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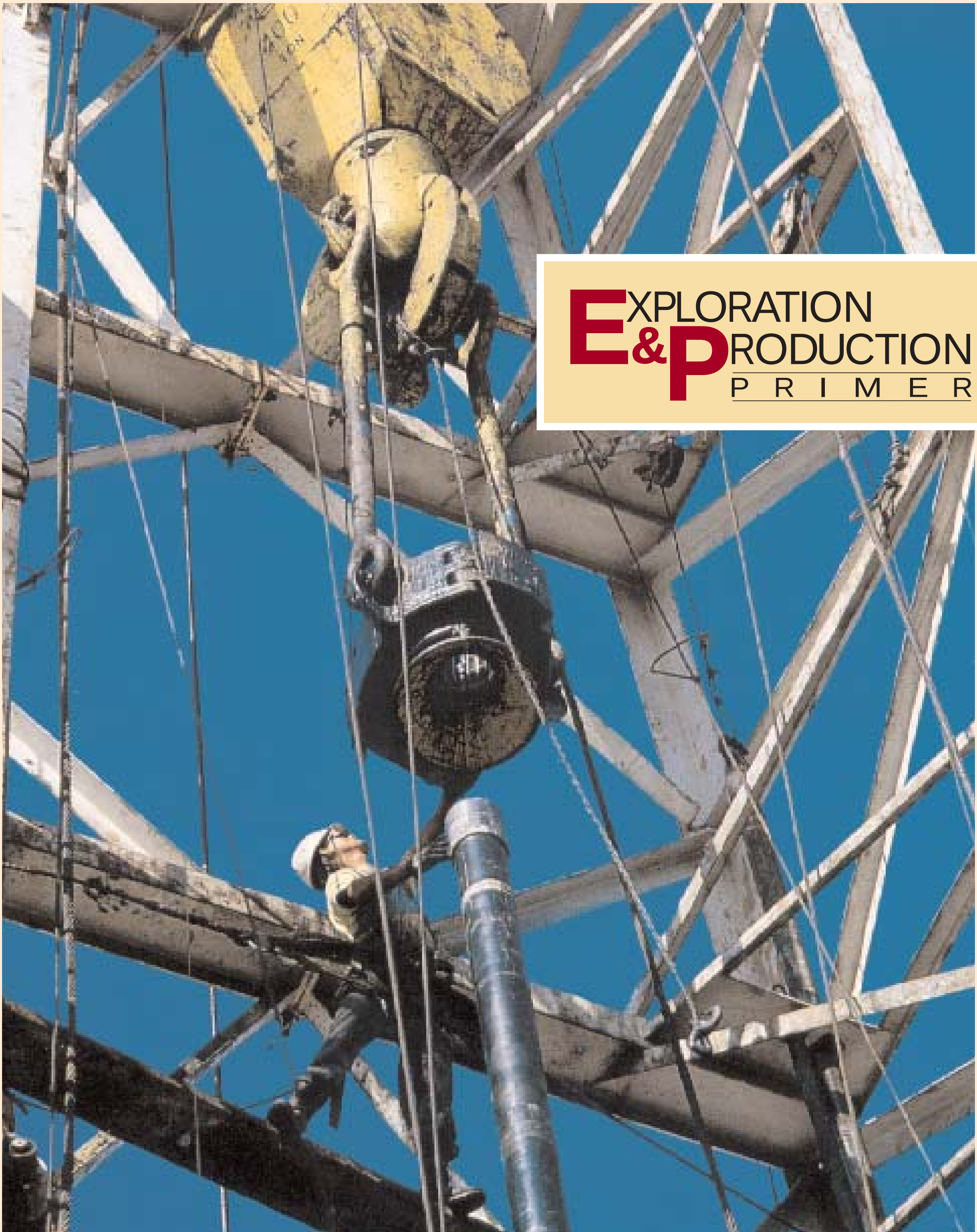
A Supplement to

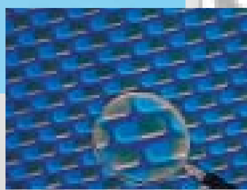
Oil and Gas Investor

A HART ENERGY PUBLICATION

EXPLORATION & PRODUCTION PRIMER



Balloons

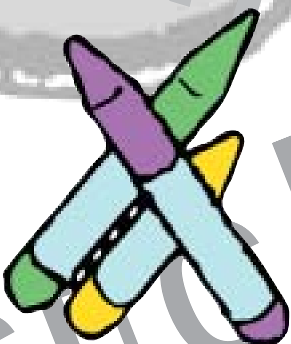


Petrochemicals:
raw material for these everyday products.

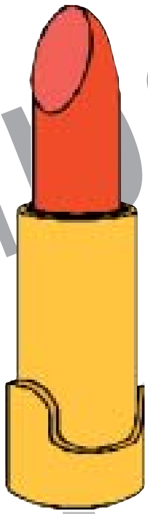
Piano Key

- Food preservatives
- Soft contact lenses
- Antihistamines
- Shampoo
- Hair dryers
- Clothing
- Safety glasses
- Toothpaste
- Blenders
- Luggage
- Life jackets
- Dishes
- Antiseptics
- Vitamin capsules
- Dyes
- Hang gliders
- Patio screens
- Foul weather gear
- House paint
- Insecticides
- Compact disks
- Piano keys
- Perfumes
- Sunglasses
- Cameras
- Tents
- Nylon rope
- Umbrellas
- Footballs
- Glue
- Fertilizers
- Digital clocks
- Photographs
- Balloons
- Slippers
- Wall plugs
- Roofing
- Candles
- Credit cards
- Aspirin
- Shaving cream
- Dentures
- Lipstick
- Crayons
- Ink
- Deodorant
- Pantyhose
- Shower curtains
- Golf balls
- Bandages

Sunglasses



Lipstick



...and thousands more.

Umbrellas

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A Supplement to

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EXPLORATION & PRODUCTION PRIMER

The Impossible Made Simple

When you think about it, it's amazing that oil and gas companies are willing to spend millions of dollars and months of hard work to prepare for, then drill, a well, with no guarantee of success. Imagine a string of drill pipe with a high-tech steerable drill bit at the end, snaking its way through layers of rock to hit a small target 3 miles below the earth's surface. The well may turn out to be a dry hole after all, sending the geologists and geophysicists back to the drawing board—the computer screen or the virtual reality seismic theater—to work up another idea.

Even if the well is a technical success and a strong producer, the price the oil and gas brings may be much less than when management first analyzed the project economics.

Obviously, these oil men and women love their industry and are risk-takers at heart. Over the last decade, they've worked to reduce finding and development costs significantly, reduce (but not eliminate) technical and geologic risk, speed up time to first production, and hedge the commodity price risk as well. Joint ventures, alliances and other special arrangements with partners and vendors complete the picture.

The federal government is getting into the act. Numerous defense labs such as the one at Los Alamos are joining with the industry to develop the next generation of tools and techniques that will help companies find enough oil and gas to power the U.S. economy. Imagine: they are even considering drilling with lasers.

Today, companies can drill directionally beneath a local golf course or school, or in water as deep as 7,000 feet in the Gulf of Mexico. This E&P primer is meant to give you a short course on how and why wells get drilled, and how economics affect every decision.

—Leslie Haines

All photos in "E&P Primer" are by Lowell Georgia, unless otherwise noted.

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In Pursuit of Petroleum

The hunt for oil and natural gas uses tried-and-true principles of petroleum accumulation combined with the latest state-of-the-art tools.

Photography by Lowell Georgia

Back in the earliest days of oil exploration, people looked for petroleum by drilling along creeks, on top of oil seeps, and on surface domes and structures (hills). Most times, luck was more of a factor in their success than skill.

The science of petroleum exploration developed along with the industry. Today, the easy oil and gas has already been found, and the hunt for hydrocarbons is an extremely sophisticated, highly technical effort. Experts say that aside from the government, the oil and gas industry has now become the largest user of computing power in the U.S.

Oil and gas are now sought in many remote locations around the globe, in water as deep as 7,000 feet in the Gulf of Mexico and offshore Brazil, to the deserts of Egypt and Mongolia, to the mountainous terrain of western Canada and Colombia, to the islands of Indonesia, and in the swamps along the coasts of Louisiana and Bohai Bay, China.

Geophone cables are piled in the staging area for a 3-D seismic shoot in Texas.

Nevertheless, the fundamentals of geology remain unchanged. Oil and gas are found in sedimentary rocks, which cover about 75% of the earth's land area. About 700 sedimentary basins dot the world; about half of these have been explored for oil and gas. Limestones, dolomites, sandstones, shales and siltstones are the hunting grounds for the petroleum geologist. It is within these layered rocks that the explorer searches for the four elements necessary for a petroleum accumulation: source, reservoir, trap and seal.

Petroleum source rocks are often thick, black marine shales laid down in ancient seas. As soon as a plant or animal dies, bacteria attack its remains. If oxygen is plentiful, as in soil, the bacteria will consume all the organic matter. But in the very fine-grained muds deposited on the sea floor, oxygen is limited and much of the organic matter escapes destruction. As these muds are buried by successive layers of sediment, the rising heat "cooks" the organic matter, throwing off water, carbon dioxide and hydrocarbons.

Generating crude oil from organic matter in source rocks is a slow process, requiring millions of years. Temperatures must be just perfect—oil can only be formed between 120 degrees Fahrenheit and 350 degrees Fahrenheit, temperatures found at burial depths between 5,000 and 21,000 feet. If the source rocks get any hotter, natural gas and graphite are formed instead.

Reservoir rocks are the hosts for hydrocarbons. Much the opposite of good source rocks, reservoir rocks have porosity and permeability and are deposited in environments of considerable energy. High-energy environments such as waves and currents remove mud particles and most of the organic matter, leaving the pores open. Reservoir-quality sandstones and limestones usually contain very little organic matter; oil and gas migrate into the reservoirs after they have been generated.

The movement of oil and gas from source rocks into reservoirs is called primary migration. Oftentimes, reservoirs are full of oil that has moved just a short distance from surrounding shales. But, huge oil accumulations also exist in areas that are hundreds of miles from the original source rocks.

Once crude oil and natural gas have formed, they continually seek lower pressures, moving through the natural conduits in the earth's layers. If no barriers intercede, the hydrocarbons will eventually seep out on the surface. However, when the oil or gas hits a high area in a reservoir rock, it has encountered a trap.

Traps can be either structural or stratigraphic. Folding or faulting of the rock layers forms a structural trap. Common structural traps include anticlines, domes and horst blocks. Stratigraphic traps form as a result of changes within the rock layers, as when porous rocks such as reefs or river-channel sandstones are surrounded by non-porous rock. Combination traps, with both structural and stratigraphic elements, are also possibilities.

Once in a trap, gas, oil and water separate by density, with the gas rising to the cap position, the oil in the middle and the water occupying the bottom. The boundary between the gas and oil is called the gas-oil contact; the boundary between the oil and water is the oil-water contact.

The final requisite for a petroleum accumulation is an adequate *seal*. Sealing layers are sedimentary rocks with negligible permeability that do not allow the oil and gas to migrate any further upward. Thick salt layers provide excellent seals, as do shales.

The tools of petroleum exploration

Maps have always been the key tools of petroleum exploration. Since the early 1900s, explorers have found many oil and gas fields by drilling domes and anticlines that could be identified from surface mapping. The size, position, dips and strikes of the surface beds are all recorded with instruments such as plane tables and Brunton compasses. Today, the map of an explorer includes this "traditional" information, as well as that gleaned from aerial photographs and satellite pictures.

Early geologists made common use of sample and drilling information from wells. As technology advanced, well *log* data and *core* data added a great deal of knowledge. Today, information from such instruments as formation sampling tools can assist in the evaluation of both rocks and fluids in a wellbore. Among the wireline tools that provide valuable insights into the subsurface are electric, radioactive and acoustic logs, as well as dipmeters, borehole imaging logs and magnetic resonance imaging logs. Data from drillstem tests are also incorporated into a subsurface picture. Even geochemical techniques, which seek to correlate surface measurements of various chemical compounds with the underground occurrence of hydrocarbons, are sometimes called into play.

Geophysicists also bring some tremendous tools to the trade of petroleum exploration. Three common geophysical methods used to look for oil are magnetic, gravity, and seismic exploration. Magnetic methods measure the strength of the Earth's magnetic field at a specific point on the surface, while gravity techniques seek to determine the strength of the Earth's gravity at a location. Both methods are useful in reconnaissance mapping and are usually employed in the early stages of basin evaluation.

A geophysical crew collects data in the transition zone in Plaquemines Parish, Louisiana, using a shot-hole drill custom-mounted on an airboat.

Seismic is the real workhorse of the industry, however. In seismic prospecting, an acoustic source such as dynamite, vibration or sonic impulses from compressed air transmits sound into the ground. As the acoustic signal passes into the subsurface, it is reflected and refracted off the various sedimentary layers. The signals that bounce back to the surface are recorded and

Making the Decision to Drill a Well

1. Acquire seismic, surface and subsurface data (well logs, cores and tests) in area of interest.
2. Generate prospect idea.
3. Acquire leases through purchase or farm-in arrangement.
4. Estimate drilling and completion costs to test prospect.
5. Predict expected volume of reserves, likely production rates and operating costs.
6. Run economic model to determine the rate of return, cash flow and expected value generated by the sale of the oil and gas if the prospect is successful.
7. Assess stratigraphic and structural risks and determine if the expected returns are sufficient to justify the capital expenditures.
8. Apply for federal and/or state drilling permits.
9. Contract drilling rig, mud-logger, cementing and well logging services.
10. Prepare location and move in rig.

Time-lapse seismic

4-D seismic, or time-lapse monitoring, lies beyond 3-D seismic on the experimental edge of oil industry technologies. Real knowledge of fluid movements through the subsurface is the goal of 4-D seismic, which adds the dimension of time to 3-D data.

Potentially, time-lapse seismic can unveil a depth and complexity of information about reservoir fluids that cannot be matched by present approaches. Despite its promise, use of this technology today is still largely confined to field studies.

processed to form a picture of the subsurface.

Much has been made in recent years of the advances in seismic technology. Indeed, 3-D seismic has captured the imaginations of the industry and investors alike. Instead of a two-dimensional slice through the earth's layers, a 3-D survey delivers a complete volume of data that allows the explorer to image the subsurface in fine detail.

Short of drilling a well, 3-D seismic supplies the most reliable subsurface information of any technique. And, this technology is constantly being refined. For offshore areas, breakthroughs like multi-streamer boats and ocean-bottom cables allow less expensive and faster acquisition, as well as data collection in highly congested or difficult areas. Onshore, the use of radio telemetry technology has opened up many marshy and transition zone areas to exploration, without laying seismic cables.

A state-of-the-art seismic vessel collects 3-D data in the deepwater Gulf of Mexico, some 160 miles south of New Orleans. Streamers towed behind the vessel hold the acoustic source and receivers.

Prospect generation: Where shall we drill?

Nonetheless, piles of highly processed 3-D data, satellite images, high-tech well logs and computer-aided mapping programs can't create oil or gas where none exists. The explorer still hunts for some basic clues.

One of the most tried-and-true axioms of petroleum exploration is that the best place to look for oil and gas is near where it's already been found. Working in a known hydrocarbon basin eliminates many of the uncertainties of source, reservoir and seal, and the hunt essentially becomes one for traps.

The first phase of exploration is a search for traps similar to those that are already producing. Explorers are also ever alert for possibilities of new trap types that have not yet been known to produce in an area, such as updip pinchouts of permeability or fault traps.

Oil and gas "shows" in previously drilled wells nearby are of supreme importance, because they are direct indications that a trap exists. Other important clues include changes in the rate of dip, dip reversal or flattening of dip of the rock layers. The location and position of faults is another key. These can indicate an unusual structural condition.

Seismic attributes offer other clues. The amplitudes of seismic signals contain tremendous geological detail, and much current effort is invested in interpreting these subtleties. One seismic signature may show a promising gas-charged sand, another may indicate a tight limestone bed with no commercial potential.

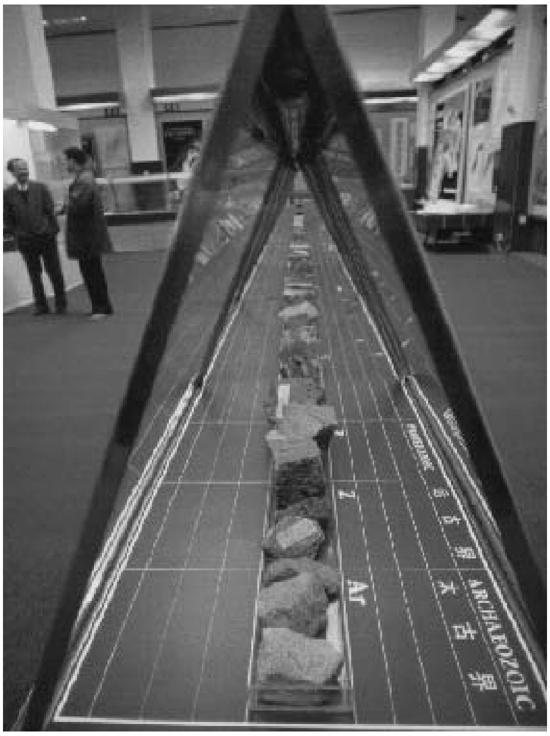
Geologists and geophysicists formerly worked with pencils and paper maps and sections; today they build complex, 3-D interpretations on desktop workstations. Volume visualization is a coming technique, in which interpreters see and manipulate 3-D data as a solid volume rather than as 2-D slices of the subsurface. The fundamentals of prospecting remain unchanged, but phenomenal strides have been made in an individual's ability to view and integrate data from many sources.

The decision to drill

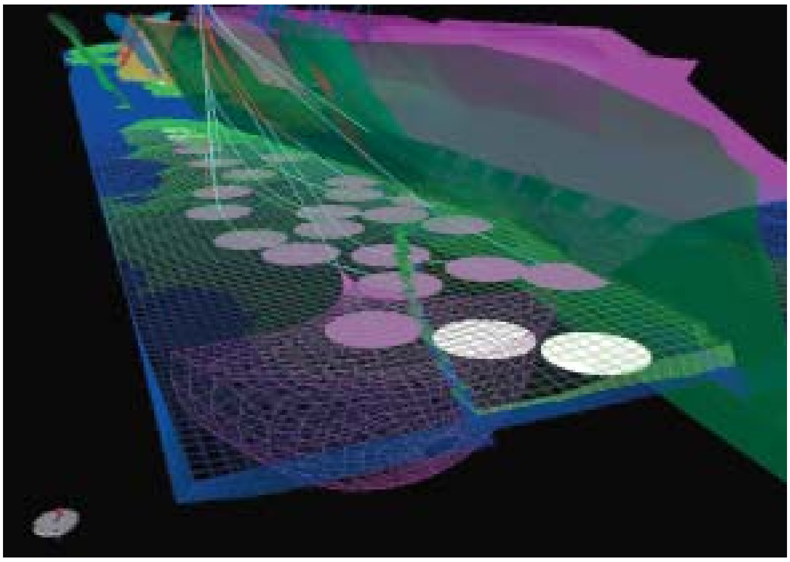
If, after carefully weighing all the data—and being fully aware of its varying degrees of reliability—an explorer still believes that an undrilled trap does exist, a prospect has been born.

The land situation, productive possibilities and expected costs must be figured to mature the idea. Lots of great prospects are never drilled because the company couldn't tie up the acreage through leasing the minerals. Other ideas are discarded because the potential oil and/or gas reserves are judged insufficient in light of the prospect's risks and the drilling expense. Some prospects that were once thought to be viable become impossible and must be deferred or canceled if oil and gas prices fall lower than the original assumptions.

A prospect is a labor of many months or even years. Companies typically have many internal



At left: A display at the Dagang oil field's Museum of Geology features core samples representing geologic strata found in China.



Powerful software tools can automatically generate drilling targets based on reservoir attributes, select site and platform locations and rapidly determine the costs for various development scenarios. Pictured is an example from Landmark Graphics' AssetPlanner software.

screenings to evaluate prospects. They consider the risks of the the geological and geophysical factors; estimate possible reserves and production rates, thus cash flows; and design the drilling and completion programs. Prospects are ranked against other opportunities available to the company, such as drilling in other U.S. basins or other countries, or acquiring reserves or acreage from another company. And, they are reexamined as oil and gas prices, company budgets and capital sources fluctuate.

If the decision to drill is made, federal or state drilling permits are secured and a drilling rig is hired. The abstract idea will finally be

Glossary

Anticline A fold, generally convex upwards, whose core contains stratigraphically older rocks.

Core data A solid column of rock up to 4 inches in diameter is taken from the wellbore so geologists may study the rock formation for clues as to whether oil or gas is present.

Drillstem test A test of the productive capacity of an oil or gas reservoir when the well is uncased. The test is conducted through the drill pipe to see if oil or gas is present in a certain formation; preliminary sampling aids the decision to complete the well and produce from it, or plug and abandon it.

Fault A fracture or fracture zone along which the sides have been displaced relative to one another. A break or fracture in the earth's crust that causes rock layers to shift.

Field An area in which a number of wells produce from a reservoir. There may be several reservoirs at various depths in a single field.

Horst An elongate, uplifted block that is bounded by faults on its long sides.

Hydrocarbon An organic compound consisting of carbon and hydrogen. Hydrocarbons can be gaseous, liquid or solid.

Log (noun or verb) A logging device is lowered into the wellbore by a wireline to gather data and transmit it to the surface, to a logging truck equipped with computerized equipment. A geologist may then interpret the data, often in real time, at the well site. Or, the data may be transmitted by satellite back to the oil company's office for interpretation there. Certain measurement-while-drilling tools can accumulate data as the drill bit drills through the rock formation.

Permeability The capacity of a rock to transmit fluids. A tight rock, sand or formation will have low permeability and thus, low capacity to produce oil or gas, unless the well can be somehow fracture stimulated to increase production. Expressed in millidarcies.

Porosity The volume of small to minute openings in a rock that allow it to hold fluids. Measured in percentages, typically from near zero to about 35%.

Prospect An area that is the potential site of an oil or gas accumulation. A lease or group of leases upon which an operator intends to drill.

Strike The direction taken by a structural surface such as a bedding or fault plane.

Transition zone A shallow, marshy area between solid land and what would be designated as truly offshore, such as is found within three miles of the South Louisiana coast.

Wellbore That part of a well that is below the surface. Hole diameters vary with the type and purpose of wells; a common wellbore diameter is a little less than nine inches.

Overall drilling success rates have improved steadily in the last decade due to better technology, and operators' strategy to drill a higher percentage of lower-risk development wells. Even so, downhole risk can never be eliminated, which is why most companies have industry partners to share the costs and spread the risk in a given well. This is even more true in offshore and international operations where risks and costs are higher.

U.S. Drilling Success Rates Are Climbing

Year	New Field Wildcat	Other Exploratory	Development Wells	All Wells
1989	15.5%	43.6%	81.0%	70.8
1990	17.9	43.5	82.4	73.7
1991	17.2	41.8	82.2	73.8
1992	20.1	44.0	81.5	73.8
1993	21.4	46.4	81.9	74.8
1994	26.3	49.6	83.9	76.1
1995	28.8	45.2	84.0	76.6
1996	27.6	46.8	84.4	77.6
1997	25.4	46.3	85.4	79.5
1998*	27.9	41.4	83.8	77.8
Average	21.8	44.8	83.0	75.3

** 1998 data is through Dec. 25.*
Source: Petroleum Information/Dwights LLC, dba IHS Energy Group

tested with money and with iron. In the end, Mother Nature will have the last word, despite all the high-tech equipment and enormous computing power that are brought to bear.

—-Peggy Williams

Whose Fault Is It?

Often, in spite of computers chock full of seismic data, months or years of study, and countless pre-drill technical reviews by hordes of geoscientists and managers, wells still come up dry. A dry hole can be defined as a well that does not produce oil or gas in commercial quantities.

There are relative degrees of dry holes, or dusters as they are often called. A hole can lack so much as a whiff of oil or gas, with no hydrocarbon shows detected by even the most sensitive gas chromatographs. Or, a well can be a near miss, with not quite enough ability to produce petroleum to make the economic cut. These latter types of dry holes are often revisited in times of high oil and gas prices.

Too, dry holes that were noncommercial years ago can sometimes be re-entered and made into producing wells, thanks to advances in completion technology.

No company drills a well with the certainty that it will yield commercial amounts of oil and gas. The farther one drills from existing production, the greater the unknowns, and the more assumptions are made. Failures stem from many factors:

1. Mechanical problems can force a company to abandon a well. Drillpipe or drilling tools can get stuck in the hole, and sometimes this means the well must be plugged and abandoned.

2. A hydrocarbon-bearing reservoir isn't present in the wellbore—even though it may be a few feet away. Why? Reservoirs can be faulted out by small structural displacements in the subsurface that can't be seen with today's seismic data. And, rocks can also change laterally; for example, a sandstone can grade into a shale interval. Shale doesn't contain oil or gas.

3. Often, wells encounter the reservoirs they were seeking, but the rock is too tight or too thin to produce.

4. Sometimes, wells drilled based on seismic anomalies find conditions that are indeed anomalous, but that do not correlate to a productive reservoir. For instance, an anomaly may look like a gas-charged sandstone on seismic data, but drilling reveals it is actually a thin, tight limestone layer.

5. Dry holes can miss their structural targets, coming in at a lower depth to projections. Many assumptions about the velocity of the rock layers in an area are built into seismic interpretations. In some situations, the conversion of information in seismic data to depth is just an approximation. Until wells are actually drilled and sophisticated downhole tools recover more information, it's hard to be precise.

6. Occasionally, the targeted rock layers occur where they were projected to be, and reservoirs are present, but hydrocarbons have leaked off because the seal wasn't adequate to contain them. Or, trap, reservoir and seal are all found, but oil and gas never migrated into this prospect in the first place.

Drilling, Completion and Production: Always an Economic Decision

Virtually every oilfield decision is founded on profitability. With no control of oil or gas prices, and facing steadily rising costs and declining reserves, all companies must make basic decisions, but based on a constantly moving target.

Photography by Lowell Georgia

Make no mistake, drilling, completing and producing oil and gas wells is an extremely complex business. One might think that the world's unslakable thirst for cheap, abundant energy resources makes profitability a sure thing. Perhaps that was true in John D. Rockefeller's day. But with no control of commodity prices, soaring costs and stiff foreign competition, the U.S. industry has had to turn to technology to preserve even the barest margins.

Oil-rich OPEC held the rest of the world hostage in the 1970s with its infamous oil embargo driving prices up, but it does not control

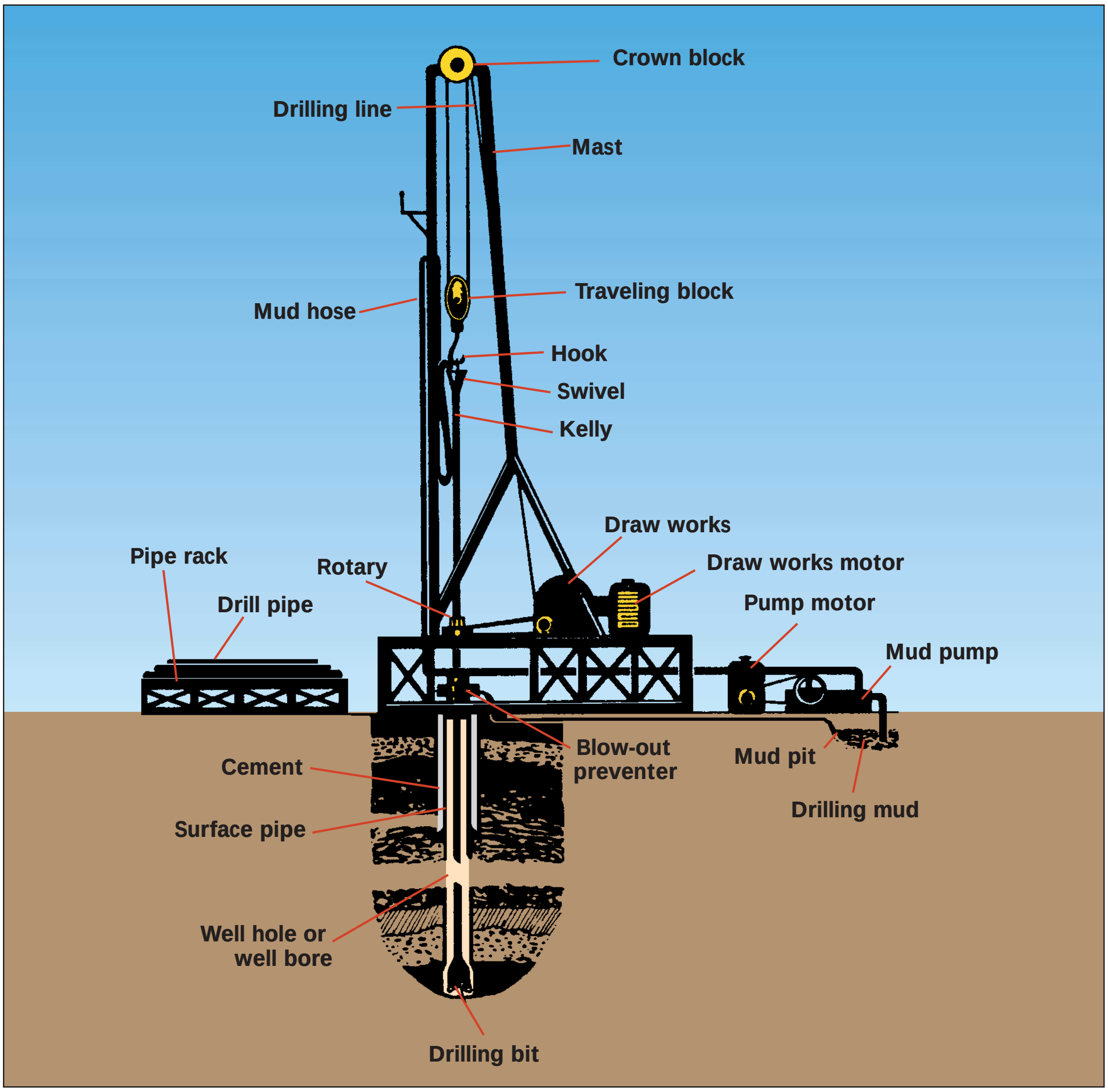
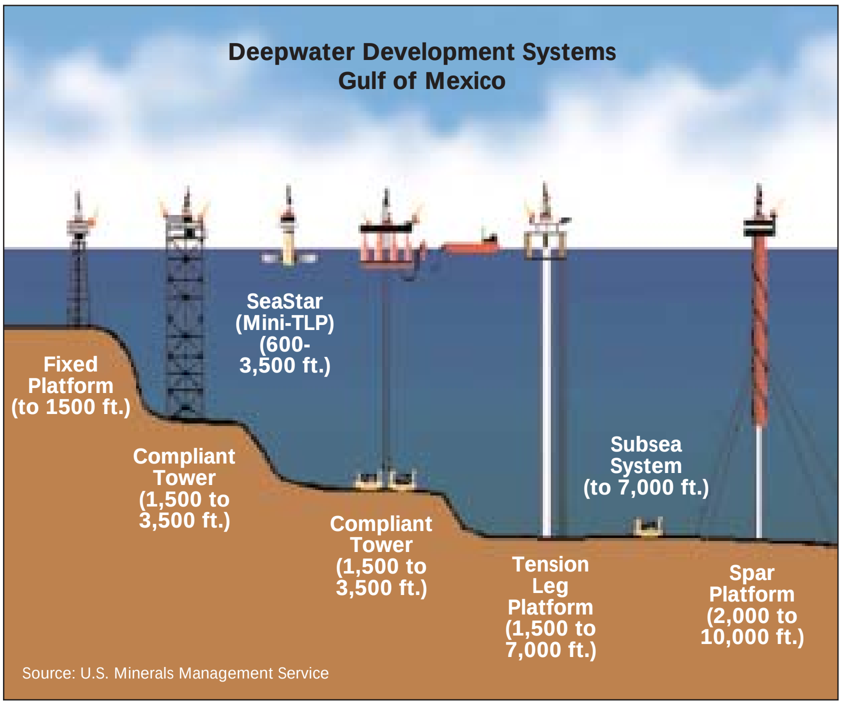


Figure 1: Modern drilling rigs often include automated pipe-handling equipment, computerized controls, thinner pipe (called coiled tubing) and other new equipment to improve efficiency and safety, or speed up time to total depth. Technology enables companies to drill into high-pressure, high temperature zones as deep as 25,000 feet and offshore wells just as deep—in water up to 7,000 feet deep.

Development systems produce oil and gas from wells. They enter the picture after rigs drill the wells and they are completed. Offshore, costs dictate that entire fields be produced from as few facilities as possible. One platform may serve 20 or more wells, for example. In the Gulf of Mexico, a variety of development systems are used, depending on water depth. The spur system can be used in ultra-deepwater.



the market any more. In today's environment, companies develop business strategies for several different price scenarios, taking into account the cost of capital and regulatory compliance.

Then they go about attempting to control the two things they can influence—their exploration success ratio and their drilling and production costs. This is where technology comes in. To use an analogy, the development and use of oilfield technology closely parallels the conquest of space. From the early days of the Wright brothers, the technology of flight has increased exponentially—the same is true for exploration and production of oil and gas.

For example, until the 1980s only one in 10 exploratory wells—called wildcats—were successful, that is, contained economically recoverable hydrocarbons. Today, thanks to improved technology, about 25% to 40% of rank wildcats are successful, and in some states, the success ratio for development wells is much higher. In the Appalachian Basin, many companies report drilling success ratios of 80% or 90% when drilling development wells to develop a field after the initial wildcat "comes in."

Drilling the well

With a few notable exceptions, the basic technique of drilling a well has not changed much. Based on data from surface exploration techniques such as 2-D and 3-D seismic, geologists and geophysicists decide on suitable acreage for drilling. Companies then secure a lease from the landowner, or from the appropriate authority in the case of federal or state land or offshore leases.

They contract a drilling rig. Contrary to popular opinion, oil companies do not have their own rigs, relying instead on an experienced cadre of drilling contractors who supply the equipment and workers to drill the well for a specific day rate. A typical rig with basic components identified is shown in Figure 1.

Modern rigs have banks of diesel-driven generators to provide the electrical power that lights the rig and drives the drill. The drilling function can be simplified by grouping it into two systems: the hoisting/rotating system and the circulating system. The former consists of the familiar derrick with its bright yellow block and cable hoist that trips the drill pipe into and out of the hole and supports its massive weight during drilling.

Rotating is accomplished by a rotary drive traditionally located on the drill floor, but more recently located atop the drill string—the so-called top drive. Top drives are a perfect example of how technology has improved safety and efficiency by reducing the number of times the drilling activity must pause to add a joint of pipe by a factor of three.

The circulating system pumps heavy drilling fluid down the drill pipe to cool and lubricate the bit, float rock cuttings to the surface, and control well pressures. Drilling fluid—commonly called mud—is really a high-tech formula containing chemicals that interact with the rock formations to ease drilling and protect the borehole wall. The high pressure imposed by the heavy column of mud balances formation pressures and prevents influx of well fluids or gas into the borehole.

This prevents the catastrophe known as a blow-out and is usually sufficient, but for added safety, each rig has a stack of valves just beneath the drill floor or on the sea bed called blow-out preventers (BOPs) that can be closed to seal the well in an emergency. Drilling mud containing rock cuttings circulates back up the outside of the drill pipe to the surface where it is filtered, de-gassed and recirculated.

Reducing drilling costs

The most notable applications of technology to reduce drilling costs have been in the areas of automated pipe-handling, improved drilling rates and geosteering, whereby real-time geological data are used to steer the bit into the target reservoir that one hopes contains oil or gas, and keep it there.

As much as 40% of non-drilling time is spent handling pipe. Now computer-driven machines are taking over this time-consuming and dangerous job. Drilling rates are facilitated by new bit designs and by the use of underbalanced drilling, whereby the well is allowed to flow under controlled conditions while it is being drilled.

New instrumented bits allow dozens of critical measurements of formation and drilling parameters to be acquired and transmitted in real time to the surface. This improves drilling efficiency and accuracy.

Finally, years of painstaking research have yielded environmentally friendly drilling and completion fluids as well as closed circulation systems, and most offshore locations follow a zero-discharge policy, meaning absolutely no well or rig effluent is put into the sea.

Some things never change, however. Drilling

Today, real-time downhole log and test data can be sent back to headquarters via satellite, for faster decision-making.

Glossary

Blowout An uncontrolled accidental release of well pressure, either to the surface or to another formation (called an underground blowout).

Blowout preventer (BOP) A series of valves, which offshore can be as high as 50 feet, to control the well and prevent a blowout.

Casing Steel pipe used to protect the wellbore from caving in. When casing is cemented in place, it forms a hydraulic seal with the rock formations, preventing well fluid from migrating up or down the outside of the casing. It also keeps the well fluids separate from ground water sources adjacent to the wellbore.

Circulation Analogous to the human circulatory system, mud is pumped into the well from a reservoir called a mud pit. It circulates down the inside of the drill pipe, flows out through ports in the bit and circulates back to the surface up the outside of the drill pipe, where it is filtered, degassed and returned to the pit.

Fishing Slang for retrieving pipe, tools, cable or objects that have dropped into the well.

Fracturing (Frac job) If the target reservoir lacks sufficient porosity or permeability to produce on its own in commercial quantities, this stimulation technique can improve the flow. Enormous pressure is applied to the reservoir by pumping in massive amounts of fluid (water or oil) to enlarge the channels between pores in the rock.

Kick An unplanned influx of formation fluid into the wellbore, caused by the unexpected presence of hydrocarbons.

Lost circulation Leak-off of mud into a subsurface formation or through a hole in the well casing. Can be stopped by circulating plugging material similar to radiator stop-leak used in automobiles.

Mud Fluid of water and chemicals that occupies the borehole during drilling or completion of a well. Its main task is to exert hydrostatic pressure on the reservoir to balance the natural formation pressure and prevent an accidental influx of formation fluid into the borehole. It prevents the sides of the well from caving in as the hole is cut. And, it transports the rock cuttings from the bottom of the hole to the surface, where the geologist can examine them for clues as to the type of rock being penetrated.

Packer A mechanical seal between tubing and casing, usually set just above the producing formation.

Perforating A downhole perforating gun, lowered by wireline, fires shaped charges through the casing into the desired rock formation, resulting in perforations through which reservoir fluids may flow into the wellbore and up to the surface.

Plug & Abandon When a well is economically depleted, a permanent plug is set to seal the bottom of the well, as much casing as possible is recovered, and the surface location is restored to its original condition. The well is abandoned and a report is filed with the governing authority.

Seismic exploration Sound waves are pulsed into the earth. They reflect off subsurface layers and the reflected waves are processed to create a subsurface image of the earth from which promising rock formations can be identified for potential drilling.

Spudding The act of beginning to drill a borehole, usually starting with driving a piece of large diameter pipe (casing) into the ground (or seabed) to guide the bit and protect the surface immediately surrounding the borehole.

Trip The act of removing the drill pipe from the borehole (to put on a fresh drill bit, for example) and/or reinserting the pipe into the hole. Each phase has a name: tripping-out, tripping-in or round-tripping. This function is usually done manually by roughnecks, or it can be done by automatic pipehandling equipment.

Tubing High-pressure pipe runs inside the casing through which the oil or gas is produced.

Wildcat An exploratory borehole drilled in virgin territory, usually at least a mile or two away from the nearest production of oil or gas. A rank wildcat is a well drilled many miles away from nearest production and is inherently more exploratory in nature, and thus more risky. On the other hand, the rank wildcat may tap into a virgin subsurface zone that has high pressure and offers much greater daily oil or gas production.

Workover An oilfield term meaning "overhaul." Periodically, wells must be worked over to address cleaning, wear and corrosion of the downhole equipment, or pressure issues. Special light-duty rigs called workover rigs perform this task at a fraction of the cost of a drilling rig.

The array of equipment needed to carry out a frac job is impressive. In addition to a vast network of pipe at the surface, there is a fleet of pumping trucks, truck-mounted blenders, sand containers and fracture fluid tanks and other support vehicles. Massive amounts of fluid are pumped into the well to crack the rock and improve flow.

is still a demanding, 24-hour-a-day job that must be accomplished safely and efficiently in all kinds of weather in some of the world's most inhospitable locations.

Testing the well

Since the beginning, oil companies have tried to evaluate their wells to answer these basic questions: Is there oil (or gas)? How much? Can it be produced technically, and economically? How fast? For how long? Should we complete this well, or abandon it now before spending any additional time and money? Where should the next well be drilled?

The answers to these questions are fundamental to every economic decision that must be made over the life of the well or reservoir. Formation evaluation technology has kept pace with drilling technology with new sophisticated well logs, cores and well tests. Periodically during drilling, the drill pipe and bit are removed, i.e., "tripped" out of the hole, so electronic instruments can be introduced into the well on a electrical cable called a wireline. The measurements made by these instruments are plotted on a chart called a log. Alternatively, some logging data can be acquired while drilling as noted earlier. Logs are used to determine the location and thicknesses of hydrocarbon-bearing strata and indicate their orientation in geospace.

Cores, once the only sure way to determine formation mineralogy and physical characteristics, are formation samples cut and recovered from the rock. Cores are now being challenged by sophisticated high-resolution log images to accurately describe formation texture, porosity and permeability.

Well tests help determine reservoir volumetrics as well as pressure and flow rate of the well once it is placed on production.

Information is the key. Now computer databases are constructed from the outset, increasing reservoir knowledge with compatibly scaled data as each measurement is taken. This knowledge base facilitates decision-making and reduces risk. Virtually every decision is prefaced by a cost-benefit analysis that projects its economic effect.

Today, real-time downhole test data can be transmitted via satellite from the field back to a company's headquarters—even in another country—so that scientists, engineers and managers at home base can evaluate the well and make the proper decisions.

Completing the well

As the well reaches its completion phase, decisions become easier because discounted cash-flow models can be used to compare the incremental benefit of each expenditure with the out-of-pocket cost. The immediate effect of technology improvements can be felt as the well is cased and casing is cemented in place to achieve hydraulic isolation of producing formations. New expandable casing technology has been proposed to reduce the cost of casing the well, and improved cements provide a higher margin of safety at less cost.

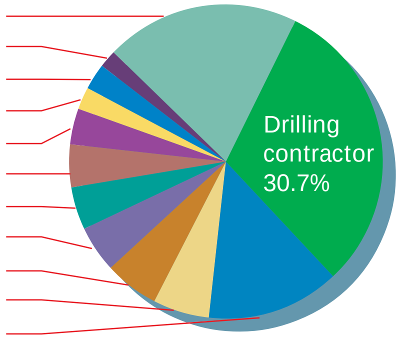
New, deep-penetrating perforating guns fire explosive charges downhole, piercing the casing of the wellbore, the cement and the rock itself to provide flow paths for the hydrocarbons to enter the well and flow to the surface.

Finally, a string of production tubing and a packer is run downhole to provide a high-pres-

Costs to Drill & Equip a Well

Purchased items:

Miscellaneous	20.0%
Wellhead equipment	1.8%
Special tool rentals	2.7%
Drill bits	2.3%
Logs & wireline testing	3.7%
Formation treating	4.4%
Road & site preparation	4.4%
Cementing	4.8%
Supervision/overhead	5.6%
Drilling mud/additives	5.8%
Pipe (casing & tubing)	13.7%



Source: Independent Petroleum Association of America

The drilling rig, the largest single cost of drilling a well, is paid for by the day or by the footage drilled. That's followed by drill pipe and tubular goods.

3 Examples of How Technology Affects Economics

As oil companies apply new or improved technology and best practices, and learn more about a particular play by drilling more wells, they are often able to reduce either the time it takes to drill and complete a well, or reduce the costs, or both. This can help them offset any commodity price weakness they may experience during the time they are developing a field.

Their goal is not just to produce oil or gas, thereby increasing a company's proved reserves, or increasing its immediate cash flow from production. Savvy companies also try to achieve an adequate return on capital employed. A company is essentially standing still if it spends $1 to achieve $1 of income.

Even if technology fosters improvements that are less than dramatic, that still matters. Here are three real-life examples from early 1999:

In Colorado's Denver-Julesburg Basin, northeast of Denver, operators are deepening existing wellbores that yield from the Codell formation, to get new gas production from the so-called J Sand, a zone that is about 500 feet deeper. A grassroots well drilled to the J Sand costs about $330,000. Deepening an existing well to that depth is cheaper, and used to cost $250,00 to $270,000, including fracture stimulation.

Today, operators have brought that cost down to $200,000 per well. What's more, drilling times have been cut from about 30 hours per well to about eight, creating significant savings and making the play more economic. The wells produce an average 600 million to 800 million cubic feet of gas over their productive lives.

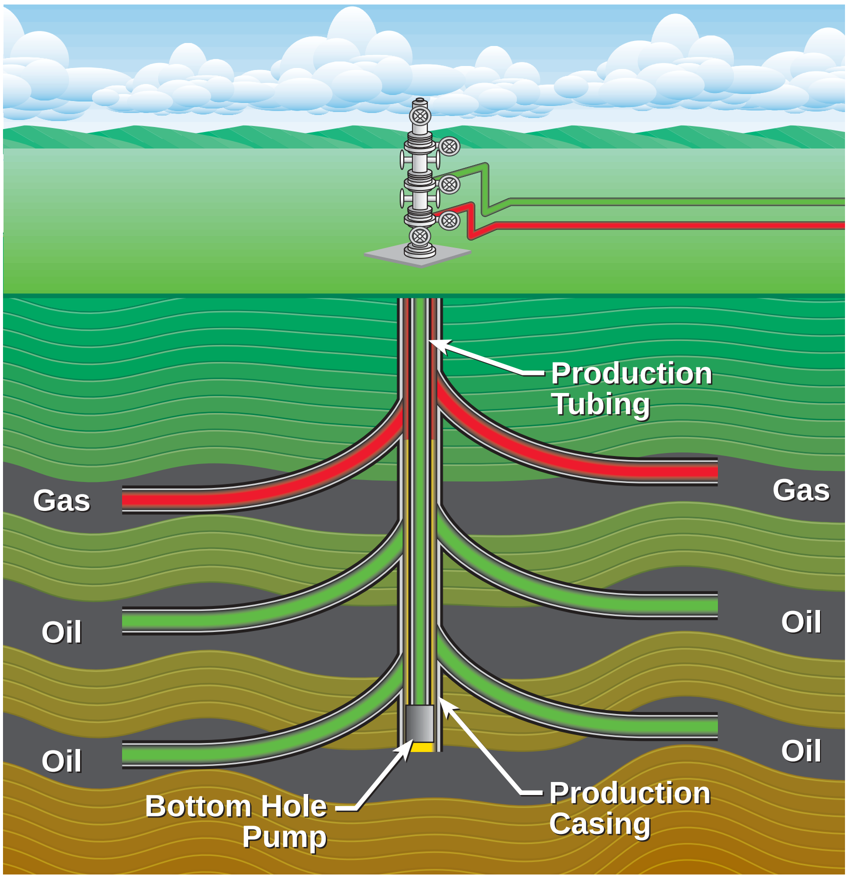
In Alaska, the economic threshold for field development on the North Slope used to be 250 million barrels of recoverable oil, a fairly large size field, due to high drilling, production and transportation costs. However, thanks to improved technologies and practices, producers are now able to produce ever-smaller fields, called satellite fields, often using tie-backs to existing surface facilities nearby.

Arco chief executive officer Mike Bowlin said at a Houston conference in February 1999 that the industry has now managed to reduce the size of an economically viable field there from 250 million barrels to 50 million. This has opened up development of reservoirs previously thought not worth the expense, and increases the amount of domestic oil available to consumers.

At Wytch Farm, along the southern coast of England, BP Amoco is applying technology to produce extremely deep offshore wells that are drilled directionally from land. These wells have reached a total depth of 31,355 feet: a vertical depth of 5,887 feet and a horizontal departure from the wellbore of another 29,324 feet—that's almost six miles of subsurface drill pipe that needs to be controlled and kept in the target producing reservoir!

Through process changes, technology, teamwork and advanced planning with the service and equipment vendors, BP Amoco was able to reduce the time it takes to drill such a long horizontal well by 40%, drilling and completing the well in a record-breaking 81 days. Measurement-while-drilling and logging-while-drilling tools were used.

From the late 1980s on, as technology and computerization advanced, the number of horizontal wells increased dramatically. Operators also drilled many more multilaterals—wells with more than one drainhole (branch) drilled off the primary wellbore (the trunk). The trunk and branches can now be horizontal, vertical or deviated (angled), and drilled onshore or offshore. These wells may cost more than traditional verticals, but they usually allow an operator to recover more oil. Multilateral completions extend a field's life span by allowing access to additional reservoir layers without drilling additional wells. These wells are only effective in certain formations, however.



sure conduit for production and the well is topped by a system of valves called a "Christmas Tree." Often the drilling rig is released once casing is set, and completion is accomplished with a smaller, less expensive unit.

Well stimulation

Regardless of the quantity of hydrocarbons present, oil and gas wells do not always behave as we would wish them to. Some require extensive, and expensive, treatments before they will produce economically. Sometimes the subsurface formation must be washed with acid to clean out clay or other materials that are clogging the pores and impairing flow.

In formations with low permeability such as limestones, hydraulic fracturing is used to crack the rock and create a greater area of flow between the wellbore and formation pores. Conversely, in unconsolidated sandstones, screens must be emplaced in the well to keep sand grains from flowing into the well bore, clogging it and eroding the tubulars. Each treatment can be accurately costed, and justified in advance using cash flow modeling based on incremental added production.

Where natural reservoir pressure is lacking, wells will not flow to the surface and must be assisted by pumps or artificial lift systems. Lifting costs can be considerable, and must be figured along with finding and development costs. In the United States, average lifting costs are about equal to average finding/development costs, making many wells uneconomical.

Complicating things is unwanted water production. More often than not, water is co-produced along with the oil or gas. Not only does each barrel of water produced mean one less barrel of oil, but the water must be safely disposed of—it is usually salty and of no value for drinking or irrigation. Typically the water is pumped into a nearby injection well, or it is trucked away from the surface location, to be safely disposed of elsewhere, according to local or state regulations. New technology allows oil and water to be separated downhole and the unwanted water is reinjected into a nearby nonproductive formation—never reaching the surface.

Workovers

Throughout the life of the individual well and reservoir, periodic interventions are made to acquire production data and perform overhauls, called workovers. Slim logging tools can pass through the production tubing and make flow measurements, or permanent gauges can be emplaced in the production string to monitor production and allow remedial steps to be taken to optimize flow.

As long as they can be economically justified, elaborate enhanced production schemes can be launched to improve the ultimate recovery factor—total percentage of recoverable oil—which can reach as much as 70% in some cases.

Enhanced Oil Recovery (EOR) methods include water flooding, where water is pumped into injection wells drilled around the flanks of the reservoir with the objective of forcing more oil out the central, producing well. Other floods include steam flooding or CO_2 injection used to melt or dissolve viscous oil deposits and improve their flow characteristics. Even more exotic methods involve fire flooding, in which a downhole fire is started to melt heavy oil, or injection of microbes, that eat the polymers that are binding the oil in place. Each of these schemes has a cost/benefit analysis done before it is attempted.

Even under the best of scenarios, a well may only produce 10% to 20% of the oil in place over its lifetime, absent stimulation.

Offshore

Offshore, costs dictate that entire fields be produced from as few facilities as possible. This is especially true in deep waters or in harsh environments such as the North Sea. Tall jacket platforms sit on the ocean floor and serve as production facilities for 20 or more wells. The wells all come together at the surface, but branch out in all directions underground to tap the farthest reaches of the reservoir.

In harsh environments huge gravity-base structures combine the roles of supporting the production facilities and serving as storage tanks for the crude oil. Recently, tension-leg platforms and spars have been introduced. These are floating platforms tethered to the ocean floor, but free to move about with wind and current. They can often be economically relocated and re-used for other fields when the original field is depleted.

With deepwater discoveries, an entirely new technology has made production economical. Floating, Production, Storage and Offloading (FPSO) vessels are converted tankers with production and processing equipment on deck. These receive oil from flexible risers connected to gathering stations and subsea wellheads located on the sea floor.

They process the crude and store it until offloaded by a shuttle tanker. In highly developed areas such as the Gulf of Mexico, FPSOs may not be as economical as running a subsea pipeline several miles from the wellhead to connect to a fixed platform in shallower waters. Subsea connectors as long as 68 miles are in use today in the Gulf of Mexico.

Current challenges

In the United States, producers face stiff challenges. More than half of our oil now comes from "stripper" wells—wells producing 10 barrels of oil per day or less. If oil fetches $11 or $12 per barrel at the wellhead, then most of these wells are uneconomical, once finding and lifting costs and taxes are factored in. However, if a well is abandoned, it might never be brought back on production. So, oil companies—most of them small independent operators—are faced with a real dilemma. They can try to hang on and hope for higher prices, they can invest in expensive cost-cutting schemes with little hope of a quick recovery, or they can shut-in their wells.

Compounding the problem is the intensification of natural decline rates from existing wells. Over time, whether it takes four years or 30 years, every well will produce less and less, until it is no longer economically viable.

U.S. reserves are being depleted faster than ever before. More discoveries are needed and more technology is required to improve existing productivity. These cost money that is not forthcoming at today's prices. Americans are going to be asked in the not-too-distant future if they are willing to accept importing as much as 75% of their oil from overseas. What national security and economic risks does this imply?

—Dick Ghiselin

Photograph by Larry Lee

The extra-large pumping unit pumps oil out of a field discovered in 1928 near Fresno, California.

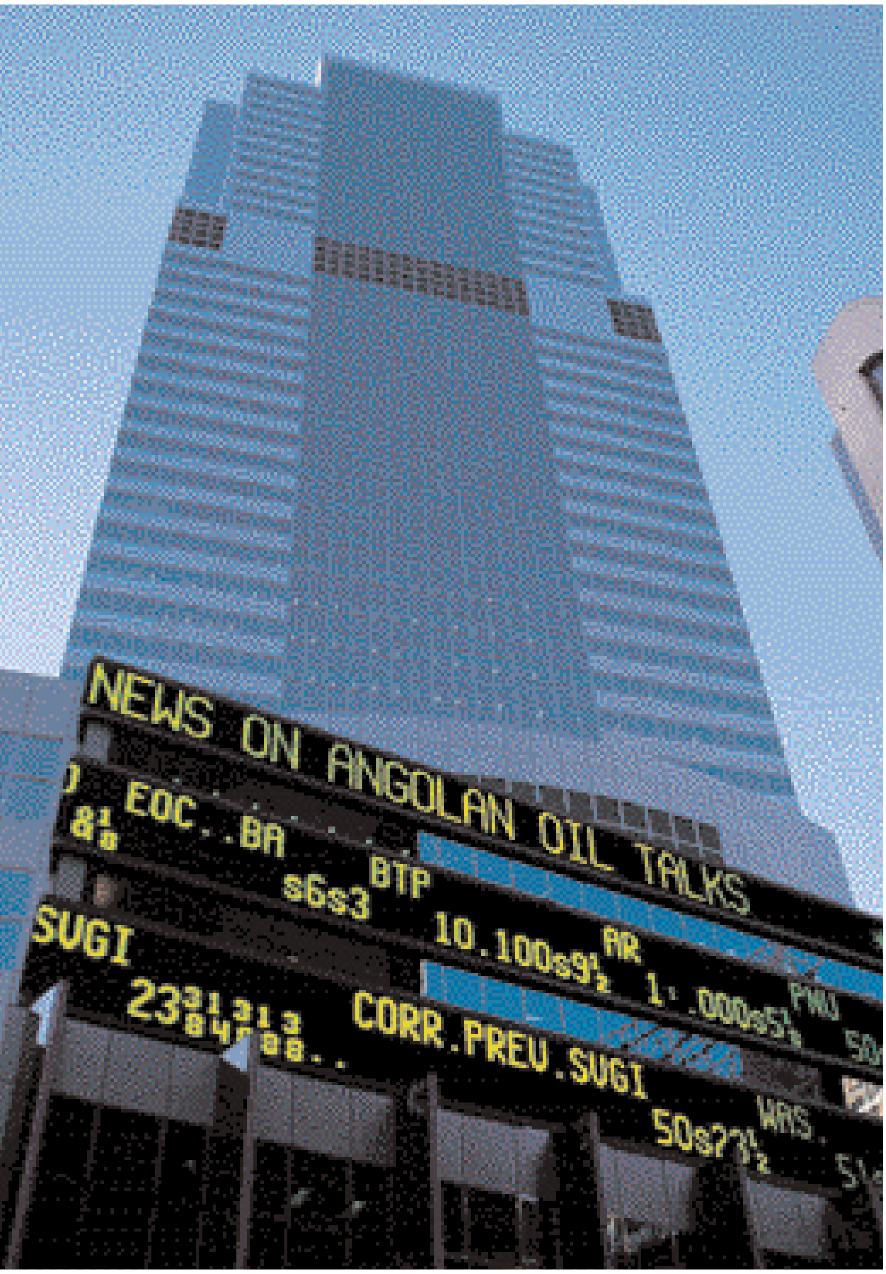
Roughnecks prepare to put a section of pipe down a new well underway in the 90-year-old Lawrence Field in Illinois.

Who Sets Oil and Gas Prices?

Once the well begins flowing or pumping in commercial quantities, the real fun begins.

Photography by Lowell Georgia

Sad but true for oil and gas producers, but commodity prices are rarely, if ever, set at the wellhead. Just as farmers don't control the price of wheat, cotton or cattle, energy producers also are price-takers, not price-makers. They operate at the mercy of a host of unpredictable domestic, international, economic and political factors beyond their control. Even the weather affects oil and gas prices. No wonder cash flows can vary greatly.



Studies show that of all commodities—wheat, sugar, orange juice, pork bellies, platinum, copper, gold, whatever—oil, gas and electricity are the most volatile of all. Their daily prices on the New York Mercantile Exchange (Nymex) change more often, and to a greater degree, than other commodities do. This in turn affects the price buyers at the wellhead will pay. Producers can mitigate this volatility, in part, by price risk management on the Nymex (commonly called hedging), or by selling forward a portion of their production at an agreed price.

Over time, the correlation between Nymex crude oil prices and the cash or spot price for West Texas Intermediate crude (the U.S. benchmark crude traded on Nymex) has proved to be very tight. In 1997, for example, the two prices differed by a penny or more per barrel only 29 days, so there is little doubt that Nymex now sets the price.

That price is formed by a complex set of factors, not the least of which are perceptions of traders and speculators. As the old joke goes, when traders from Long Island emerge from the subway, Manhattan's weather sets the tone for that day's trading. More seriously, analysts note the affect on Nymex of speculative hedge funds and others who can move the price based on their own perceptions. When oil can swing by as much as $1.50 per barrel in one day, that's not only world supply and demand affecting the price, it's someone's perception, fear or greed.

Who trades on Nymex? Oil companies, refiners, end users such as airlines and manufacturers, and oil and gas marketers involved directly in the industry, who understand the fundamentals, typically hold about 60% to 70% of the crude contracts on any given day. The rest are held by speculators, hedge funds and Wall Street investment houses, and by the odd-lot holders of a small number of contracts.

Each day they react to weather conditions, global and national news events, and weekly and monthly reports from various agencies. Some of the most closely watched data on international supply, demand and storage come from three sources: the International Energy Agency (IEA) in Paris; the American Petro-

No.2 heating oil began trading on Nymex in 1978, crude oil futures in 1983, natural gas in 1990, and electricity in 1996. Instantaneous price transparency and computerized communication affect the worldwide price each day and in overnight trading as well.

The vast majority of oil and gas traded on Nymex are never delivered anywhere. Instead, the trade is closed, or liquidated, by assuming an equal and opposite position in the market. What's left over is the paper profit or loss. Oil that is delivered must be delivered at Cushing, Oklahoma, where many major oil pipelines intersect and there are more than 21 million barrels of storage. Gas must be delivered at the Henry Hub, a gas pipeline intersection near Erath, Louisiana.

Typical daily Nymex oil trading volume exceeds the equivalent of 100 million barrels of oil, more than the total that are physically produced each day—about 75 million barrels—the world's largest commodity.

Factors Affecting Oil and Gas Prices

Going Up

From the Demand Side:

The global or U.S. economy improves, or turns out to be more robust than forecast, boosting the need for oil used in transportation, oil or gas in manufacturing and petrochemicals, or other.

A colder winter than normal hikes demand in Canada, U.S, Europe, Russia, Japan.

A hotter summer than normal boosts air conditioning demand.

From the Supply Side:

Global oil production or the amount in storage is lower than forecast, lagging demand growth. The "guesstimates" were wrong.

Unexpected and/or temporary production shortfalls occur due to bad weather, labor strikes in the North Sea, problem wells, disappointing drilling results, project delays in bringing new production to market, pipeline restraints, or civil unrest in producing areas such as Nigeria or Colombia.

The global or U.S. rig count falls unexpectedly, or by more than forecast, leading eventually to reduced available supply.

Refinery shutins due to emergency or routine maintenance.

Geopolitics:

OPEC meetings and informal OPEC pronouncements spook oil markets and traders.

War in the Middle East or elsewhere causes major supply disruptions.

Guerillas sabotage oil or gas pipelines or other production facilities.

State or federal regulation, legislation or tax changes make drilling and production more economic, thus boosting activity.

Going Down

From the Demand Side:

A slowdown in overseas or U.S. economies reduces demand for oil or refined products (diesel fuel, jet fuel, kerosene, etc.) or natural gas.

A warmer winter than usual reduces the need for heating oil or gas.

From the Supply Side:

Global oil production or U.S. gas output turns out to be higher than forecast, or higher than demand, creating a supply glut.

The amount of oil or gas in storage keeps rising, outpacing demand and creating a glut that takes time to be absorbed by the market.

Unexpected production increases occur due to more drilling, or more successes per well drilled because of technology advances. Or, more companies enter the industry and start drilling.

As oil prices rise, unaccounted-for inventories surface, curtailing the price rise.

Geopolitics:

OPEC meetings or pronouncements spook oil markets and traders.

State or federal regulations, legislation or tax changes suddenly make drilling and production less attractive.

leum Institute, a Washington, D.C., trade group; and the U.S. Department of Energy's Energy Information Administration (EIA).

Recently, some experts have begun to question the accuracy of this data. Indeed, in March 1999, the EIA admitted it had underestimated U.S. demand and overestimated U.S. output for 1998, and revised its figures. Meanwhile, Congress has asked the Office of Management and Budget to investigate how the Paris-based IEA comes up with its international production data.

As the world produces about 75 million barrels per day, and the U.S. produces about 21 trillion cubic feet of gas per year, it is difficult to monitor and measure specific production and demand numbers. It is also difficult to track barrels or cubic feet that are in storage owned by governments and individual companies, and barrels that are in transport on the high seas.

In the end, all this leads back to the wellhead in the field, where wholesale oil and gas buyers and brokers post the price they will pay each day. Typically they arrange to buy for a 30-day period, as negotiated with the producer. Increasingly, these spot cash prices are tied to the closing price recorded on Nymex a day or two earlier.

—Leslie Haines

Crude à la Carte

They call it black gold, but it isn't always black and the amount of gold it puts in a producer's pocket varies greatly. In addition to global and national supply, demand and storage trends, Nymex prices, and the cost of transporting oil from wellhead to refinery gate, the physical attributes of the crude itself matter, too.

These attributes include the oil's viscosity, gravity (density as compared to water), and its sulphur, water and salt content. Crude gravity and volume vary with temperature.

Gravity refers to the density of the crude, expressed in a scale originated by the American Petroleum Institute. In the scale, water has a gravity of 10 degrees API. Liquids lighter than water (most crudes) typically have gravities numerically greater than 10, up to about 40. Hydrocarbons greater than 40˚ gravity may be condensates.

Some crudes, such as those found in parts of Oklahoma, Alberta and British Columbia, flow freely from the wellhead without pumps, and are so light in color and viscosity, they resemble white wine. They are almost ready to use in a combustion engine. These crudes command top dollar.

Other crudes, such as some found in Nevada, California and Venezuela's Orinoco Basin, are so black, heavy and putty-like, they cannot be poured once they reach the surface. Water, gas, steam, CO_2, nitrogen, polymers or other chemicals must be injected into the well first, to get the oil to the surface and through the pipeline. These crudes command less money per barrel since they require more sophisticated and costly refining processes.

Lighter oils lend themselves to refining or manufacture of higher-priced products such as gasoline, jet fuel and kerosene. Heavier oils are refined into lower-priced products such as bunker fuel and asphalt.

Every producer receives a different price for crude depending on its physical qualities and distance from the pipeline. Photo by Nick DeSciose

Posted prices as of Jan. 1, 1999*

	$/Barrel
West Texas Intermediate	11.25
Oklahoma Sweet	11.25
Southern Louisiana Light	11.00
Wyoming Sweet	10.75
Gulf Coast Sweet	10.50
West Texas Sour	10.25
East Texas Flat	9.30
Alaska North Slope/27˚	8.77
California Lost Hills	8.70
North Dakota Sweet	8.30
Michigan Sour	7.50
California Kern River Heavy/13˚	7.00

*40˚ gravity unless shown otherwise

Sources: Marathon Oil, *Oil & Gas Journal*, *Platt's Oilgram*

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