md
Low Permeability	Lost Hill, Diatomite, CA	600-1200 ft	35 to 65 %	Avg = 0.001 md
Reservoirs	Codell Sandstone, CO	10 to 35 ft	8 to 22 %	1 md
	Bryant-G-Devonian Field, West Texas	40 ft	4%	0.04 md
Heavy Oil	Midway Sunset Field, CA	400 ft	28%	1 to 6 darcies
Reservoirs	Dos Cuadras Field, CA	130 ft		1.5 to 2 darcies
	Countess Upper Manville "RR" Canada		18 to 24%	250 to 5200 md
	Cactus Lake North McLaren, Canada	40 ft	30 to 33%	> 5 darcies
	Winter Field, Canada	100 ft	30%	6 darcies
	Edam West, Sparky Sandstone, Canada	65 ro 100 ft	34%	1 to 10 darcies
Gas Reservoirs	Devonian (L.Huron Shale)	15 to 50 ft	2%	0.13 to 0.43 md
	Big Sandy Field, Kentucky	250 ft (Gross)	2%	0.045 md
	Carthage Field, TX	5 to 55 ft	15%	35 md
	Gulf of Mexico	40 ft	33%	6 darcies
	West Delta 54, Gulf of Mexico	30 ft	30%	750
Waterflooding	Yowlumne Field, CA	0 to 400 ft	15 to 20 %	6 md
	San Andres, TX	30 ft	10%	1 md
	New Hope Shallow Unit, TX	18 ft	12%	2 md
	Weyburn Field, Canada	20 ft	3 % to 26%	0.01 to 500 md
EOR (Thermal)	Tulare Sand, CA (Thermal)	10 to 35 ft	35%	3 darcies
	Wilmington Field, CA (Thermal and Waterflood)	60 ft		
	Cold Lake, Canada (Thermal)	35 to 40 ft	10%	565 md
	Talngleflags North Field, Canada (Thermal)	90 ft	33%	4 darcies
EOR (Miscible)	Aneth Field, Utah (Miscible)	57 ft	11%	0.2 to 5 md
	Sundown Slaughter Unit, TX (CO2 Flood)	13 to 45 ft	20%	50 md
	Rainbow Keg River G Pool, Canada	35 to 40 ft	10%	565 md
	Pembina Nisku Field, Canada	130 to 330 ft	10 to 30 %	1.5 to 10 darcies

Table 2: An Example Comparison of Horizontal Well Drilling

	Evaluation Based on Common Success/Failure Criteria					
	No. of wells	Cost per well	Total Cost	Present value return per well	Present value profit per well	Total Profit
Sucessful Wells	5	$500,000	$2,500,000	$2,000,000	$1,500,000	$7,500,000
Dry Holes	15	$500,000	$7,500,000	$0	-$500,000	-$7,500,000
Project Profitability			$10,000,000			$0
	Percent Present Value Profit			0.00		

	Evaluation Based on Economic/Uneconomic Success/Failure Criteria					
	No. of Wells	Cost per well	Total Cost	Present value return per well	Present value profit per well	Total Profit
Economic Wells	5	$500,000	$2,500,000	$2,000,000	$1,500,000	$ 7,500,000
Uneconomic Wells	11	$500,000	$5,500,000	$300,000	-$200,000	-$2,200,000
Dry Holes	4	$500,000	$2,000,000	$0	-$500,000	-$2,200,000
Project Profitability			$10,000,000			$ 3,000,000
	Percent Present Value Profit			33.00		