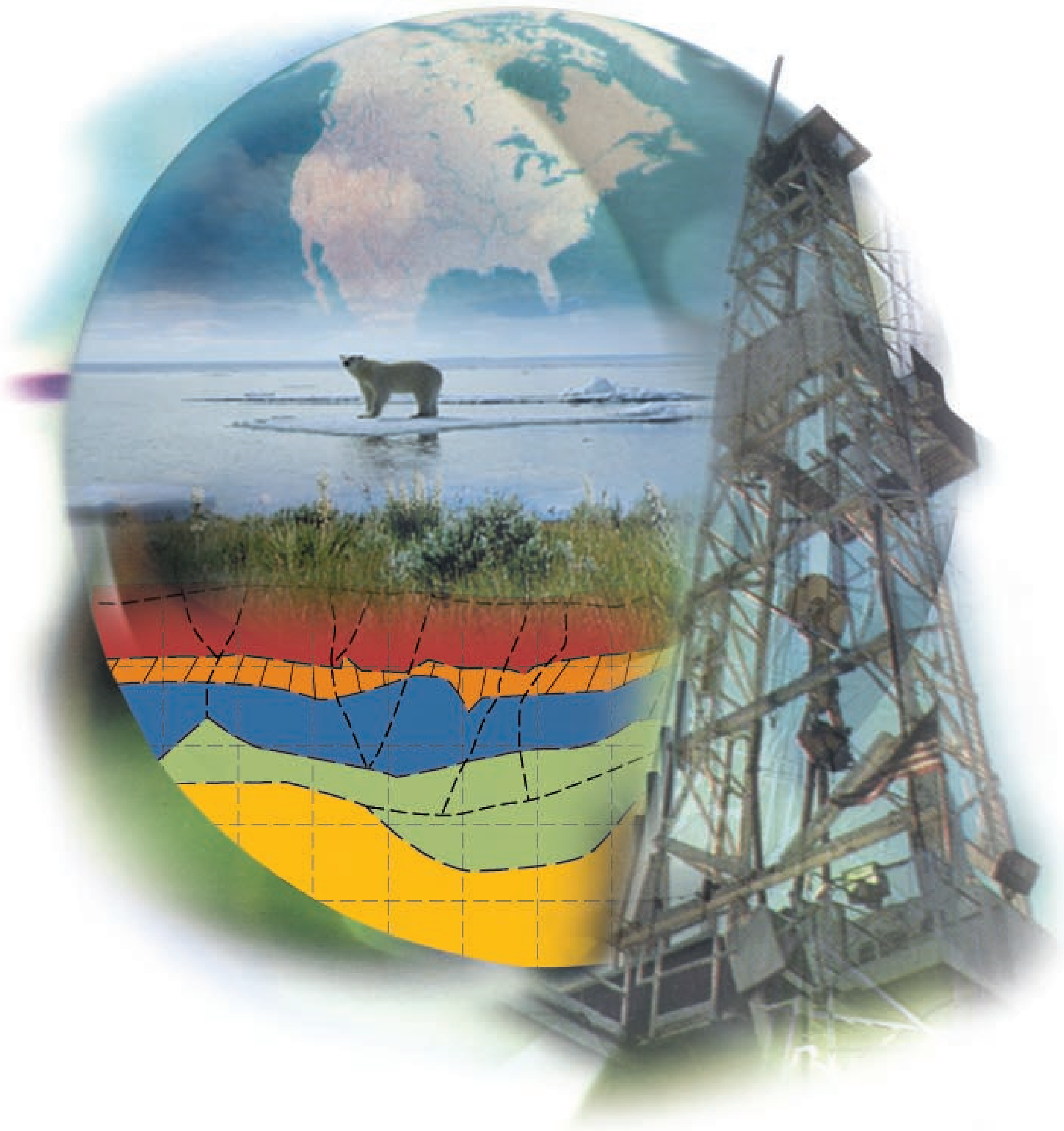
U.S. Department *of* Energy
Office *of* Fossil Energy



Environmental Benefits *of* Advanced Oil *and* Gas Exploration *and* Production Technology

Introduction

THROUGHOUT THE OIL AND GAS LIFE CYCLE, THE INDUSTRY HAS APPLIED AN ARRAY OF ADVANCED TECHNOLOGIES TO IMPROVE EFFICIENCY, PRODUCTIVITY, AND ENVIRONMENTAL PERFORMANCE. THIS REPORT FOCUSES SPECIFICALLY ON ADVANCES IN EXPLORATION AND PRODUCTION (E&P) OPERATIONS (SHOWN IN COLOR BELOW).

From fossil resources to products, the entire oil and gas life cycle typically spans 7 to 10 years. Development of more challenging resource areas, however, such as the Outer Continental Shelf, can take up to 20 years.

Fossil Resources → Exploration | Drilling and Completion | Production

Operations in Sensitive Environments

Contents

Oil and gas resources are organic, formed by the effects of heat and pressure on sediments trapped beneath the earth's surface over millions of years. While ancient societies made some use of these resources, the modern petroleum age began less than a century and a half ago. Advances in technology have steadily improved our ability to find and extract oil and gas, and to convert them to efficient fuels and useful consumer products.

A WORD FROM THE OFFICE OF NATURAL GAS AND PETROLEUM TECHNOLOGY

SITE RESTORATION | TRANSPORTATION | REFINING AND PRODUCTION | PRODUCTS | POWER GENERATION

IN THE PAST THREE DECADES, the petroleum business has transformed itself into a high-technology industry. Dramatic advances in technology for exploration, drilling and completion, production, and site restoration have enabled the industry to keep up with the ever-increasing demand for reliable supplies of oil and natural gas at reasonable prices. The productivity gains and cost reductions attributable to these advances have been widely described and broadly recognized. But public awareness of the significant and impressive environmental benefits from new exploration and production (E&P) technology advances remains limited. • THE U.S. DEPARTMENT OF ENERGY is responsible for achieving national objectives in the fields of energy and the environment. We believe it is important to tell this remarkable story of environmental progress in E&P technology. Greater awareness of the industry's achievements in environmental protection will provide the context for effective policy, and for informed decision making by both the private and public sectors. • LOOKING FORWARD, the domestic oil and gas industry will be challenged to continue extending the frontiers of technology. Ongoing advances in E&P productivity are essential if producers are to keep pace with steadily growing demand for oil and gas, both in the United States and worldwide. Continuing innovation will also be needed to sustain the industry's leadership in the intensely competitive international arena, and to retain high-paying oil and gas industry jobs at home. Progressively cleaner, less intrusive, and more efficient technology will be instrumental in enhancing environmental protection in the future. • OUR NATION has come to expect the benefits of fossil-based fuels and products and a clean environment. The oil and gas industry has consistently responded to provide both. The Department of Energy looks forward to increased dialogue with the oil and gas industry and other stakeholders. With commitment to a shared vision, with collaboration, and with continued private and public investments, the oil and gas industry can continue to deliver essential energy resources and protect the environment, for ourselves and for the generations to come.

The U.S. oil and gas industry employs 1.4 million people and generates about 4 percent of U.S. economic activity. It is larger than the domestic auto industry and larger than education and social services, the computer industry, and the steel industry combined. The exploration and production sector alone employed nearly 326,000 people in 1998.

Photo: © SPE, 1993

Executive Summary

Oil and Natural Gas Are Critical to the U.S. Economy

Oil and natural gas account for virtually all transportation fuel in the United States and a majority of our total energy use, and provide the raw materials for countless products used in our daily lives. Americans have come to take these resources and products largely for granted and expect them to be available and affordable.

For over a century, the oil and gas industry has successfully met rising demand for these valuable resources.

Continuous innovation has characterized the oil and gas industry throughout its history. In recent decades, new technologies have been key to finding and extracting recoverable oil and gas resources—located in deeper and more remote locations, in more challenging geologic formations, in difficult terrain, in smaller pockets, under sensitive wetlands and tundra, and far out at sea. As the world's most mature oil and gas province—and home of some of the world's most rigorous environmental standards—the United States has been the site of much of the industry's innovation in exploration and production (E&P) technology.

American ingenuity, know-how, and entrepreneurial spirit have created the necessary technology to maintain reliable oil and gas supplies in a volatile marketplace.

Technology innovation has enabled the domestic industry to remain viable in an energy business where highly competitive global markets determine prices. The industry has developed more efficient E&P technology to enable continued exploration, development, and production through the boom and bust cycles that are characteristic of world oil markets.

Nowhere have the dual requirements of producing more challenging resources and protecting the environment been as pressing as in the United States.

Hand-in-hand with overcoming tough geologic and geographic conditions, the industry has also developed new technology and management techniques for enhanced protection of our environment.

While increasing productivity, technology innovation has also yielded environmental benefits.

Today's exploration technology, for example, is boosting industry success rates in pinpointing new resources. The results: fewer dry holes, reduced waste volumes, and less environmental disruption. Across the E&P spectrum, new technology is delivering:

- *More efficient recovery of oil and gas resources.* Continuing improvements in recovery efficiency per well translate into fewer wells (and less impact from drilling operations) to achieve the same level of reserves.
- *Smaller footprints.* Smaller, lighter rigs and advances in directional and extended-reach drilling shrink the footprint of oil and gas operations and reduce surface disturbance.
- *Cleaner, safer operations.* Advanced, more energy-efficient drilling and production methods cut emissions of air pollutants and greenhouse gases, practically eliminate spills from offshore platforms, and translate into enhanced worker safety, lower risk of blowouts, and better protection of groundwater resources.

Environmental Protection is Good Business

THE U.S. OIL AND GAS INDUSTRY has integrated an environmental ethic into its business culture and operations. The industry has come to recognize that high environmental standards and responsible development are good business, and it is demonstrating its commitment to protecting the environment in research and technology investments, policies and practices, and participation in a host of voluntary environmental protection programs. Industry's use of smarter, more efficient technology complements these trends.

Advanced E&P technology provides environmental benefits beyond the oil and gas industry.

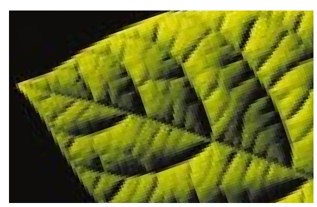
Innovations pioneered by the oil and gas industry are now being used in a wide range of applications. Geologic and geophysical technology are providing information on the fundamental characteristics of the earth's crust, enabling better prediction and evaluation of earthquakes and other geologic hazards. Reservoir simulation and performance-monitoring technology are being used to predict groundwater flow patterns. And the same principles used to increase the recovery of oil—such as thermal and microbial processes—are now applied to clean up chemical spills.

Continued technology progress will be essential in meeting the challenges of the 21st century.

Further increases in productivity will be essential to sustain the viability of the U.S. petroleum industry in the face of a sometimes volatile world oil market. Industry and government leadership and American ingenuity will be necessary to preserve our Nation's oil and gas production capacity and energy security. In the longer term, technology innovation will be critical to ensure optimal recovery of America's oil and gas resources, while respecting the environment and other public values. Technology innovation will be key to overcoming the constraints of an increasingly challenging resource base, domestically and around the world.

Industry and government both have roles in advancing E&P technology progress and environmental performance.

Environmental quality will be a continuing issue for the oil and gas industry. America's oil and gas industry must find the means, including new technology, to address future environmental challenges, such as global climate change. Industry must continue to demonstrate its commitment to responsible development. Government must provide a rational regulatory framework and reasonable access to resources. Open communication is also critical to meeting these objectives. Continued investment, both private and public, will be required to advance E&P science and technology.



America's legacy of technology progress and improved environmental management in E&P provides a solid foundation for meeting the challenges of the future.

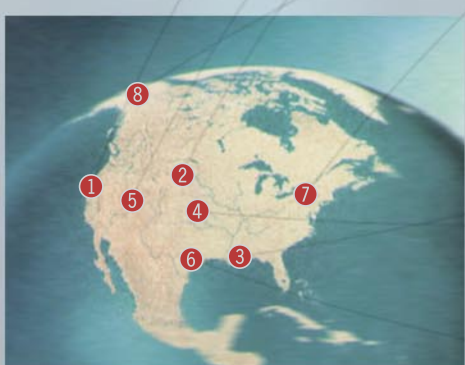
INNOVATION IN OIL AND GAS E&P TECHNOLOGY:

MAKING A DIFFERENCE TO THE ENVIRONMENT

Right Where We Live and Around the Globe

FROM COAST TO COAST, INNOVATIVE E&P approaches are making a difference to the environment. With advanced technologies, the oil and gas industry can pinpoint resources more accurately, extract them more efficiently and with less surface disturbance, minimize associated wastes, and, ultimately, restore sites to original or better condition. Most of these advances have been pioneered in the United States, but many are now also providing benefits around the globe.

Increasingly, in our own backyards and in all corners of the earth, innovation is the key to producing oil and gas while protecting neighborhoods and natural habitats. Here are just a few examples of the contributions being made by new technology.



WEST COAST

California

- ARCO Long Beach, Inc.'s production operations in Long Beach Harbor represent a model approach to operating in sensitive urban environments. To shield the harbor's operations from the public, drilling rigs are disguised as high-rise buildings, and other above-ground facilities have been masked with palm trees, concrete sculptures, waterfalls, and colorful night-lighting. Advanced horizontal drilling and hydraulic fracturing technology, combined with the largest waterflood in California's history, have increased production by approximately 30 percent in recent years.
- In the southern California town of La Habra, the area's rolling hills, once the site of oil production from the West Coyote field, are now covered with premium homes, thanks to painstaking site restoration upon the field's closure.
- Thermal enhanced oil recovery technology is increasing production rates and ultimate recovery from the mature, "heavy" oil fields of Kern County, California, and surrounding areas. For example, decades-old steam floods are facilitating production at some of the Nation's largest, most mature fields, including Midway-Sunset, South Belridge, and Kern River.

■ Major areas of oil and gas potential

NORTHERN PLAINS

Montana, North Dakota, South Dakota

- Advanced horizontal drilling and measurement-while-drilling technology are enabling recovery of previously untapped resources in the Williston Basin's Red River B Formation, spread across Montana and the Dakotas. In 1994, horizontal drilling technology facilitated the discovery of the Cedar Hills play, the Nation's largest onshore discovery in the last 25 years.

GULF OF MEXICO AND GULF COAST

Texas, Louisiana, Mississippi, Alabama, Florida

- New subsalt imaging technologies, aided by today's super-powered computers and advanced mathematical modeling concepts, are enabling operators to get a clearer picture of the Gulf's hydrocarbon-rich subsalt play, facilitating exploration success and greater resource recovery.

- Advanced offshore platforms—tension leg platforms; mini-TLPs; spars; and floating production, storage, and offloading systems—and subsea completions are equipping offshore operators to explore and produce in deeper, more remote, and harsher environments. These advances enable increased access to deepwater resources, while minimizing disruptions to ocean ecosystems.
- State-operated artificial reef programs turn decommissioned offshore platforms into permanent reef structures, creating complex and vibrant subsea “living communities” and also enhancing commercial and recreational fishing opportunities.
- Synthetic drilling fluids are fast becoming the drilling fluid of choice for many complex deepwater drilling operations. Combining the advanced operational properties of oil-based muds with the environmental benefits of water-based drilling fluids, synthetic fluids enable operators to drill faster and cheaper, with less overall environmental impacts.

ROCKY MOUNTAINS

Wyoming, Colorado, New Mexico

- In the gas-rich San Juan Basin, advanced coalbed methane production and completion technologies—such as nitrogen injection and CO_2 flooding—are unlocking clean-burning methane from coal seams, substantially increasing our domestic gas supply.
- Smarter operations in the Rockies enable successful exploration and production while protecting an environment marked by rugged mountains, sensitive Federal lands, and fragile habitats. For example, in Wyoming’s Bridger-Teton National Forest, drilling operations were conducted using a helicopter to transport the drilling rig and other heavy equipment, minimizing environmental impacts.

APPALACHIA

Pennsylvania and Kentucky

- Field trials in central Pennsylvania and the Devonian Shales of Kentucky indicate that innovative CO_2-sand fracturing technology can significantly increase gas production in certain types of wells and reservoirs, while reducing waste volumes and formation damage.
- In Pennsylvania, “roadspreading” brine produced from oil and gas wells has proven to be an effective dust suppressor and road stabilizer on unpaved secondary roads. This beneficial use of an oilfield waste reduces the volume of wastes that would otherwise need to be disposed of by oil and gas operators.

MID-CONTINENT

Nebraska, Kansas, Oklahoma

- Visitors to Oklahoma City’s Will Rogers World Airport are greeted with the sight of pumpjacks and other production equipment and facilities—the airport is located in the heart of an active oil field.
- Funded exclusively through voluntary contributions by Oklahoma’s oil and gas producers and royalty owners, the Oklahoma Energy Resources Board (OERB) restores orphaned and abandoned well sites around the State. By removing abandoned oilfield tanks and other equipment and remediating saltwater erosion and oil-stained soil, OERB is returning land to productive use, at no cost to landowners.

TEXAS

- Advances in horizontal and multilateral drilling have been critical to increasing production in the mature, highly fractured Austin Chalk play in southeast Texas. In the Clay NE field, for example, horizontal drilling has increased gas production fourfold since 1991. The Chalk has been the site of 90 percent of U.S. horizontal land rigs since the late 1980s.
- Since the early 1970s, the Permian Basin region of west Texas and southeast New Mexico has been home to innovative miscible CO_2-injection enhanced oil recovery projects. The largest and oldest of these projects, the SACROC Unit in Scurry, Texas, is a fieldwide project over nearly 50,000 acres that began over 25 years ago.

ALASKA

- Ice roads and ice pads have significantly reduced the impacts of exploratory drilling operations on the North Slope, protecting the area’s fragile tundra and ecosystem.
- Extended-reach, horizontal, multilateral, and “designer” directional drilling technology has enabled North Slope operators to tap more resources, while minimizing drilling footprints and avoiding sensitive habitats.
- In the past 30 years, production footprints have shrunk dramatically. Production pads have been reduced by up to 80 percent, and wellhead surface spacing has been reduced by over 75 percent. If built today, the Prudhoe Bay oilfield’s footprint would be 64 percent smaller.

Our Quality of Life Relies

The lifestyle U.S. citizens enjoy, the envy of much of the world, was built in large measure on reliable, affordable oil and natural gas supplies. Over the past century, these valuable resources have been instrumental in transforming America's economy from agrarian to industrial to high-technology, steadily improving our standard of living. • Energy remains the lifeblood of our economy, powering our factories and communities, heating and cooling our homes, and moving people and goods. We rely on oil and gas to supply two-thirds of our energy needs. Fuels derived from oil and gas provide virtually 100 percent of our transportation demand, and an ever-increasing proportion of our electricity.

Exploration

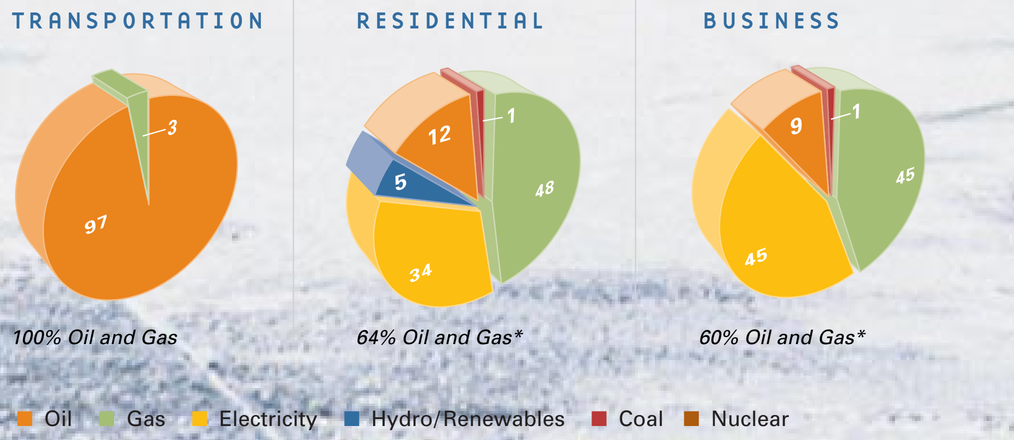
Drilling and Completion

Production

Site Restoration

Operations in Sensitive Environments

The U.S. Runs on Oil and Gas



*Electricity share is prorated.
Source: Energy Information Administration

Life on Oil and Gas

FUELS, PLASTICS, POWER ...AND MUCH MORE

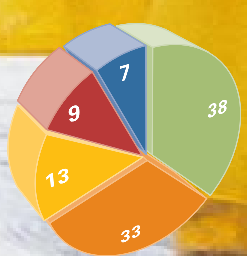
Americans depend on the benefits of oil and gas without always being aware of the vital role these resources play in their daily lives. The use of petroleum-based products extends far beyond fuels and power for our homes, cars, and factories. The strength, durability, and flexibility of petroleum-based plastics, resins, and foams make them an inexpensive, resilient, and lightweight alternative to non-petroleum materials such as wood, iron, and steel.

Petroleum products touch our lives hundreds of times in a typical day. When we wake to a digital clock, brush our teeth, take a vitamin, see our kids off for school in their vinyl raincoats, and commute to work… When we work on computers, use our credit cards, play golf, and fertilize the garden… When we cook dinner, touch up paint on the shutters, and tuck the kids into bed in their flame-retardant pajamas. In all of these activities, we rely on products derived from petroleum.

Photo: Walt Seng

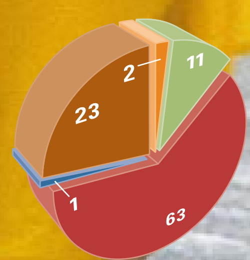
In thousands of products — as diverse as food preservatives, clothing, toys, sports equipment, antiseptics, and computers — we rely on petroleum-based materials.

INDUSTRY



*72% Oil and Gas**

ELECTRICITY



13% Oil and Gas

Demand for Natural Gas and Oil Continues to Grow

Providing Abundant Supplies at Reasonable Prices

Even as industry, government, and academia conduct research and development on alternative sources of energy, reliance on oil and natural gas for fuels, electric power, and other products will continue into the foreseeable future. With the potential of technology to affordably meet almost any need, American consumers demand the convenience and benefits of gas- and petroleum-based fuels in abundant quantities, at reasonable prices, and with minimal environmental impact.

The U.S. Energy Information Administration (EIA) projects that U.S. demand for refined petroleum products will grow by over 35 percent in the next two decades, increasing from 18.0 million barrels per day in 1996 to 24.6 million barrels per day by 2020. Natural gas demand is expected to rise even faster, by at least 45 percent, from 22 trillion cubic feet (Tcf) per year in 1996 to between 32 and 37 Tcf in 2020. Actual rates of growth will depend on the effects of ongoing electric utility restructuring, more stringent air emission controls, advances in transportation technology and infrastructure, and efforts to minimize the potential impacts of global climate change.

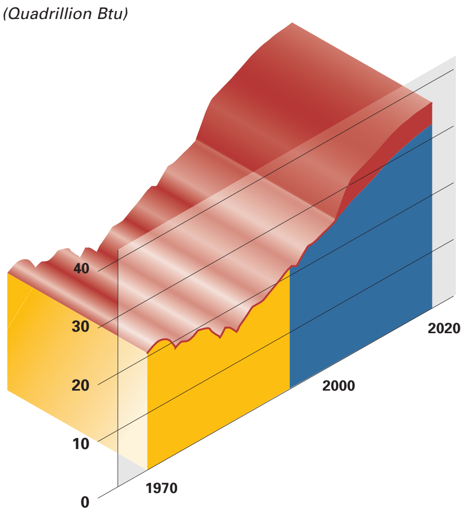
Natural Gas... the Cleaner Choice

As concerns about greenhouse gas emissions and global climate change have intensified, cleaner-burning natural gas has become the fuel of choice. Though coal and oil will remain the dominant fossil fuels for decades to come, natural gas will certainly play an increasing role in the Nation's energy future. Whether discovered and produced in isolation or in association with crude oil production, natural gas has always been an economical and popular fuel for heating, lighting, and cooking.

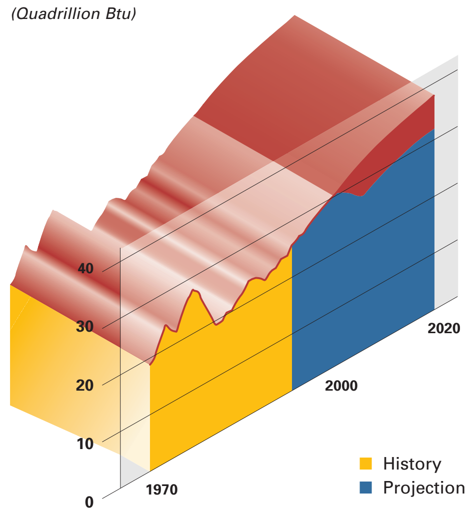
Unlike oil and refined liquids, however, natural gas must be transported by pipeline. Until recently, where pipelines were not technically or economically feasible, wells where only gas was discovered were frequently plugged and abandoned.

Fortunately, in recognition of its environmental desirability, natural gas use has grown. Major advances in natural gas technology and supply have occurred over the past 25 years. New technology for finding, producing, transporting, storing, and using natural gas has been developed. Increasingly higher estimates of economically producible natural gas resources have improved the market's confidence in the reliability of long-term supplies.

Projections of U.S. Natural Gas Consumption, 1970–2020
(Quadrillion Btu)

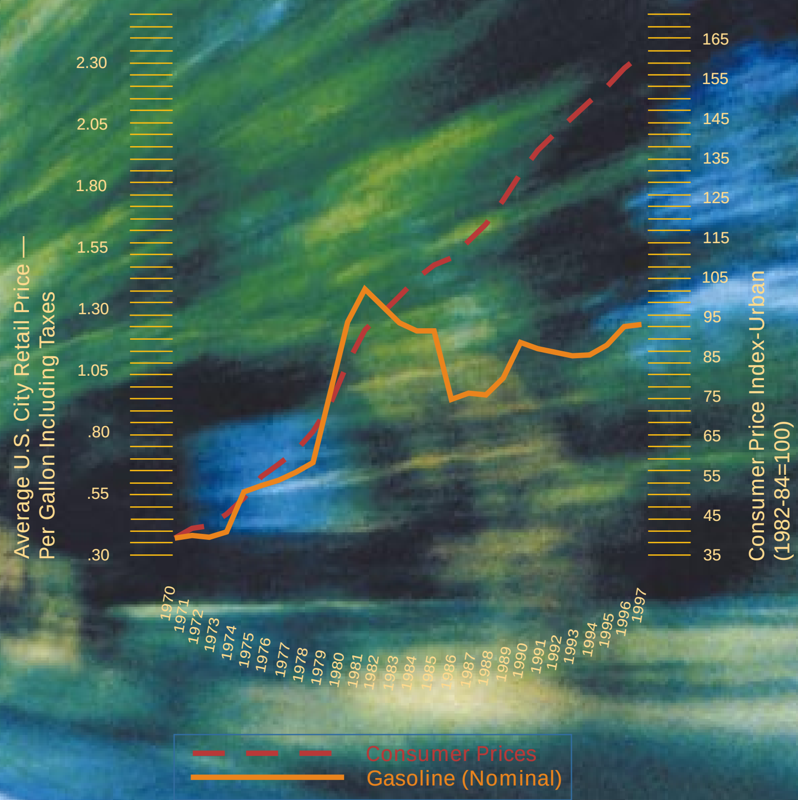


Projections of U.S. Petroleum Consumption, 1970–2020
(Quadrillion Btu)



Source: Energy Information Administration, 1998

Motor Gasoline Prices vs. General Consumer Prices: 1970-1997



Source: American Petroleum Institute and Bureau of Labor Statistics

Fueling a Mobile Society

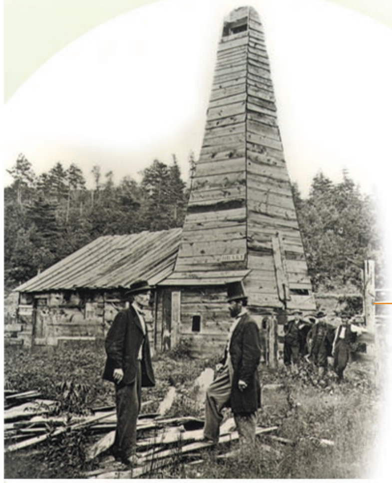
A quarter of a century after the 1973 Arab Oil Embargo, when Americans waited in lines for gasoline, crude oil and refined products (in real terms) are relatively inexpensive. In fact, gasoline prices declined by 6 percent in real terms between 1970 and 1997.

An "unscientific comparison pricing" survey released in April 1998 demonstrates just how great a bargain petroleum-based fuels are compared to other widely used consumer products. The survey—by Connecticut-based research firm John S. Herold Inc.—found that a barrel of crude oil ($15.25) or gasoline ($45.36) is significantly cheaper than Coca Cola® ($78.38), milk ($126.00), Evian® water ($189.80), or orange juice ($251.16). Visine® topped the list at $238,133 per barrel.

Source: Oil and Gas Investor, June 1998

A History of

Throughout its history, the oil and gas industry has been shaped by the vision and initiative of technologists. Today's innovators and entrepreneurs can be found in service companies, engineering and consulting firms, small independent producers, multinational integrated oil and gas companies, government, and academia. They are responding to current challenges with the same driving focus on opportunity that characterized the industry's earliest days.



The petroleum industry has progressed from Colonel Drake's shallow 1859 well to satellite and computer-guided technology operating miles above and below the earth's surface.

Photo: Pennsylvania Historical & Museum Commission, Drake Well Museum Collection, Titusville, Pennsylvania

A New Generation of Pioneers for a New Millennium

From the moment that the first U.S. oil well was drilled in 1859, the progress of the oil and gas industry has been a chronicle of technological advancement. In the early "oil boom" decades, explorers joined forces with entrepreneurs, engineers, and skilled craft workers to invent a dynamic industry. Through experimentation, hard work, and simple necessity, these pioneers rapidly developed the fundamental tools and systems for finding, extracting, transporting, and processing oil. As the industry matured, its scientists and technologists led the way in improving our understanding of earth sciences, geology, geophysics, and chemistry.

Now, another wave of technological innovation is transforming the oil and gas industry. The focus this time is on finding economically viable ways to continue discovering and producing oil and gas from an increasingly challenging and more remote U.S. resource base. Without new solutions to extend their productive life, more U.S. oil and gas fields will have to be abandoned. Complex environmental protection standards add to the costs and challenges. The industry seeks ways to cost-effectively meet Federal and State requirements, and to produce from sensitive environments in wetlands, in coastal and offshore waters, or under the frozen tundra of Alaska.

More resource-efficient and less intrusive E&P approaches are key to meeting these challenges. This report highlights the dramatic progress of the past two decades in enhancing the power, productivity, safety, and environmental performance of oil and gas technology. It is a record of achievement that would have seemed a fantasy to the wildcatters in the industry's early days.

INNOVATION

Milestones

- **1859** Drake well dug by hand
- **'70** First cable tool rig
- **'90** Rotary drilling developed
- **1933** First whipstock for directional drilling
- **'35** First tri-cone bit
- **'39** First horizontal well drilled (Havener Run field in Morgan County, OH)
- **'47** First offshore directional wells drilled (Gulf of Mexico)
- **'53** First truly multilateral well drilled
- **'54** First hydraulic rotary rig
  - First directional drilling assembly
- **'55** Craig-Geffen-Morse waterflooding model developed
- **'61** First use of dynamic positioning
- **'66** Computerized well data monitoring
- **'69** First coiled tubing rig job
- **'71** Polycrystalline diamond compact bit introduced
  - 2-D seismic prevalent, computers convert drill velocity data into geological information
- **'72** Landsat satellite becomes available for remote sensing
- **'74** 3-D seismic data acquisition tested in Gulf of Mexico
- **'75** First floating production system begins operation
  - First commercial 3-D seismic survey recorded
- **'78** First measurement-while-drilling (MWD) system
- **'80** Cost of 3-D post time depth migration (PTDM) estimated at $8 million for 50 square miles
- **'81** First offshore horizontal well (Rospo Mare field, offshore Italy)
- **'83** Horizontal wells drilled from vertical shaft (Kern River, CA)
- **'84** First steerable drilling system
  - New resistivity measurement devices
- **'85** 3-D vertical seismic profiling developed
- **'86** Metal sealed-bearing roller cone bits
  - Neutron porosity measurement capability added to MWD
- **'87** First logging while drilling (LWD) tool
- **'88** Extended-reach drilling exceeds 60-degree radius
  - First horizontal well drilled from semisubmersible drill rig
- **'89** Only 5% of Gulf of Mexico wells based on 3-D seismic data
- **'90** Horizontal well achieves 14,585 linear feet
- **'91** 15,000-foot horizontal well drilled with directionally controlled coiled tubing
- **'92** Slimhole horizontal well ($3\frac{3}{8}$") drilled 801 feet
- **'93** 3-D surveys worldwide cost $1 million for 50 square miles
  - MWD tools advance—smaller, broader temperature range, pressure detection, geosteering
- **'94** Digital image processing of 3-D
- **'95** 3-D seismic used for 75% of U.S. onshore surveys
  - 4-D seismic emerges
- **'96** 80% of Gulf of Mexico wells based on 3-D seismic data
  - 4-D seismic characterization methodology applied to previously recorded seismic surveys
- **'97** Extended-reach drilling achieves 26,450 feet horizontal displacement in South China Sea
  - Magnetic resonance imaging begins on MWD
  - 3-D PTDM cost reduced to $90,000 for 50 square miles by the year 2000

Photo: Larry Lee

E&P Trends: Smarter, Farther, Deeper, Cleaner

Exploring Frontiers and Embracing Change

On the threshold of the new millennium, the oil and gas industry has transformed every phase of exploration and production operations, from initial prospect identification to final project closure and site restoration. Today's advanced exploration and production operations are models of high technology and resource efficiency. They incorporate high-speed computing, remote sensing and imaging, geologic interpretation, and visualization technology. They use global positioning systems, the latest geographical information systems, and 3-D seismic and 4-D imaging capabilities.

> "The oil industry still produces oil, but it has been infused by so many new technologies that it should be thought of as one of the new manmade, brain-power industries like biotechnology."
>
> Lester Thurow
> *Economist*
>
> *Source: Price Waterhouse World Energy Conference, November 1997*

Today's optical and radar satellites cost-effectively pinpoint promising geological formations.

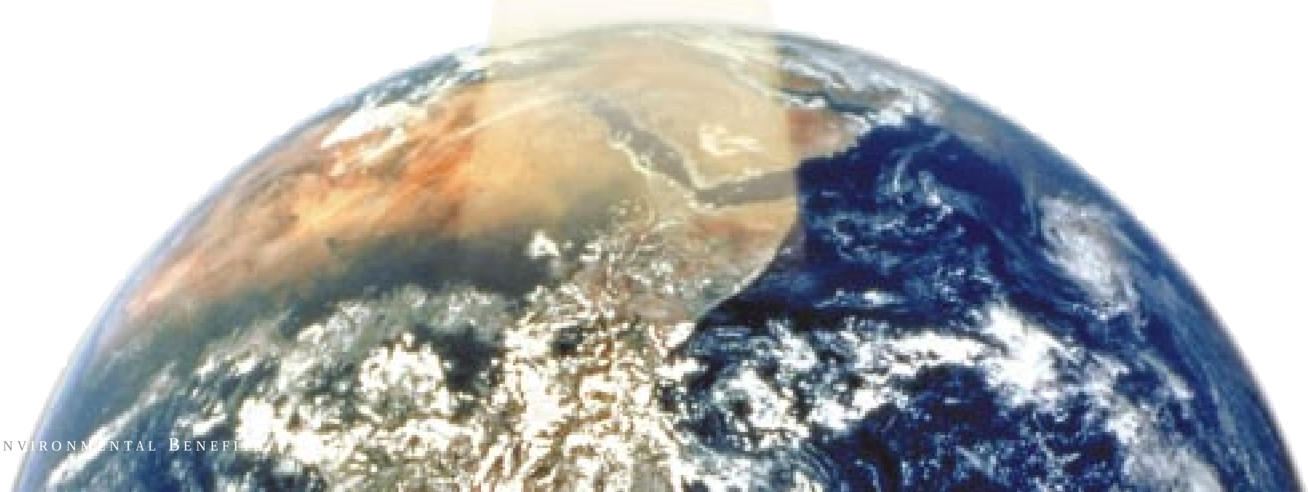
Photos: Corbis Images

Higher Success Rates, Enhanced Productivity, Reduced Impacts

Thanks to productivity gains from advanced E&P technology, the oil and gas industry has dramatically increased the ultimate recovery of resources from existing fields and become progressively more successful in pinpointing promising new reservoirs. In turn, higher productivity means less impact on the environment and better protection of our precious resources.

Technology Leadership for a Strong U.S. Economy

The United States has been the proving ground for developments on all these fronts, as market-based drivers have fostered flexibility and innovation. In striving to reduce costs and remain competitive, the E&P industry has embraced new technology at a rapid pace. Simultaneously, a sizeable number of smaller companies have come on the scene, carving out profitable niches based on specialized technological capabilities. Recent trends toward more alliances and mergers in the oil and gas industry—created largely to fill gaps in technological strengths—may further accelerate the rate of future innovation. The domestic industry's aggressive application of new technology positions U.S. companies to remain world leaders in E&P technology.



Oil and Gas Operations

Exploration

Techniques have progressed from surface observation and divining rods to the use of satellites, microprocessors, remote sensing, and super computers to generate three-dimensional and four-dimensional time-lapse imaging of subsurface reservoirs. Sharply increased drilling success rates have cut the number of both wells drilled and dry holes.

Drilling and Completion

Technology has advanced from gravity-driven cable tools in vertical wells to top-drive rotary rigs, coiled tubing units, advanced drilling fluids, and systems that monitor wellbore conditions during drilling operations. Current technology allows directional and horizontal drilling to reach previously inaccessible resources as well as to drill in deeper offshore waters. Durable forged alloys and polycrystalline diamond have replaced brittle cast iron bits, boosting drilling productivity and efficiency. Enhanced worker safety, habitat protection, lower and less-toxic waste volumes, and increased well productivity are the results.

Production

Techniques have evolved from collecting crude oil in wooden barrels from open gushers, which recovered less than 10 percent of the oil-in-place, to gas, thermal, and chemical injection techniques that can recover, in some cases, up to 50 percent or more of the original oil-in-place without spilling a drop. Today's techniques for reducing emissions of methane (natural gas) have allowed operators to recover an ever-increasing proportion of this valuable resource. These recovery techniques, which are enhanced with 4-D time-lapse imaging, are directly transferable to other industries, such as groundwater resource management and industrial pollution remediation.

Site Restoration

Despite the continued advance of technology, mature oil fields eventually cease being economic, must be shut down, and the production site restored to near-original conditions or conditions appropriate for alternative uses. Once capped at the surface and abandoned, wells are now plugged below ground and restored, leaving little or no visible evidence they ever existed. Rigs toppled offshore in "rigs-to-reefs" programs actually improve the habitat for marine life, yielding benefits to oil and gas producers, commercial and recreational fishing industries, and the marine environment.

Operations in Sensitive Environments

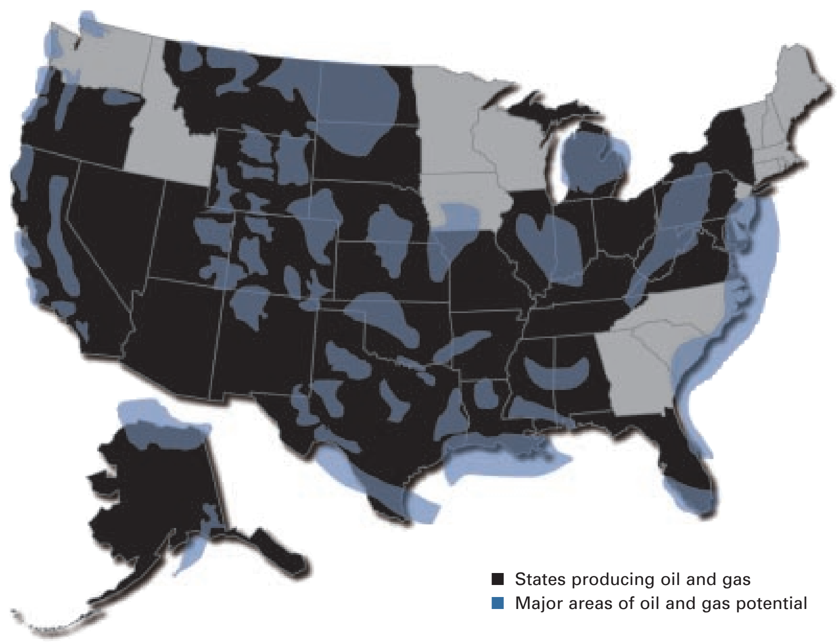
Resources underlying arctic regions, coastal and deep offshore waters, sensitive wetlands and wildlife habitats, public lands, and even cities and airports can now be contacted and produced without disrupting surface features above them. Wildlife preserves and conservation easements are created and managed jointly by industry, environmental, and government stakeholders. In Alaska, such new approaches as ice pads and roads, multilateral completions, and annular injection of drilling wastes minimize environmental impacts while also reducing costs.

Meeting the Challenges of a Mature Resource Base

Mature Resource Base: Perception vs. Reality

The United States is the most mature petroleum-producing province in the world—much of our easy-to-find resource base has been depleted. So should we be concerned that the United States will soon stop producing oil and gas? Not if the past two decades are any indication.

With our easily recoverable resources largely depleted, it would be logical to expect resource development opportunities in the United States, relative to the rest of the world, to continue to diminish. Conventional wisdom would predict a relentless drop in U.S. reserve additions and well productivity and a continued increase in finding costs. In fact, quite the opposite has been the case.

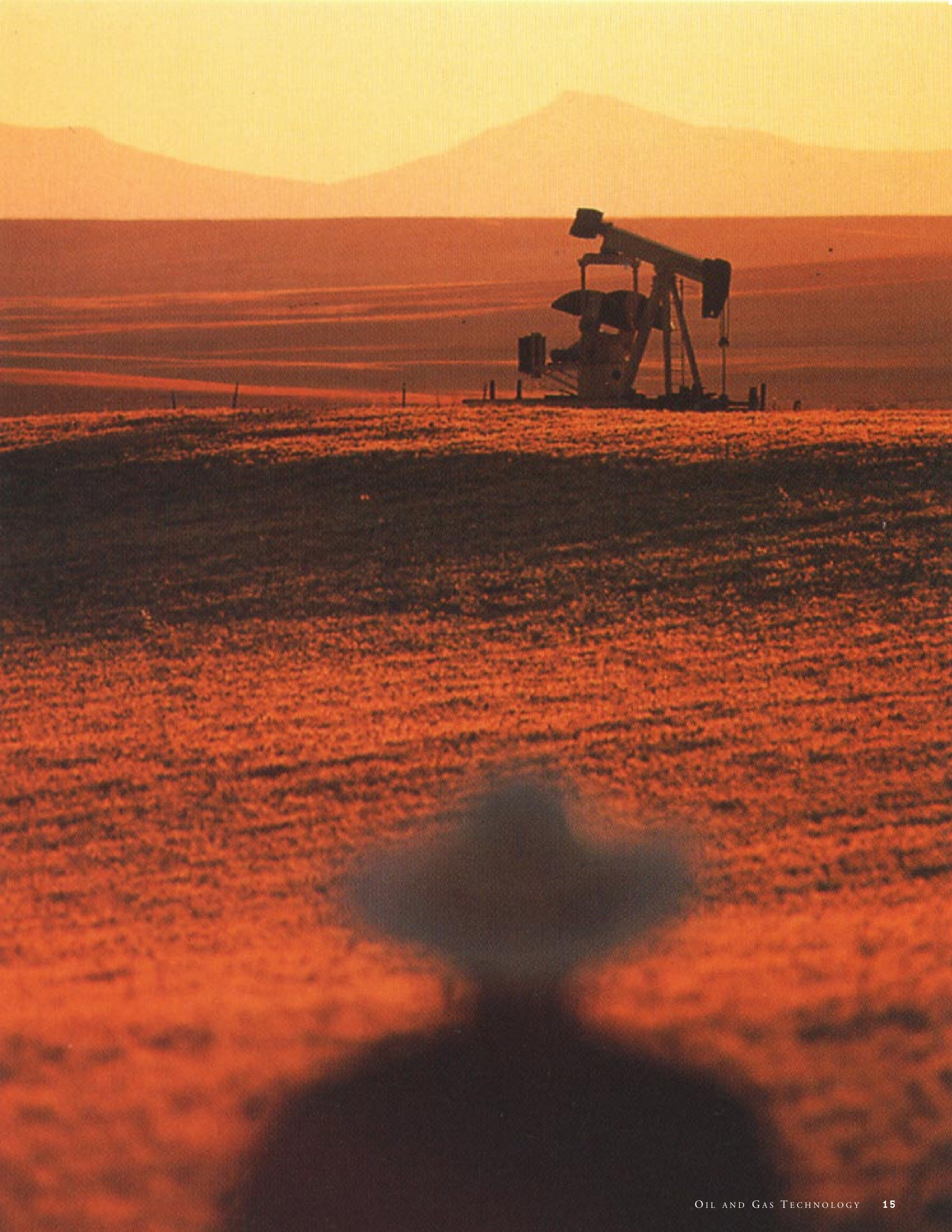


Source: U.S. Geological Survey, modified by ICF Resources Incorporated

E&P Successes Defy Conventional Wisdom

Despite the fact that the United States is the most mature hydrocarbon region of the world, 11 percent of all the petroleum reserves ever added in the United States (since 1859) have been added in just the last eight years. Over these eight years, the United States has replaced 100 percent of the gas it has produced, 104 percent of the natural gas liquids, and 79 percent of the crude oil. The overall replacement rate for hydrocarbons in the United States over the last eight years is 92 percent, despite high rates of production. And in the past three years, total hydrocarbon reserve additions have exceeded production by 8 percent. Advanced technologies have been behind the logic-defying trends in E&P, allowing economic access to domestic resources that are concentrated in deeper formations, tighter zones, deeper water, more sensitive environments, and increasingly more unconventional settings.

> "This industry...can, at $15 or $16 a barrel, do things that it thought it couldn't do at $30 a barrel a decade ago. It's an industry that's being transformed by technology and computers. It's an industry that can do much better at lower prices. It's an industry that's surprised itself."
>
> Daniel Yergin
> *Chairman*
> *Cambridge Energy Research Associates*
>
> Source: New York Times, August 16, 1998



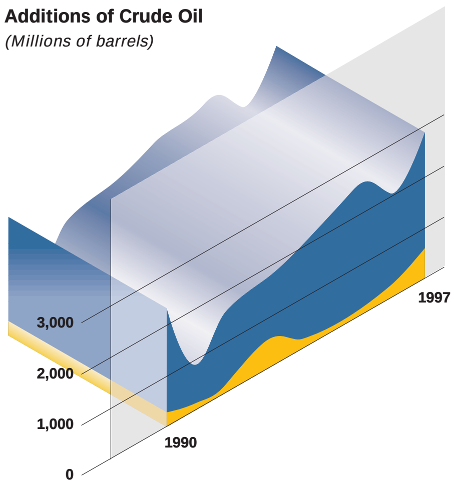
Tapping Resources Once Thought Unreachable

CONTINUAL INNOVATION OVER THE last three decades has enabled the E&P industry to drill ever deeper, with fewer dry holes, and to recover more reserves per well drilled. When onshore production in the lower-48 States began to decline in the 1970s, for example, waterflooding and gas pressure maintenance practices helped to increase U.S. crude oil production. Enhanced oil recovery technologies were used as early as 1967 and gained serious attention when the price and import supply shocks of 1973, the Iranian revolution, and the Iran/Iraq war stimulated significant research and development investments by industry and the U.S. Department of Energy. More recently, sophisticated imaging technologies, including 3-D seismic and 4-D time-lapse systems, have provided oil and gas professionals with detailed pictures of reservoirs and formations, enabling more accurate and productive exploration and development efforts.

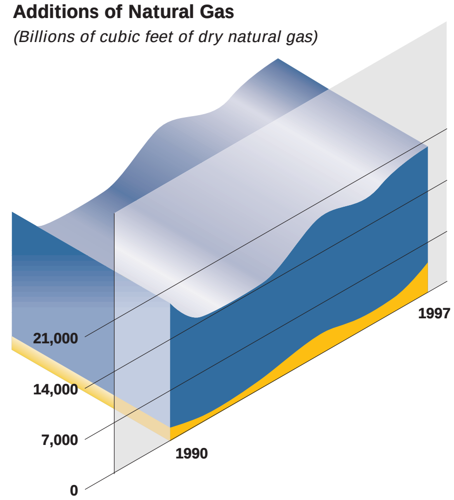
E&P Capabilities Spell Opportunity

THESE AND MANY OTHER ADVANCED E&P technologies have literally redefined reserves. Oil and gas at depths recently considered unreachable can now be tapped. Smaller accumulations once thought to be uneconomic can now be produced profitably. Fields under wetlands or cities can be accessed without disruption of the surface.

Annual Reserve Additions of Crude Oil
(Millions of barrels)



Annual Reserve Additions of Natural Gas
(Billions of cubic feet of dry natural gas)



- Reserve additions in known fields
- New field discoveries

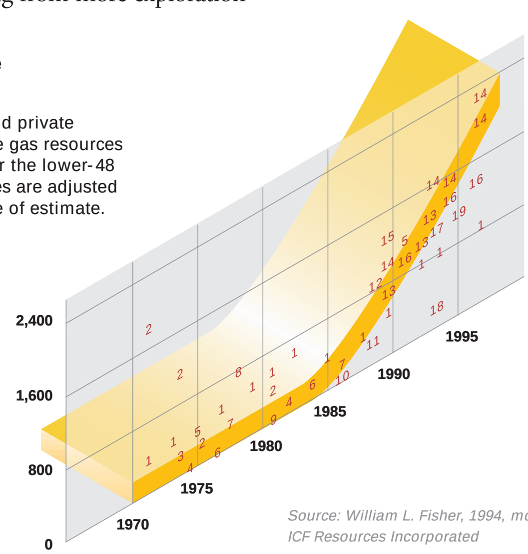
Source: Energy Information Administration, 1998

Particularly impressive is the industry's track record in effectively extracting additional resources from previously discovered, older fields. Since 1990, the vast majority of reserve additions in the United States—89 percent of oil reserve additions and 92 percent of gas reserve additions—have come from finding new reserves in old fields. Recent studies found that about half of these additions are from development-dominated growth (growth from more intensive development within the limits of known reservoirs), with the other half coming from more exploration-dominated growth (growth from finding new reservoirs in old fields and in extending the boundaries of oil fields).

As E&P capabilities continue to grow, so does the consensus of estimates of recoverable U.S. oil and gas resources. For example, in the 1970s, the consensus of estimates of ultimately recoverable gas resources was on the order of 400 trillion cubic feet (Tcf). Today, adjusting for what has already been produced, estimates range from 1,200 to over 2,000 Tcf.

Estimated Recoverable Gas Resources *(Tcf)*

Range of government and private estimates on recoverable gas resources (several estimates are for the lower-48 States only). All estimates are adjusted for production since date of estimate.



1. PGC
2. USGS
3. Mobil
4. Hubbert
5. NRC
6. Exxon
7. Shell
8. Hefner
9. Nehring
10. Sohio
11. DOI
12. DOE
13. Enron
14. GRI
15. AAPG
16. EIA
17. NPC
18. Smith & Lidsky
19. USGS/MMS

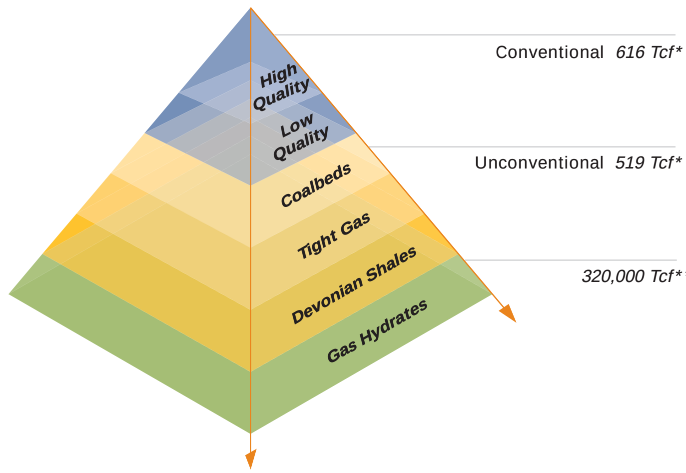
Source: William L. Fisher, 1994, modified by ICF Resources Incorporated

High Stakes in Unconventional Settings

TODAY, THE E&P INDUSTRY IS confronting formidable new technology challenges. Both the stakes and the potential rewards are great. Among the opportunities? Finding cost-effective ways to tap plentiful, less conventional resources that could potentially extend the world's oil and gas supplies for hundreds of years. Less conventional oil resources are found in heavy oil deposits, oil shales, and tar sands. Gas is now found in coal seams, large shale deposits, and gas hydrates. All told, the world's unconventional resources contain energy deposits many times larger than the world's remaining conventional resources. In fact, a fundamental characteristic of the world's hydrocarbon resources is that the more challenging and technically difficult the resource is to exploit, the more of that resource there is to pursue.

If these resources can be successfully extracted and refined, we may well need to change the definition of a "mature" resource base. When unconventional resources are factored into the U.S. resource base, our Nation does not seem to be such a mature province after all. With more than a century of oil production behind us, more than two-thirds of the over 600 billion barrels of the Nation's known oil resources remain untapped.

Natural Gas Resource Base

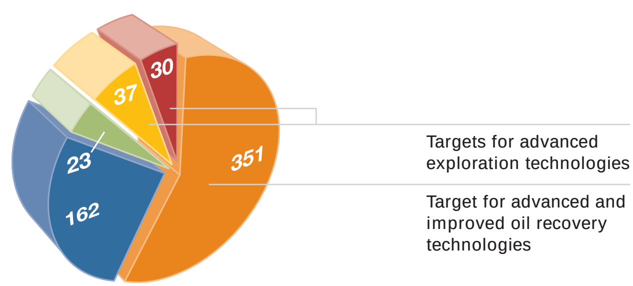


*Technically recoverable domestic resource base
**Mean estimate of U.S. hydrate resource base

Source: U.S. Department of Energy and U.S. Geological Survey

Targets for Advanced Exploration and Production Technology
(In billions of barrels)

Of the approximately 603 billion barrels of the United States' known oil resources, over two-thirds remain untapped. Advanced exploration and recovery technologies are key to reaching these undiscovered or currently unrecoverable resources.



- Cumulative production
- Proved reserves
- Discovered, unrecoverable by current technology (45% already abandoned)
- Undiscovered, recoverable by current technology
- Undiscovered, unrecoverable by current technology

Source: U.S. Department of Energy, 1998

More Efficient, More Effective, More Protective of the Environment

Environmental Awareness, Commitment, and Results

As science and technology have evolved, so too has our awareness of the impacts of human activity on the environment. In the past 30 years we have begun to more fully understand the effects of human activities on soils and vegetation, air and water quality, wildlife, and health. A heightened respect for the environment has become pervasive in our society—in education, industry, and government.

In the petroleum sector, oil and natural gas must be discovered, produced, processed, and consumed in a manner that respects and protects the environment. This has become the standard to which both government and the industry are committed.

Government Has Responded to Environmental Concerns

Protection of the environment began in the early years of the industry. While many early regulations were designed to conserve oil and gas resources, these mandates served the environment at the same time. Later, as understanding grew of the potential risks associated with E&P operations, regulations to protect public health and the environment were implemented.

Before World War I, States began implementing requirements to case and cement wellbores to prevent possible contamination of freshwater aquifers. Based on new technology and operational techniques developed by the industry, States continued to advance new standards of protection or restricted the use of less protective alternative practices.

Industry and government are working to protect the environment for future generations.

Since 1970, State and Federal governments have passed legislation and promulgated regulations to ensure higher levels of environmental protection. Federal legislation cuts across the spectrum of environmental concerns. Among others, these statutes include the Clean Air Act, Safe Drinking Water Act, Clean Water Act, Coastal Zone Management Act, Resource Conservation and Recovery Act, Endangered Species Act, and Occupational Safety and Health Act. Many of these statutes are implemented primarily by State agencies, which have developed programs that apply to unique and diverse environmental settings. These programs must meet or exceed the Federal requirements.

The Environmental Protection Agency has acknowledged a need for individually tailored regulations for waste management at the State and local levels that take into account differences in environmental conditions, geology, and production economics. Most States base the protective measures they require on site-specific conditions. This approach allows the State the flexibility to require additional protection where needed without unnecessarily adding requirements and costs on operations by imposing a uniform statewide standard. Although Federal regulations sometimes restrict this State flexibility, site-specific regulations appear to be an appropriate tool to assist the States in balancing the dual goals of environmental protection and oil and gas production.

A Fundamental of Effective Business Management

Industry policies and field practices have changed dramatically in recent decades, often leading or defining new regulatory requirements. The oil and gas industry's environmental orientation has become part and parcel of its business operations, domestic and worldwide. Companies have recognized that sound environmental practices are a prerequisite for society's consent to conduct their operations.

Operators are becoming increasingly involved in the regulatory development process at both State and Federal levels to assist in finding a balance between oil and gas production and environmental protection. Many operators have developed innovative approaches to increase environmental protection, and may employ practices that exceed the requirements set forth under State and Federal regulations.

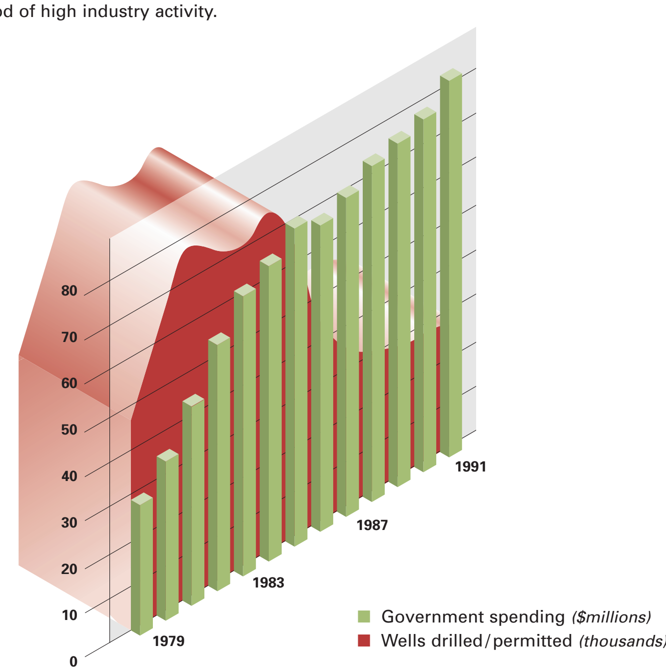
Photo: Corbis Images

Most companies have integrated environmental issues and activities into their operational planning and management, policies, and education and training. Most conduct extensive internal audits of their impacts on the environment, and many have adopted internal standards for monitoring and continuously improving their environmental performance. In many cases, companies have adopted international environmental performance protocols such as ISO 14000* as standard business practice for their operations around the world. Meeting or exceeding regulatory requirements and maintaining a high level of environmental performance are recognized as cornerstones of the oil and gas industry.

The industry—both in the United States and worldwide—commits enormous financial resources to specific measures for caring for the environment. In total, the industry spent over $8 billion on the environment in the United States in 1996—more than the U.S. Environmental Protection Agency's entire budget and more money than the industry spends annually on exploration for oil and gas in the United States.

State Spending on Oil and Gas Regulatory Activities

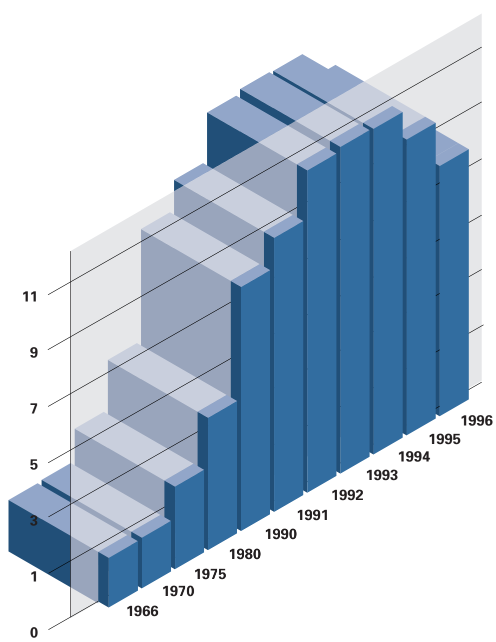
State spending on oil and gas regulatory activities nearly tripled during the 1980s in the largest oil- and gas-producing States. Spending rose fastest between 1979 and 1985, a period of high industry activity.



Source: Department of Energy and Interstate Oil & Gas Compact Commission, June 1993

Industry Spending on Environmental Protection, 1966–1996
(Billions of nominal dollars)

From 1966 to 1993, the U.S. petroleum industry's spending on environmental protection rose steadily, peaking at $10.6 billion. The decline since 1994 is primarily attributable to the completion of major capital projects in the refining sector.



Source: American Petroleum Institute, 1998

**The ISO 14000 series, a project of the International Organization for Standardization, is a collection of voluntary consensus standards that have been developed to assist organizations to achieve environmental and economic gains through the implementation of effective environmental management systems.*

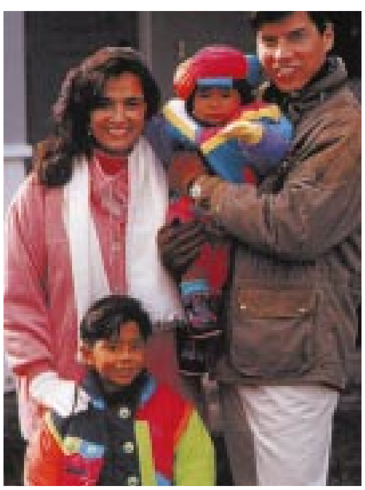
Photo: Corbis Images

Recognizing Excellence in Safe Operations

The Minerals Management Service Safety Award for Excellence, the SAFE award, first given in 1983, recognizes and commends Outer Continental Shelf operators that conduct operations in a safe and pollution-free manner. In referring to 1997 SAFE recipients Newfield Exploration Company and Kerr-McGee Corporation, MMS Director Cynthia Quarterman noted: "This prestigious award recognizes these two companies' exemplary performance, as well as their corporate commitment to safety and environmental protection while conducting operations on the Nation's Outer Continental Shelf."

Voluntary Industry Programs for Environmental Protection

In 1996, the petroleum industry spent an estimated $187 million on company environmental departments and voluntary programs to improve environmental quality and to support community and environmental groups.



Programs include:

API Step

The American Petroleum Institute's STEP Program ("Strategies for Today's Environmental Partnerships") encourages companies to reflect environmental commitments in their principles and policies, and to develop programs that prevent pollution, promote safe operating practices, and conserve resources in partnership with government, the public, and other key stakeholders.

EPA Natural Gas STAR

Nearly 70 exploration, production, transmission, and distribution companies are members of the Environmental Protection Agency's Natural Gas STAR program. Natural Gas STAR seeks to reduce methane emissions by identifying best management practices that reduce emissions and disseminating these advanced technologies to other companies to use when it makes economic sense to do so.

OSHA Voluntary Protection Programs

Participants are a select group of facilities across all industries with outstanding health and worker safety programs that go beyond compliance with Occupational Safety and Health Act (OSHA) regulations. E&P industry participants include BP Exploration's Endicott Island, Alaska site and Texaco Exploration's operations in Maysville, Oklahoma. The programs establish a cooperative relationship among management, labor, and OSHA to ensure a safe and healthful workplace. Once OSHA verifies that the program meets established criteria, the site is removed from routine scheduled inspection lists. OSHA reassesses periodically to confirm that the site continues to meet the criteria.

Safety and Environmental Management Program (SEMP)

SEMP is a voluntary, nonregulatory strategy for identifying and reducing risks of accidents, injuries, and oil spills associated with developing oil and natural gas on the Nation's Outer Continental Shelf (OCS). Operators representing over 99 percent of production from the OCS have a SEMP in place or are developing one. The program was developed by the Minerals Management Service (MMS) in partnership with industry. Proper implementation of the program can help operators comply with MMS operating regulations, decrease operational risks, and enhance worker safety.

Myths about the Oil and Gas Industry

Myth: **The oil and gas industry is frequently characterized as Big Oil.**

Reality: **The Big Oil image is misleading. Independent oil and gas producers—small businesses typically employing 10 full-time and 3 part-time employees—drill 85 percent of the Nation's wells and produce 65 percent of the natural gas and nearly 40 percent of the oil consumed by Americans. Across America, the owners and employees of these businesses may be your neighbors, serving as a cornerstone of economic activity in smaller rural communities. Accordingly, the Department of Energy has technology transfer programs targeted specifically to small independent producers.**

Myth: **Many Americans believe that the spills from oil and gas E&P are the leading cause of oil pollution in the oceans and in the Nation's rivers and streams.**

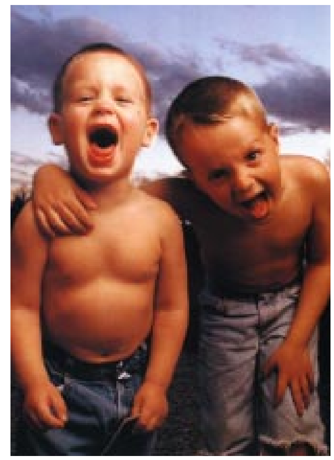
Reality: **To the contrary, the National Academy of Sciences found that offshore oil and gas E&P accounts for only 2 percent of the oil in the marine environment; marine transportation accounts for 45 percent; industrial and municipal discharges, including urban runoff, 36 percent; atmospheric pollution, 9 percent; and natural sources such as oil seeps, 8 percent.**

"While fiercely supportive of efforts to preserve and protect the environment, most Americans are using yesterday's news while making critical decisions about behavior and policy on key environmental issues. This dependence on mythology threatens to block progress on important environmental initiatives . . . it is vital that we debunk these myths so that the public can most effectively address the environmental needs of today."

Kevin J. Coyle
President
National Environmental Education & Training Foundation

International Protocols

On an international basis, the E&P industry is sharing "best environmental practices" and setting voluntary operating guidelines to improve environmental performance. Key associations include the European-based E&P Forum; the Western Hemisphere Oil and Gas Environmental Forum, a cooperative effort among over 30 private and State-owned oil and gas companies in the United States and Latin America; the International Association of Geophysical Contractors; and the International Petroleum Industry Environmental Conservation Association.



Steps Toward Reductions in Greenhouse Gas Emissions

Oil and gas companies all over the world are voluntarily reducing emissions of carbon dioxide and other greenhouse gases. Industry giants BP Amoco and Royal Dutch/Shell Group have taken the lead in this area, publicly committing to reduce future greenhouse gas emissions to levels below those set forth in the Kyoto Protocol. In recent years, individual companies have implemented hundreds of emissions reduction initiatives and projects—from the reduction of natural gas flaring and venting, to innovative gas-to-liquids and gas liquefaction technology, to the development of creative, market-based emissions trading programs.

Wetlands Restoration

In States where a substantial amount of oil and gas operations occur in sensitive wetlands, the oil and gas industry is actively restoring and protecting the fragile ecosystems in which it operates. Louisiana Land and Exploration

Wildlife Protection Programs

With the help of Shell Oil Company Foundation and Exxon Corporation, the National Fish and Wildlife Foundation (NFWF), a nonprofit organization dedicated to promoting conservation and sustainable use of our natural resources, has been able to significantly enhance its habitat and wildlife protection programs. Multi-million-dollar, multi-year grants from these companies have enabled NFWF to establish two important grant programs: the Shell Marine Habitant Program—dedicated to protecting and enhancing the Gulf of Mexico ecosystem—and the *Save the Tiger Fund,* an international effort launched with Exxon to assist in the long-term survival of Asia's remaining population of wild tigers.

Company (which merged with Burlington Resources in 1997), for example, began studying wetlands restoration methods as early as the 1950s and later implemented an award-winning wetlands conservation program.

Today, in LaTerre, Louisiana, Fina has undertaken an extensive program to halt erosion on over 7,000 acres of marsh by planting cordgrass and constructing a series of weirs and dams, helping to restore the marsh and its declining alligator population.

Coastal and Marine Habitat Protection

The industry actively collaborates with private conservation groups to protect sensitive coastal and marine habitats and wildlife. For example, Shell Oil Company Foundation recently provided a 5-year, $500,000 grant to The Nature Conservancy of Texas for conservation research and field-based environmental educational programs at the Mad Island Marsh Preserve along the Texas Gulf Coast. On Shamrock Island in Corpus Christi Bay, The Nature Conservancy of Texas and Bristol Resources are collaborating to restore and protect habitats impacted by past oil and gas operations. On Galveston Bay, Mobil Oil recently donated over 2,200 acres of wetlands and grasslands for use as a preserve for the area's wild prairie chicken, one of North America's most endangered species.

Federal Lands Stewardship

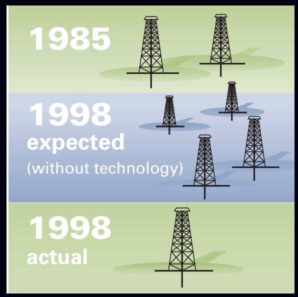
Whether tailoring operations to protect Federal lands or assisting the government in enacting sound resource development policies, the domestic petroleum industry plays a vital stewardship role on our Nation's Federal lands. For example, a recent exchange of over 18,000 acres of land in North Dakota's Badlands enabled the Bureau of Land Management to consolidate ownership of prime bighorn sheep habitat, and provided Burlington Resources with access to Federal mineral rights on lands away from these critical habitats.

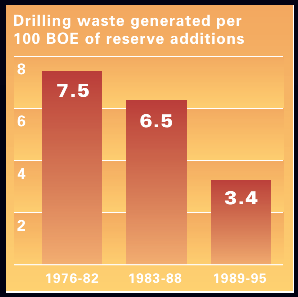
Equally crucial is the industry's commitment to environmental excellence when exploring or producing on Federal lands—Unocal Alaska's award-winning operations in Alaska's Kenai National Wildlife Refuge and Conoco's management of its operations in the Aransas National Wildlife Refuge on Texas' Gulf Coast typify this commitment.

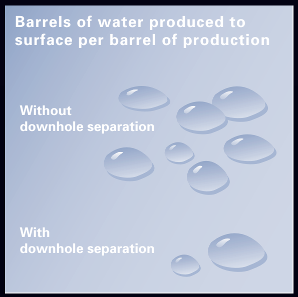
Environmental Advanced E&P

Thanks to advances in exploration and production technology, today's industry is better equipped than ever to find and produce valuable oil and gas — even as these resources become concentrated in deeper, more remote, and more technically challenging areas. Many of the same advances also support our Nation's goals for environmental protection. With each step up in performance and efficiency, the industry can recover more resources with fewer wells drilled, resulting in

- Exploration
- Drilling and Completion
- Production
- Site Restoration
- Operations in Sensitive Environments







Fewer Wells to Add Same Level of Reserves

If technology had not advanced since 1985, four domestic wells would have to be drilled today to maintain the production levels achieved by two wells in 1985. But, in fact, technology advances have boosted productivity so successfully that 1985-level production can be achieved today with only one well.

Lower Drilling Waste Volumes

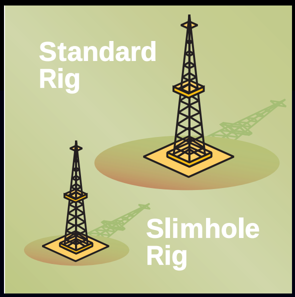
Volumes of drilling muds and drill cuttings per barrel of new oil reserves have steadily declined thanks to improvements in drilling efficiency.

Lower Produced Water Volumes

Emerging downhole separation technology has the potential to dramatically reduce volumes of produced water, which is the largest waste stream associated with oil and gas production.

Benefits of Technology

smaller volumes of cuttings, drilling muds and fluids, and produced waters. Technologies such as slimhole, directional, and multilateral drilling reduce the footprint of drilling rigs and minimize surface impacts. Other benefits of advanced technology include reduced energy consumption, reduced noise from operations, decreased visibility of facilities, reduced emissions of greenhouse gases and hazardous air pollutants, better protection of water resources, preservation of habitats and wildlife, and enhanced worker safety.

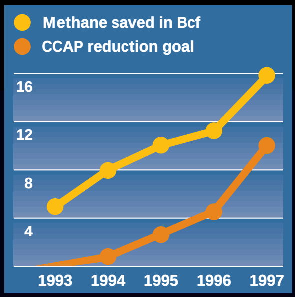


Smaller Footprints

Using modular drilling rigs and slimhole drilling, operators can develop the same volume of resources with a rig up to 75 percent smaller and lighter than a standard rig, reducing impacts on surface environments.

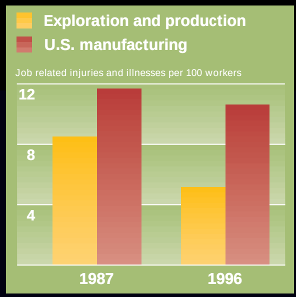
Protection of Sensitive Environments

Directional drilling, slimhole rigs, and other advances enable production of valuable oil and gas resources with less disturbance to wetlands and other sensitive environments.



Reduced Greenhouse Gas Emissions

Through the EPA's voluntary Natural Gas STAR program, the gas industry's use of innovative best management practices has reduced methane emissions by nearly 55 billion cubic feet since 1991, well exceeding the annual goals set by the Climate Change Action Plan. The natural gas production sector alone has accounted for two-thirds of this reduction.



Enhanced Worker Safety

Job-related injuries and illnesses in oil exploration and production are well below the rates in the U.S. manufacturing sector. Advanced drilling, completion, and production technologies have contributed to steady improvements in worker safety, by decreasing workers' time on site and enhancing wellbore control.

Photo: Larry Lee

Exploration

TODAY, FINDING BLACK GOLD IS A HIGH-TECHNOLOGY VENTURE. HIGHER SUCCESS RATES MEAN FEWER DRY HOLES, FEWER WELLS DRILLED, AND LESS IMPACT ON THE ENVIRONMENT.

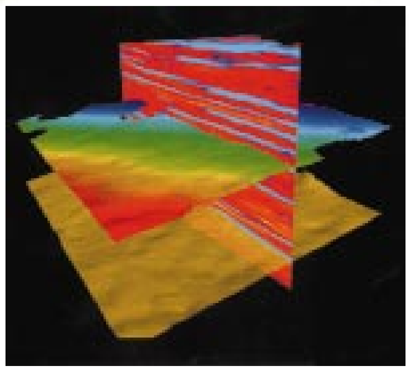

ZAPATA

CUTTING-EDGE TECHNOLOGY REVOLUTIONIZES EXPLORATION

The Gulf of Mexico's coastal transition zone is among the most prospective, unexplored oil and gas regions in the country. Yet, the region's geological and operational complexities have long hampered E&P activities. Now, thanks to next-generation 3-D seismic imaging, new drilling capabilities, and associated technologies, the zone is coming alive with new discoveries—including successful strikes in old fields. For example, Spirit Energy '76 (Unocal Corporation's E&P unit) recently began drilling deeper targets, based on newly acquired 3-D seismic data, around the 40-year-old Vermilion 14 field, located in State waters off central coastal Louisiana. Barry Gouger, Central Gulf asset manager, reported in 1998 that 10 million barrels of oil equivalent had been added to the field's reserves since the acquisition of 3-D seismic.

"The 3-D seismic has allowed us to sharpshoot for bypassed pay and new targets within the field and new opportunities around the field," Gouger explained. "The effort and expense of acquiring 3-D seismic over these older giant fields is well worth it. We are finding significant new reserves in and around the field, and just as important are the wells that we do not drill because of the 3-D coverage." It's a story being replicated throughout the Gulf transition zone, where 3-D seismic is minimizing environmental disruption by effectively targeting new prospects and extending the life of existing reservoirs.

Source: American Oil & Gas Reporter, April 1998



Advanced technologies like seismic imaging have raised exploration success rates by 50 percent or more.

Photo: Texaco Production Operations

SEARCHING FOR HYDROCARBONS today is about as far removed as possible from old movie images of wildcat drillers hoping for a gusher. It involves teams of geologists, geophysicists, and petroleum engineers seeking to identify, characterize, and pursue geologic prospects that may contain commercial quantities of oil and gas. Because these prospects lie thousands of feet below the earth's surface, uncertainty and trial-and-error pervade the exploration process. It is a painstaking and hugely expensive enterprise, with low success rates. Historically, new field wildcat exploration has succeeded at a rate of one productive well for every five to 10 wells drilled.

Over time, the more easily discovered resources in the United States have been found, developed, depleted, and then plugged and abandoned when they reached their economic limit. New fields now being discovered in the United States are generally smaller in size and found in deeper, more subtle, and more challenging geologic formations. Yet, despite the increased difficulty of discovering remaining domestic resources, technology developments have enabled the oil and gas industry to maintain or, in many cases, improve upon, historical levels of exploration success.

Today, experts can interpret geological and geophysical data more completely; manage, visualize, and evaluate larger volumes of data simultaneously; and communicate interpretations based on these data more accurately.

Advanced techniques now allow the scientist to virtually "see" the inside of the formation. Three-dimensional seismic technology, first commercially available nearly 25 years ago, bounces acoustic or electrical vibrations off subsurface structures, generating massive amounts of data. Then powerful computers manipulate the data to create fully visualized multidimensional representations of the subsurface. Even more exciting is 4-D time-lapse imaging—an emerging technology developed only within the past 5 to 10 years—which adds the dimension of time, allowing scientists to understand how the flow pattern of hydrocarbons changes in the formation over time.

Fundamentals of Exploration

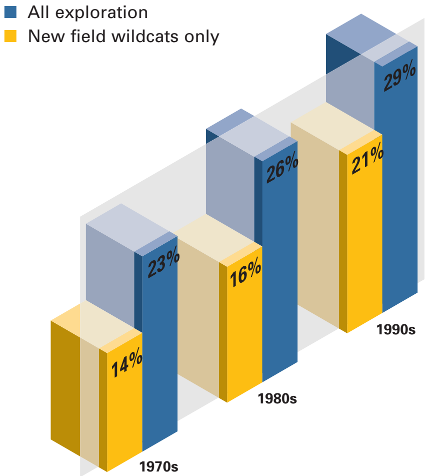
Searching for Oil and Gas

Exploration includes:

- **Surveying and mapping surface and subsurface geologic features to identify structures where oil and gas may have accumulated.**
- **Determining a geologic formation's potential for containing commercial quantities of economically producible oil and/or gas.**
- **Identifying the best location to drill an exploratory well to test the structure.**
- **Drilling exploration and delineation wells to determine where hydrocarbons are present and to measure the area and thickness of the oil- and/or gas-bearing reservoir.**
- **Logging and coring wells to measure permeability, porosity, and other properties of the geologic formation(s) encountered.**
- **Completing wells deemed capable of producing commercial quantities of hydrocarbons.**

Exploration Success Rates

Despite a dwindling resource base, U.S. exploration success rates continue to improve.



Source: American Petroleum Institute

Fewer Dry Holes, More Production and Reserve Additions per Well

Improvements in 3-D seismic and 4-D time-lapse visualization, remote sensing, and other exploration technology allow explorationists to target higher-quality prospects and to improve success rates by as much as 50 percent or more. The result: fewer wells need to be drilled to find a given target, and production per well is increased, in some cases by 100 percent.

Today, fewer than half as many wells are required to achieve the same reserve additions as two decades ago. Annual reserve additions for new exploratory drilling have quadrupled, from a per-well average of about 10,000 barrels of oil equivalent (BOE)* in the 1970s and 1980s to over 40,000 BOE in the 1990s.

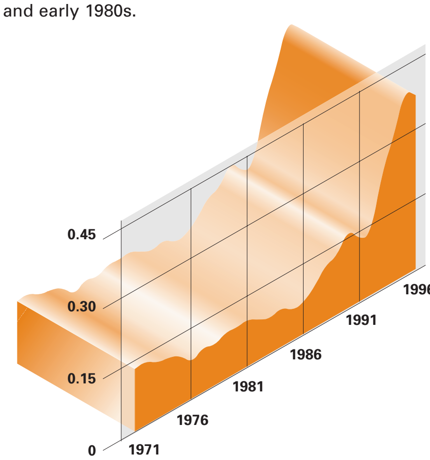
Thanks to today's technology, whole new categories of resources, considered inaccessible just 20 years ago, are now counted as part of the domestic resource base. Advances in exploration drilling technology have been particularly dramatic in deepwater areas, where significant expansion of the known resource base has resulted.

In aggregate, technology improvements have slashed the average cost of finding oil and gas reserves in the United States from roughly $12 to $16 per BOE of reserves added in the 1970s and 1980s to $4 to $8 today.

BOE New Reservoir and New Field Reserve Additions per Exploratory Well

(Million barrels of oil equivalent per well)

The volume of reserves added per exploratory well has increased dramatically since the 1970s and early 1980s.



Source: U.S. Department of Energy

**Natural gas is converted to "barrels of oil equivalent" on the basis of 0.178 barrels of oil per thousand cubic feet of gas.*

The sharply increased success rates and well productivity improvements attributable to advanced exploration technology yield substantial environmental benefits. Fewer wells drilled means reduced volumes of wastes to be managed, such as cuttings and drilling fluids (which lubricate the drill bit, circulate cuttings, and stabilize wellbore pressures).

New Resources in Old Fields

IMPROVEMENTS IN EXPLORATION and production technology enable operators today to better tap resources that remain in existing fields. Advances in 3-D and interwell seismic technology allow operators to take another look at older producing areas, such as the fields in Appalachia, California, and West Texas, and see untapped zones of hydrocarbons that were bypassed or could not be seen in the past.

Improved computer-processing technology and interpretation software allow older seismic data to be reprocessed and reevaluated.

Photo: Sundowner Offshore Services

On the Cutting Edge

Exploration Applies High Technology

Advances in widely varied technical disciplines have boosted exploration efficiency over the past 20 years:

- **Advances in computer power, speed, and accuracy**
- **Remote sensing and image-processing technology**
- **Satellite-derived gravity and bathymetry data that enable remote sensing for offshore deepwater exploration**
- **Developments in global positioning systems (GPS)**
- **Advances in geographical information systems (GIS)**
- **Three-dimensional (3-D) and 4-D time-lapse imaging technology that permit better characterization of geologic structures and reservoir fluids below the surface**
- **Improved logging tools that enhance industry's geoscientific understanding of specific basins, plays, and reservoirs**
- **Advances in drilling that allow explorationists to more cost-effectively tap undepleted zones in maturing fields, test deeper zones in existing fields, and explore new regions**

Once untapped zones are identified, new techniques for sidetrack drilling (drilling a lateral extension 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.

Exploring New Frontiers

NEW DEEPWATER DRILLING TECHnology enables exploratory drilling in ever deeper offshore waters, making promising new resources accessible for the first time. Advances include high-technology floating drillships, jackup rigs, semisubmersible drilling rigs, and modular rigs. When commercial quantities of resources are discovered, discovery wells are capped until permanent production platforms can be set in place. Where dry holes are found, wells are plugged and the rigs are redeployed swiftly. As offshore technology extends exploratory reach, the industry continuously pushes to advance development and production technology to operate cost-effectively in ever deeper waters.

The 4-D Difference

At BP Amoco/ Shell's Foenhaven field, estimated recovery rates of oil-in-place are expected to reach 65 to 70 percent with 4-D seismic, compared to 25 to 30 percent with 2-D technology and 40 to 50 percent with 3-D technology.

Outfitted with state-of-the-art electronics and computers, seismic survey vessels collect and process invaluable subsurface geological data to aid offshore exploration.

More Advances in Exploration Technology

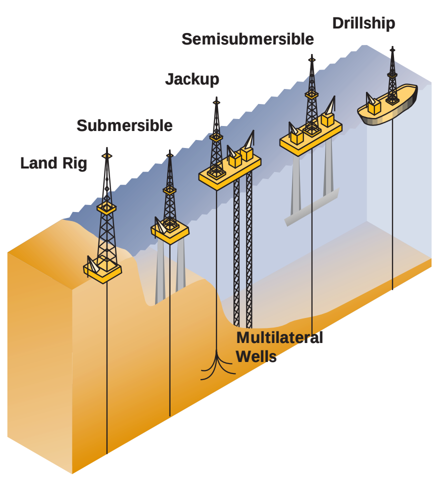
Beyond advanced imaging, other new exploration approaches are being applied throughout the country to reduce environmental impacts, particularly in sensitive environmental areas. Redesign of drill rigs has minimized surface loading. Seismic techniques also have been redesigned to reduce impacts resulting from explosive shocks—for instance, through more flexible positioning of shotholes and geophones, redesign of shothole loading procedures, and use of ramming instead of drilling to set charges in hydrophones. These new acoustical and vibration devices replace explosives for generating seismic signals onshore and offshore, reducing noise, and protecting human, marine, and animal life.

These advances are enabling exploratory drilling in water depths of a mile or more, extending drilling seasons in the Arctic without disturbing the tundra or wildlife migratory patterns, and opening commercial development prospects in complex geological basins.

Beyond the Oil Patch

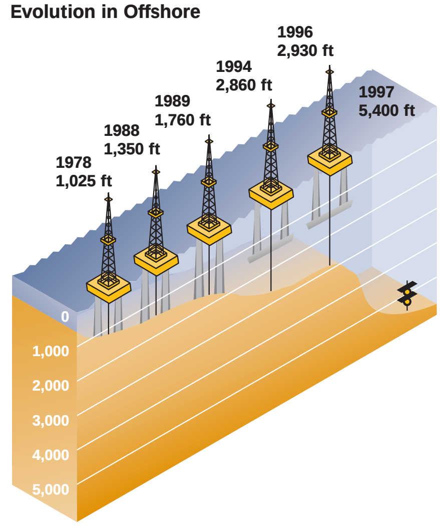
- **Advances in 3-D and 4-D seismic technology and earth-imaging systems have helped in the understanding of subsurface fluid flow, not just for oil and gas, but for groundwater monitoring and pollutant transport.**
- **Advances in geological and geophysical technologies have assisted in improving our overall understanding of "earth systems," or the major processes influencing activity in the earth's crust.**
- **Improved logging and interpretation technologies have helped us learn more about the characteristics of the earth's crust.**

Exploration Drilling Techniques from Land to Deepwater



Source: Minerals Management Service

Exploration Drilling Technology Evolution in Offshore



Drilling and Completion

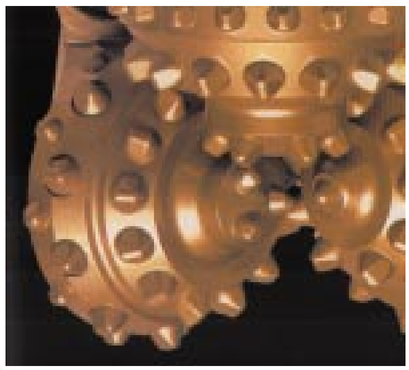
Successful drilling often means going faster and deeper, through harder rock, and in multiple directions from a single wellbore. The result? More resources are contacted with fewer wells, less drilling waste, and less surface disturbance.

GREATER DRILLING EFFICIENCY, LESS ENVIRONMENTAL IMPACT

With horizontal drilling, today's oil and gas industry has an extraordinary capability: the power to navigate three-dimensionally through the earth, contacting and economically producing resources while minimizing surface disruption. A case in point is the Red River B Formation in the Williston Basin (North Dakota, South Dakota, and Montana), where Burlington Resources Inc. and Continental Resources are using horizontal technology to drain a narrow but oil-rich, low-permeability dolomite zone. Historically, vertical wells completed in the Red River B produced an uneconomic 20 or 30 barrels a day. New wells penetrate the zone laterally, extending a mile or more within a porosity window of only 2 feet. Initial daily production from the longest of the 123 horizontal wells drilled and completed to date was 575 barrels of oil.

Horizontal drilling was instrumental in Burlington Resources' discovery of an estimated 150 million barrels of recoverable oil in the Cedar Hills play in the Williston Basin, the largest onshore discovery in the last 25 years. The technique complements waterflood recovery efforts there. "With two horizontal wells per section, Burlington is replacing traditional line-drive techniques in the area where operators have typically drilled eight to 10 wells per section," said drilling manager Doug Harris. "In fact, the horizontal wells will result in a more efficient flood than the vertical-drilled line-drive patterns, with only one-fourth the number of wells."

Source: American Oil & Gas Reporter, September 1998



Advanced drill bits reduce time on site and associated environmental impacts.

Photo: RBI-Gearhart

DRILLING IS THE MOMENT OF truth for oil and gas producers. After all of the analyses and preparation, have explorationists pinpointed the reservoir? Will it be productive? Are development wells being drilled in the right pattern for efficient extraction?

Substantial investments ride on the answers. Drilling activities for a given field or reservoir may require the investment of hundreds of millions of dollars or more. Justifying such investments in developing domestic resources is increasingly difficult, since much of our Nation's remaining oil and gas is locked away in geologically complex and challenging structures that necessitate deeper drilling or enhanced completion and production technologies.

Despite these challenges, drilling is now safer, faster, more efficient, and less costly than in the past. High-resolution 3-D seismic and improved reservoir imaging and characterization are combined with improvements in drilling technology to increase drilling success rates, reduce drilling costs, and reduce the environmental impacts of both exploratory and development drilling.

Onshore, typical drilling and completion costs have dropped by about 20 percent, from an average of about $500,000 per well in the 1980s, to about $400,000 per well today, adjusting for inflation, depth, type of well, and locations of wells drilled. Similarly, offshore drilling and completion costs of about $5.5 million per well in the 1980s have dropped to an average of $4.3 million today.

In addition to expanding the deepwater oil and gas resource base, technology advances in drilling and completion have added new gas reserves from sources once considered uneconomic—including Devonian shales, deep gas formations, coalbeds, and low-permeability "tight" gas sands.

"High technology has migrated to almost all phases of exploration and production, and that includes stepping right up to the drilling rig floor. That's right, the rig floor—the domain of the roughneck and the pipe wrench, where the real 'nitty gritty' gets done—is becoming more technology-oriented by the day.... Technology is markedly improving drilling performance and enhancing safety even as it helps trim cost."

MAGGIE LEE

Source: The American Oil & Gas Reporter, April 1998

Photo: CANRIG

Fewer Wells Mean Less Waste

ENVIRONMENTAL BENEFITS FROM drilling and completion advances are significant. For example, new exploration and drilling technology has, on average, doubled the amount of oil or gas supplies developed per well since 1985. Thanks to this productivity increase, today's level of reserve additions is achieved with 22,000 fewer wells annually than would have been required with 1985-era technology.

Reducing the number of wells decreases wastes generated from drilling operations. Assuming an average well depth of 5,600 feet and 1.2 barrels of waste per foot drilled, with 22,000 fewer wells, the average annual volume of drilling waste is reduced by approximately 148 million barrels. Avoiding this waste—enough to cover about 1,440 football fields to a depth of 10 feet—reduces waste management and disposal requirements.

Other environmental benefits of advanced drilling and completion technology include:

- Smaller footprints
- Reduced noise and visual impacts
- Less frequent well maintenance and workovers, with less associated waste
- Reduced fuel use and associated emissions
- Enhanced well control, for greater worker safety and protection of groundwater
- Less time on site, with fewer associated environmental impacts
- Lower toxicity of discharges
- Better protection of sensitive environments

Fundamentals of Drilling and Completion

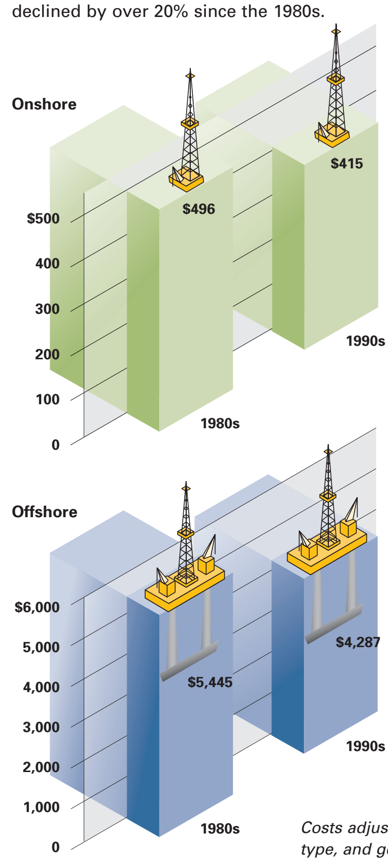
Contacting a targeted formation involves:

- **Using rotary equipment and hardened drill bits, weighted and lubricated by drilling fluids, to penetrate the earth's surface.**
- **Inserting casing and tubing into each well to protect the subsurface and control the flow of fluids (oil, gas, and water) from the reservoir.**
- **Perforating the well casing at the depth of the producing formation to allow flow of fluids from the formation into the wellbore.**
- **Installing a wellhead at the surface to regulate and monitor fluid flow and prevent potentially dangerous blowouts.**

Average Onshore and Offshore Drilling Costs

(Dollars per well, in thousands)

Both onshore and offshore drilling costs have declined by over 20% since the 1980s.



Costs adjusted for 1996 activity (i.e., depth, type, and general location of wells drilled).

Source: American Petroleum Institute

Some technology advances key to improved drilling and completion efficiency are described below:

Horizontal and directional drilling

Oil and gas wells traditionally have been drilled vertically, at depths ranging from a few thousand feet to as deep as 5 miles. Depending on subsurface geology, technology advances now allow wells to deviate from the strictly vertical orientation by anywhere from a few degrees to completely horizontal, or even inverted toward the surface. About 90 percent of all horizontal wells have been drilled into carbonate formations, which account for about 30 percent of all U.S. reserves.

Directional and horizontal drilling enable producers to reach reservoirs that are not located directly beneath the drilling rig, a capability that is particularly useful in avoiding sensitive surface and subsurface environmental features. New methods and technology allow industry to produce resources far beneath sensitive environments and scenic vistas in Louisiana wetlands, California wildlife habitats and beaches, Rocky Mountain pine forests, and recreational areas on the Texas Gulf Coast. Even some offshore resources, including many off the coast of California, can be produced from onshore wells.

Horizontal drilling may also allow a producer to contact more of the reservoir, so that more resources can be recovered from a single well. In Mississippi's Black Warrior Basin, for example, horizontal wells provide six times as much natural gas deliverability as conventional vertical wells do at the Goodwin natural gas storage field. In growing numbers of operations, the benefits from this increased production far outweigh the added cost for these wells. This was the case in the remote South China Sea, where Phillips China Inc. recently used advanced horizontal drilling and completion technologies to successfully complete a 5-mile-long extended-reach well.

Advances in directional drilling also facilitate multilateral drilling and completion, enabling multiple offshoots from a single wellbore to radiate in different directions or contact resources at different depths. Recent and very rapid development of such radial drilling technology has spurred a boom in horizontal drilling. Since the mid-1980s, the drilling of horizontal wells has grown from a few to more than 2,700 wells per year worldwide. In the United States, horizontal drilling now accounts for 5 to 8 percent of the land well count at any given time.

Environmental benefits of horizontal and directional drilling include:

- Fewer wells
- Lower waste volumes
- Protection of sensitive environments

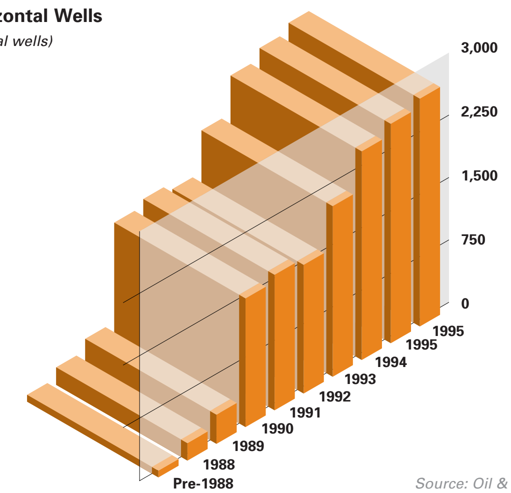
METRICS

Measures of Success for Horizontal Drilling

According to a 1995 DOE study, horizontal drilling has improved:

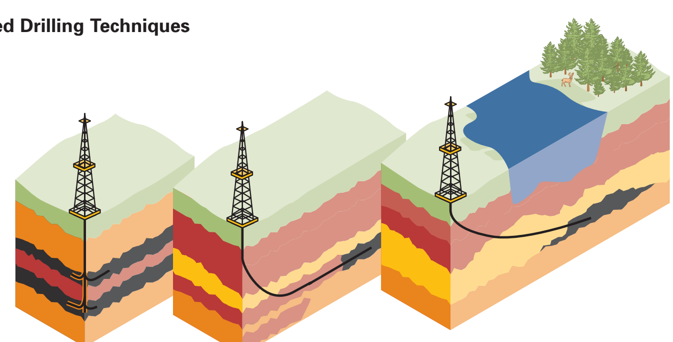
- **Reserve additions: Reserves are potentially increased by an estimated 10 billion barrels of oil, nearly 2 percent of original oil-in-place in the United States.**
- **Speed of delivery: Carbonate production is nearly 400 percent greater in horizontal projects than with vertical wells, yet costs are only 80 percent more.**
- **Average production ratio: The ratio is 3.2 to 1 for horizontal compared to vertical drilling, offsetting a higher average cost ratio of 2 to 1. Average increase in reserves derived from horizontal well applications is approximately 9 percent.**

Worldwide Horizontal Wells
(Number of horizontal wells)

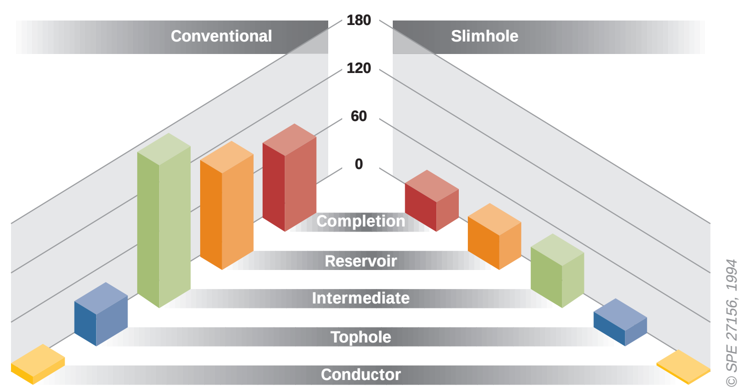


Source: Oil & Gas Journal, November 23, 1998

Advanced Drilling Techniques



Mud Disposal Reduction in Slimhole Coiled Tubing Operations vs. Conventional Drilling Operations
Maximum fluid volume (m3)



Slimhole drilling and coiled tubing

Slimhole drilling—a technique gaining widespread use for tapping into reserves in mature fields—significantly decreases waste volumes. For example, a slimhole drilled to 14,760 feet and ending with a 4⅛-inch bottomhole produces one-third less volume of cuttings than a standard well at the same depth. 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 operations. In contrast, if technology development had stopped in 1985, today's drill pads would cover an additional 17,000 acres of land in the United States, an area roughly the size of 12,900 football fields.

Coiled tubing technology—a cost-effective solution for drilling in reentry, underbalanced, and highly deviated wells—has similarly impressive benefits, reducing drilling wastes and minimizing equipment footprints. A typical coiled tubing layout requires a working space about half that of a conventional light workover hoist. The drilling site is easier to restore when operations are completed, and the impact of equipment mobilization on the environment is reduced.

In addition, coiled tubing and slimhole drilling enable less disruptive, quieter drilling operations, minimizing the noise impact on wildlife or humans near the well site. Since coiled tubing is a continuous pipe, most noises associated with conventional drilling pipes are avoided. Efficient insulation and the equipment's smaller size further reduce noise levels. For example, the noise level of a conventional rig at a 1,300-foot radius is 55 decibels, while a coiled tubing unit's noise level at the same distance is 40 decibels, or 27 percent less. The smaller size of coiled tubing drilling also cuts fuel use and reduces emission of gaseous air pollutants, compared with traditional rotary drilling.

Environmental benefits of slimhole drilling and coiled tubing include:

- Lower waste volumes
- Smaller footprints
- Reduced noise and visual impacts
- Reduced fuel use and emissions
- Protection of sensitive environments

Use of coiled tubing redefines equipment footprints.

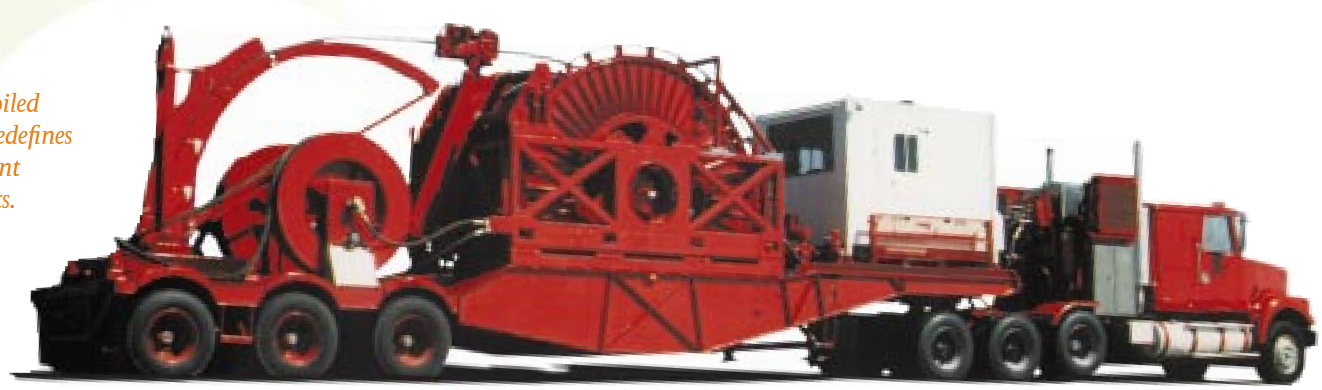


Photo: Haliburton Energy Serivces

METRICS

Impressive Performance from Modern Diamond Bits

Polycrystalline diamond compact (PDC) drill bits have become increasingly effective:

- **Between 1988 and 1994, technology advances increased the average footage drilled per PDC bit by over 260 percent (from approximately 1,600 to 4,200 feet per bit).**
- **Total footage drilled worldwide by diamond bits has climbed steadily, from approximately 1 percent in 1978, to 10 percent in 1985, and to 25 percent in 1997.**
- **Latest-generation PDC bits drill 150 to 200 percent faster than similar bits just a few years ago.**

Light modular drilling rigs

Now in production, new light modular drilling rigs can be deployed more easily in remote areas than conventional rigs. Fabricated from lighter and stronger materials, these rigs are built in pieces that can be transported individually and assembled on site. The lower weight of components and the rig reduces surface impacts during transport and use. The modular design also allows the rigs to be quickly disassembled and removed when drilling operations are completed.

Environmental benefits of light modular drilling rigs are:

- Smaller footprints
- Reduced fuel use and emissions
- Protection of sensitive environments (decreased surface impacts of transportation)

Measurement-while-drilling (MWD)

MWD systems measure downhole and formation parameters to allow more efficient and accurate drilling. By providing precise, real-time drilling data on bottomhole conditions, these systems reduce costs and improve the safety of drilling operations.

Combined with advanced interpretive software, MWD tools allow drilling engineers to more accurately determine formation pore pressures and fracture pressures as the well is being drilled. Such accurate geopressure analysis can help reduce the risk of life-threatening blowouts and fires. In the event of the loss of well control, MWD tools help engineers to quickly steer a relief well and regain control.

Environmental benefits of MWD systems include:

- Fewer wells
- Enhanced well control
- Less time on site

Improved drill bits

Advances in materials technology and bit hydraulics, spurred by competition between roller cone and polycrystalline diamond compact bits, have yielded tremendous improvement in drilling performance. Extensive field data indicate that, on average, a 15,000-foot well in Roger Mills County, Oklahoma, takes about 39 days to drill today, while that same well would have taken over 80 days in the 1970s. By reducing the time for the rig to be on site, advanced drill bits reduce potential impacts on soils, groundwater, wildlife, and air quality.

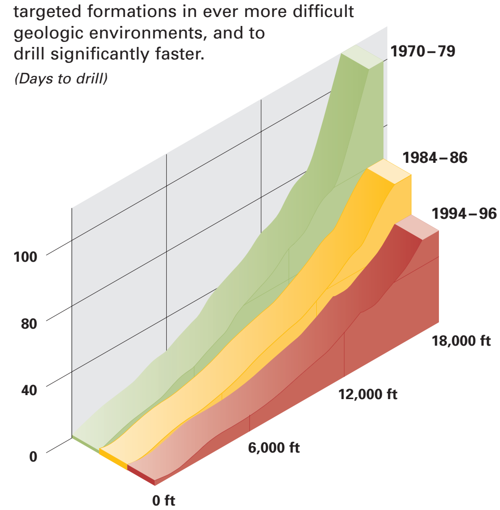
Environmental benefits of improved drill bits are:

- Lower waste volumes
- Reduced maintenance and workovers
- Reduced fuel use and emissions
- Enhanced well control,
- Less time on site

Decreased Drilling Time

Modern drill bits enable operators to contact targeted formations in ever more difficult geologic environments, and to drill significantly faster.

(Days to drill)



Source: Hart's Oil & Gas World, November 1996

METRICS

Synthetic Drilling Fluids (Muds) Cut Costs

An operator in the Gulf of Mexico found that synthetics significantly outperformed water-based fluids in a recent drilling operation. Of eight wells drilled under comparable conditions to the same depth:

- **The three wells drilled using synthetic fluids were completed in an average of 53 days at an average cost of $5.5 million.**
- **The five wells drilled using water-based fluids were completed in an average of 195 days at an average cost of $12.4 million.**

Advanced synthetic drilling fluids

Today's drilling fluids (muds) must perform effectively in extreme temperature and pressure environments, support industry's use of increasingly sophisticated drilling and completion technology, and be compatible with current environmental disposal standards. To meet these challenges in deepwater formations, synthetic drilling fluids combine the higher drilling performance of oil-based fluids with the lower toxicity and environmental impacts of water-based fluids. Because synthetic fluids can be recycled, they generate less waste than water-based fluids. Also, unlike oil-based fluids, these synthetics produce wastes that are thought to be environmentally benign, thus minimizing impact on marine life. Moreover, by eliminating the use of diesel as a mud base, synthetic fluids have low-toxicity and low-irritant properties that significantly enhance worker health and safety.

Environmental benefits of synthetic drilling fluids vs. water-based fluids are:

- Lower waste volumes
- Enhanced well control
- Lower toxicity of discharges
- Less time on site
- Protection of sensitive environments

Air percussion drilling

Air percussion or pneumatic drilling—used for natural gas wells in regions such as Appalachia—can eliminate the need for drilling liquids during drilling operations. As a result, only drill cuttings are generated, significantly reducing requirements for waste management and disposal. Although this technology has limited application, it can be an effective underbalanced drilling tool in mature fields, in formations with low downhole pressures, and in fluid-sensitive formations.

Environmental benefits of air percussion drilling include:

- Lower waste volumes
- Protection of sensitive environments

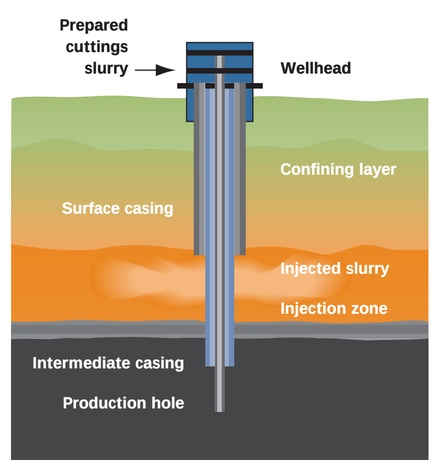
Annular injection of cuttings

In certain settings—such as deep onshore wells, remote offshore operations, and Alaska's North Slope—drilling cuttings can be disposed of by reinjecting them into the annulus around the drill pipe. Reinjecting wastes down the annulus eliminates several needs on the surface: waste management facilities, drilling waste reserve pits, and off-site transport. Returning the wastes to geologic formations far below the earth's surface minimizes the impacts of drilling operations on sensitive environments, and in many cases reduces the costs of drilling operations in these environments.

Environmental benefits of annular injection of cuttings include:

- Smaller footprints
- Lower toxicity of discharges
- Protection of sensitive environments

Downhole Cuttings Injection
Annular injection wellbore configuration



METRICS

Productivity Gains from CO_2-Sand Fracturing

CO_2-sand fracturing may greatly improve productivity in certain wells. After 37 months of DOE-supported field trials at 15 Devonian Shale test wells, wells fractured with CO_2-sand technology produced:

- **Four times as much gas per well as wells fractured with nitrogen foam and proppant.**
- **Twice as much gas per well as wells fractured with nitrogen gas.**

METRICS

A Major Contribution

In addition to being critical to natural gas production, hydraulic fracturing has enabled recovery of 8 billion barrels of additional oil reserves in North America.

Corrosion-resistant alloys

New alloys and composites for drill bits, drill pipe, and coiled tubing—particularly for equipment designed to operate in deep, hot, and sour (high concentrations of H_2S) wells—reduce well failure rates and the frequency of workovers and increase equipment life.

Environmental benefits of corrosion-resistant alloys are:

- Fewer wells
- Reduced maintenance and workovers
- Enhanced wellbore control
- Protection of sensitive environments

Improved completion and stimulation technology

Advanced completion and stimulation technology includes CO_2-sand fracturing, which yields clean fractures to increase well deliverability while avoiding the waste management and well maintenance costs associated with more traditional fracturing operations. In addition, advances in hydraulic fracturing technology—such as state-of-the-art fracture simulators and improved microseismic fracture mapping—have improved well placement and design, and increased ultimate recovery. In the over-pressured, highly permeable San Juan Basin fairway, operators are using advanced open hole cavitation techniques to produce more coalbed methane. Operators have found that dynamic open hole cavitation boosts production when compared with conventional cased and fractured completions, generally by three to seven times as much.

Environmental benefits of improved completion and stimulation technology include:

- Increased recovery
- Lower waste volumes
- Fewer wells drilled
- Protection of groundwater resources

Improved offshore drilling and completion technology

Today's offshore operations include more stable rigs and platforms, can drill in far greater water depths, and apply new controls to prevent spills. Subsea completion technology, for example, allows multiple wells to be drilled through steel templates on the seafloor. A small number of lines (or risers) then carry produced fluids from the templates to production facilities on the surface or to a platform collection system. This technology reduces the risks of spills and allows safe production from multiple wells as the industry approaches water depths of 10,000 feet.

New offshore platforms and wells feature extensive blowout prevention, well control, oil-spill contingency, and safety systems. All offshore wells have storm chokes that detect damage to surface valves and shut in the well to prevent spills. Blowout preventers are located at the seafloor instead of at the platform level, protecting sea beds and sea life, and sensors continuously monitor subsurface and subsea-bed conditions.

Environmental benefits of improved offshore drilling and completion technology include:

- Fewer wells
- Lower waste volumes
- Reduced maintenance and workovers
- Enhanced well control

Beyond the Oil Patch

- **Advances in horizontal drilling and technologies supporting its application, such as measurement-while-drilling (MWD) and coiled tubing, have expanded the technology's application to such areas as groundwater remediation and pipeline construction.**
- **Advances in drilling technologies for E&P, such as slimhole drilling, have been adapted for mining, geothermal, and water supply applications, as well as for application to research geology.**

Production

WITH ADVANCED RESERVOIR MANAGEMENT AND OTHER PRODUCTION TECHNOLOGIES, PRODUCERS RECOVER MORE RESOURCES FROM OIL AND GAS OPERATIONS, WHILE MINIMIZING PRODUCED WATER AND OTHER WASTES.

Higher Yields Plus a Cleaner Environment

Since the beginning of the commercial oil industry in 1859, just a handful of U.S. oil fields have topped the 1-billion-barrel mark for production. California's South Belridge field recently joined their ranks, thanks in large part to enhanced oil recovery technology.

The discovery at South Belridge in Kern County was described in 1911 by a San Francisco newspaper as "a small quantity of oil, not sufficient it is believed to be a commercial success." Production levels remained modest throughout the field's early years. A new era began for the field in the 1960s with the advent of steam injection to increase oil recovery. From an average production of 11,370 barrels per day at the end of the 1950s, the field by the end of December 1979 was producing 49,500 barrels per day. With a major development program by Shell, production peaked in 1987 at an average of 174,800 barrels per day. Though decline had set in, the field remained the Nation's fifth most productive oil field in 1994, with production averaging 120,000 barrels per day. By extending the productive life of fields such as South Belridge, enhanced oil recovery technology reduces the need for new exploration and drilling operations—and eliminates their associated environmental impacts.

Source: Oil & Gas Journal, October 16, 1995

Once a field is brought on production, good reservoir management is required to ensure that as much oil and gas as possible is produced as cost-effectively as possible, with minimal waste and environmental impact. Early producers, relying on natural pressure and primitive pumps, recovered only about 10 percent of the oil in a given field. They sometimes vented or flared natural gas produced in association with the oil. In contrast, today's producers use an arsenal of advanced recovery techniques to keep oil and gas resources flowing, enabling them to produce as much as 50 percent or more of the oil resources and 75 percent or more of the natural gas in a typical reservoir.

Progress has been particularly impressive in the last decade. In response to declining crude oil prices and relatively flat natural gas prices in the 1990s, operators throughout North America have initiated major programs to reduce production expenditures, resulting in further technological advances and more streamlined operations. Technology improvements have brought a dramatic decrease in the average cost of producing oil and gas, from a range of $9 to $15 per BOE in the 1980s to today's average of roughly $5 to $9 per BOE.

Producing Energy and Environmental Benefits

Improved production technology has greatly reduced environmental impacts as well as costs. For example, better reservoir management has decreased volumes of produced water, which, at about 15 billion barrels per year, is the largest waste stream generated in U.S. oil and gas exploration and production. On average, the industry produces about 6 barrels of water for every barrel of oil. Since management of produced water is expensive—ranging from about $0.10 to more than $4.00 per barrel—technology to minimize produced water volumes can yield significant cost efficiencies.

Many other advances—such as improved treatment of produced water, better control of hazardous air pollutants, more energy-efficient production operations, and reduction of greenhouse gas emissions from E&P operations—have also made oil and gas production progressively less waste-intensive and more productive.

Production from oil and gas operations generally flows around the clock. A constant stream of performance data allows a producer to reevaluate operations and make appropriate decisions over time.

Surface facilities gather the produced oil, gas, sands, and water into distinct streams. These streams are then processed to remove impurities from oil and gas products, capture gas and water for reinjection if enhanced recovery techniques are in use, and treat and properly use or dispose of any water or solid wastes. Finally, the product is transported to market.

Fundamentals of Production

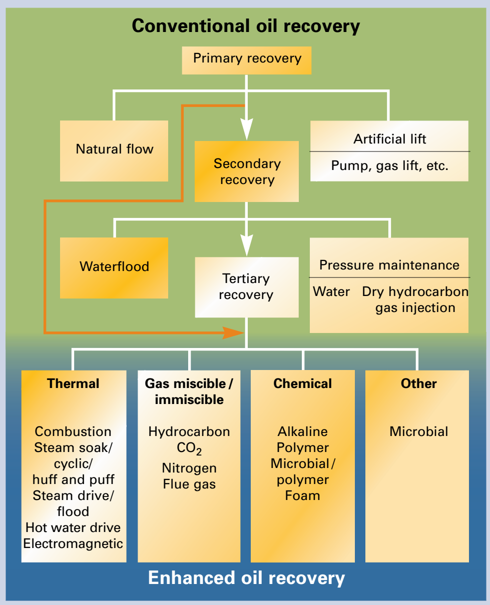
Advances in production technology that contribute significant environmental benefits include:

Improved recovery processes

Rapidly evolving oil recovery technology allows today's operators to extract more residual oil from existing reservoirs, after primary and secondary recovery. Residual oil may be either too viscous to be produced, trapped by interfacial tension, or lying in zones that have not been swept by injected fluids. The application of improved recovery technology has expanded to all producing areas of the country, allowing for production of some of the approximately 350 billion barrels of discovered but unproduced crude oil in the United States. Without improved recovery technologies, such as polymer-augmented waterflooding, the thermal processes of steam or hot water injection, and the injection of gases such as CO_2, flue gas, or nitrogen, these resources would be prematurely abandoned.

Oil and Gas Recovery Processes

Field development can occur in three distinct phases:

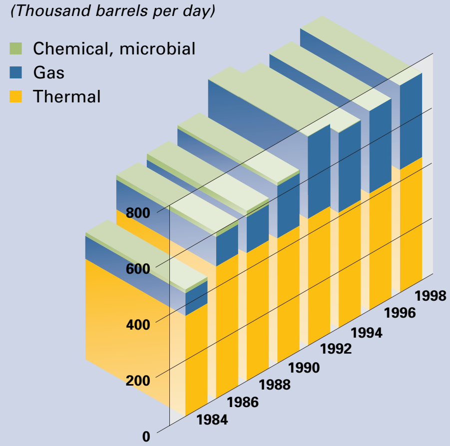


Source: Oil & Gas Journal, April 20, 1998

Enhanced Oil Recovery in the United States

Crude production from enhanced oil recovery

(Thousand barrels per day)



Source: Oil & Gas Journal, April 20, 1998

Primary Recovery

Primary recovery produces oil, gas, and/or water using the natural pressure in the reservoir. Wells can be stimulated through injection of acids or other fluids, which fracture the hydrocarbon-bearing formation to improve the flow of oil and gas from the reservoir to the wellbore. Other techniques, including artificial lift, pumping, and gas lift, help production when the reservoir's natural pressure dissipates.

Secondary Recovery

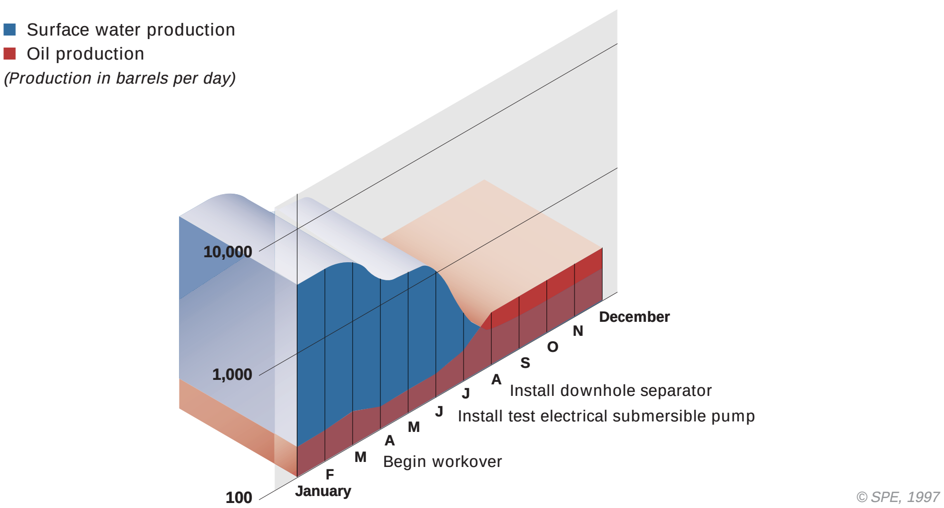
Secondary recovery uses other mechanisms—such as gas reinjection and water flooding—to energize the reservoir and displace fluids not produced in the primary recovery phase.

Enhanced Oil Recovery

Enhanced oil recovery involves the injection of other liquids or gases (such as surfactants, polymers, or carbon dioxide) or sources of heat (such as steam or hot water) to stimulate oil and gas flow and mobilize reservoir fluids that were bypassed in the primary and secondary recovery phases.

METRICS

Actual Example of Reduction in Produced Water Using Downhole Separation



Currently being tested in pilot-scale projects throughout the world, downhole separation may someday deliver significant cost savings and environmental benefits in settings where the technology is applicable. In one recent demonstration (illustrated here), down-hole separation decreased surface water production by 95 percent and increased oil production by 50 percent, resulting in a 4-month payback period.

Better reservoir management to reduce water production

Improved understanding of the flow mechanics of reservoirs—resulting from crosswell tomography, crosswell seismology, better logging tools, and other reservoir characterization advances—allows operators to reduce produced water volumes through more selective well placement and selective shutting in of some wells. Developments in completion technology, especially as applied in horizontal wells, are also helping to delay water breakthrough and maintain the ratio of produced oil to produced water as high and as long as possible.

Improved produced water treatment technology

In locations where surface discharge of produced water is still permitted (such as offshore and low-rate stripper wells in Appalachia), a variety of methods are being pursued to treat and reuse the water or discharge it to the surface without environ-mental impact. Approaches include hydro-cyclones, gas flotation, membrane separation, granular activated carbon fluidized-bed reactors, and biotreatment technology.

One particularly promising technology for low-rate well application in some climates and operational settings is the freeze-thaw/evaporation (FTE) process. Using a freeze crystallization process in winter and natural evaporation in summer, produced waters are separated into fresh water, concentrated brine, and solids. The resulting fresh water can be used for horticulture, livestock, and other beneficial uses. The remaining volume of wastes (solids and semisolids) requiring disposal is significantly reduced. This process requires large amounts of land and high volumes of produced water retention and is limited to climates with cold winters and dry summers, such as the Rocky Mountain region, the Northern Great Plains, and virtually all of Canada.

Downhole separation technology

In certain settings, downhole separation represents a potential solution to a significant environmental and cost issue for oil and gas operators: the management and disposal of produced water. In today's operations, water is generally pumped to the surface along with oil, then separated from the oil. Since volumes of produced water can exceed oil production by 10 times or more, companies incur size-able costs to lift the unwanted water, manage it on the surface, and dispose of it (usually by reinjection into the earth's subsurface). The approach also has the disadvantage of bring-ing contaminants up through the well piping.

In downhole separation, mechanical or natural methods are used in the wellbore to separate the formation's oil and water. The oil is then brought to the surface, while the water is directly pumped into a subsurface injection zone. In its current state of develop-ment, downhole separation is thought to be applicable only to light oil wells with relatively high flow rates and meeting minimum casing diameter and water-to-oil ratio standards.

Field tests are demonstrating that this technology, effectively deployed, has the potential to significantly reduce the produced water brought to the surface in applicable wells, directly reducing fluid lifting and disposal costs, as well as any associated environmental concerns. Downhole separation can also increase oil production in proportion to the decrease in water production.

In many parts of the country, the high cost of produced water management is the main reason for well abandonment. By controlling the increasing costs normally incurred as water volumes increase, downhole separation can potentially increase U.S. oil production and recoverable reserves.

In some cases, downhole separation may also enable increased oil production and recovery of original oil in place through improved or altered water flow distribution in the reservoir. In addition, dynamic control of the oil-water contact can be achieved through dual completion and reinjection.

Depending on how widely downhole separation is applied in the future, as much as 5 billion barrels per year of produced water that otherwise would have been brought to the surface will remain in the ground.

Better leak detection, measurement, and control systems for hazardous air pollutants

Technology advances on several fronts are reducing emissions of hazardous air pollutants in E&P operations. In the last decade, for example, many approaches have been developed to detect, measure, and control air pollutants from a variety of oil and gas field equipment. State-of-the-art leak detection and measurement systems pinpoint fugitive gas leaks, conserving valuable natural gas and identifying potentially life-threatening hazards to workers and the community. Vapor recovery units—economical for large operations with relatively high reservoir pressures and vapor releases—are being employed to reduce emissions of volatile organic compounds from storage tanks by as much as 95 percent. Improved management approaches for glycol dehydrators are also helping to reduce emissions substantially. In addition, new technology for removal and recovery of acid gas (hydrogen sulfide, mercaptans, and carbon dioxide) shows cost savings of 40 percent compared to current technology.

More energy-efficient production operations

Operators increasingly are focusing on ways to reduce energy use in their operations. For example, new stripper well beam pumps have reduced electricity consumption substantially. Improvements in energy efficiency result in corresponding reductions in emissions of air pollutants associated with energy use in production operations.

Better facility-wide waste management planning

The E&P industry, working with States, is aggressively employing technology and practices to reduce or eliminate waste by preventing it at the source. Techniques include better planning, materials management, materials reclamation, and recycling; major changes to E&P processes; improved auditing and maintenance procedures; changes in day-to-day operations to control waste generation; and more targeted employee training.

Increased focus on reducing greenhouse gas emissions

A wide variety of approaches are currently being pursued to reduce emissions of methane, a potent greenhouse gas thought to contribute to global climate change. Methane losses from oil and gas industry operations are considerable, and emission reduction techniques reduce both global emissions of greenhouse gases and the losses of a valuable product. Technology being pursued includes glycol dehydration using a separator-condenser (which can result in emissions recovery of over 95 percent), and replacing high-bleed pneumatic controllers (a particularly large source of methane emissions) with low-bleed pneumatic devices.

METRICS

Nature's technology provides water for agricultural and other beneficial uses. In suitable environments and under certain operating conditions, initial field tests indicate the freeze-thaw/evaporation process may reduce the volume of produced water requiring disposal by 80 percent.

Recent advances in coalbed reservoir engineering and completion practices have also turned coalbed methane—historically considered a safety hazard for mines and vented to the atmosphere—into a reliable energy resource. This resource now accounts for over 5 percent of U.S. gas production and 6 percent of proved gas reserves. Recovery rates are being further enhanced by the injection of carbon dioxide or nitrogen.

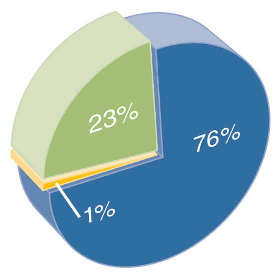
Gas-to-liquids technology is still on the cutting edge, but promises to make vast quantities of previously untapped natural gas transportable and marketable. The process chemically alters natural gas to form a stable synthetic liquid that performs more efficiently and with fewer greenhouse emissions than conventional fuels. The North Slope of Alaska alone is estimated to have 25 trillion cubic feet of natural gas that is currently undeveloped because transporting it to markets would be uneconomical. Gas-to-liquids technology may soon enable natural gas, the fuel of choice for environmental performance, to be transported around the world.

BEYOND THE OIL PATCH

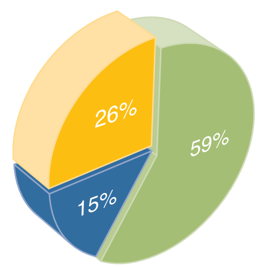
- **Developments in reservoir engineering and reservoir simulation technologies and processes have advanced our ability to predict groundwater flows, pollutant fate, and transport in groundwater, and to simulate the diffusion of air pollutants in the atmosphere.**
- **Adaptations of microbial enhanced oil recovery technology, originally developed for enhancing crude oil recovery, has proven to be quite effective in the remediation of hydrocarbon-contaminated sites.**

U.S. OIL PRODUCTION

Producing oil wells

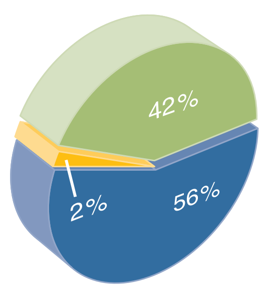


Crude oil production

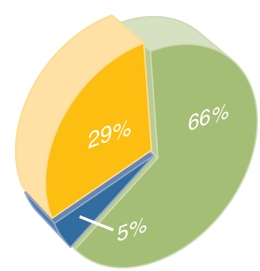


U.S. GAS PRODUCTION

Producing gas wells



Natural gas production



- Offshore
- Onshore–Stripper
- Onshore–Other

In the 33 oil- and gas-producing States, approximately 574,000 oil wells and 300,000 gas wells currently yield approximately 6.5 million barrels of oil and 54 billion cubic feet of gas per day. Most of these wells—approximately 435,000 oil wells and 170,000 gas wells—are classified as "stripper wells" because they produce less than 10 barrels of oil or 60,000 cubic feet of gas per day.

About 26 percent of U.S. oil production and 29 percent of gas production comes from offshore operations, predominantly in the Gulf of Mexico. Currently, there are over 5,000 producing structures in Federal offshore waters.

Source: American Petroleum Institute; U.S. Department of Energy; Independent Petroleum Association of America; and Interstate Oil and Gas Compact Commission

Site Restoration

ON LAND AND OFFSHORE, OIL AND GAS PRODUCERS HAVE DEVELOPED INNOVATIVE WAYS TO RESTORE SITES TO ORIGINAL—AND SOMETIMES BETTER-THAN ORIGINAL—CONDITION, FOR DIVERSE USES RANGING FROM HOUSING TO AGRICULTURE TO WILDLIFE HABITATS.

Photo: Corbis Images

LEAVING A POSITIVE ENVIRONMENTAL LEGACY

Diamond Y Spring in West Texas, a rare desert spring habitat, has been the site of an actively producing oil and gas field for decades. It also has been the focus of preservationists since the 1960s, with the discovery there of the Leon Springs pupfish, a species thought to be extinct. Pecos County cattle rancher M. R. Gonzales, who bought the property in 1969, was instrumental in bringing the spring's ecological significance to the attention of oil companies operating in the area. After a series of oil spills around the property, a diversion dike was build in 1974 to protect the headspring from any future spills.

The Nature Conservancy turned to the oil companies active in the area to provide funds for the purchase of Diamond Y Spring in 1990. Donations were made by Enron Corporation, Exxon, and the Mobil Foundation, and an innovative partnership was forged with these and other oil companies to establish protection and reclamation projects in the area of the springs. Old flow lines were replaced, pipelines near the spring system were encased in steel, many well sites were diked and bermed, abandoned wells were plugged, road construction was minimized, and areas were revegetated with native grasses and marshland flora. Today, the Leon Springs pupfish—together with rare snails, a unique salt-tolerant sunflower, the endangered Pecos gambusia fish, javelinas, foxes, and other species—continue to flourish on this unique desert spring property.

Source: The Nature Conservancy

Farming and oil and gas production have coexisted beneficially for decades in rural America.

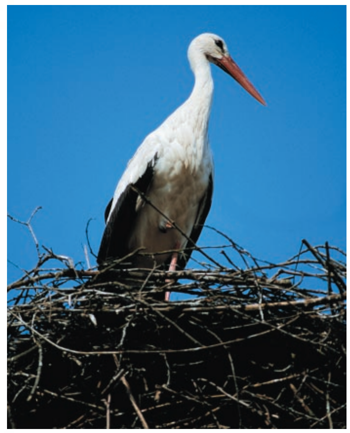
AFTER 15 TO 30 YEARS OF production, most oil or natural gas wells reach their economic limit. It is time to pack up and move on. Wellheads, pumpjacks, tanks, pipes, facilities, equipment... everything has to be removed from the site. The wells are then permanently plugged with cement to prevent future flow of subterranean fluids into the wellbore.

The vast majority of abandoned or ophaned wells in the United States today are a legacy of the industry's earliest environmental practices, when operators took only rudimentary steps to inhibit the fluids left in the formation or the wellbore from flowing to the surface, to restore the land, or to remove used equipment. These practices often created animosity with landowners, prompting State governments to address issues associated with past closures. Today's industry is responding to the environmental challenges of past closures and is treating site restoration as a critical operational activity. Specialized teams now handle site restorations, using new technology and approaches that often result in reduced liability as well as enhanced environmental conditions.

At land-based sites, the wellbore is plugged to confine the producing formation and to protect valuable groundwater resources. Waste-handling pits and other facilities are closed, and the location is then restored to near-original condition or prepared for its intended future use, whether as agricultural land, as a wildlife habitat, or as an industrial, residential, or commercial development site. Current strategies include maximizing reuse of equipment and materials still appropriate for other applications.

Closure of offshore facilities has begun only recently, so the legacy of past practices is not at issue here as it is with land-based sites. Decommissioning and removing offshore installations is a complex process, both legally and technically. It is essential to meet the wide variety of regulatory requirements and to ensure that the marine environment is not compromised. Alternative approaches are total or partial removal of the installation, or toppling on site. All require planning and preparation years in advance.

Advanced site restoration techniques enhance marine habitats.



Restoring, and Even Improving, Habitats

Today's site restoration strategies are significantly more environmentally protective than past approaches. In some instances, these strategies actually enhance the environment and create economic benefits.

"Rigs-to-reefs"...presenting homes for marine life

Decommissioning operations, especially in the Gulf of Mexico, have been largely dependent on the use of explosives. But shock waves from the blasts can damage sea life, other nearby installations, and surface vessels. And when an obsolete rig structure is towed to shore, cut up, and sold for scrap metal, the platform's artificial reef habitat is eliminated and the area's ecosystem is upset.

In the "rigs-to-reefs" approach, massive offshore platforms are toppled and sent to the bottom of the ocean, providing several acres of living and feeding habitat for thousands of underwater species. The first planned rigs-to-reefs conversion took place in Florida in 1979. In 1983, the Minerals Management Service—the agency that manages leasing, exploration, and development of Federal offshore lands—announced its support for rigs-to-reefs programs. These programs are beneficial from many perspectives. Marine life is enhanced. Oil companies realize considerable savings from avoided removal costs. And States receive a share of the savings as the companies donate operating platforms or obsolete rigs, construct reefs, and donate funds from their savings to support and enhance the State's marine ecosystems.

In 1984, the Federal government passed the National Fishing Enhancement Act, which further strengthened the program. Louisiana and Texas followed suit in 1986 and 1990, respectively, forming their own programs. Today all five States bordering the Gulf of Mexico have artificial reef programs, and such reefs also are found in other locations around the world.

Rigs make ideal artificial reefs. Constructed of corrosion-resistant steel that withstands displacement or breakup, rigs have a large, open structure that allows easy circulation for fish and provides havens for barnacles, corals, sponges, clams, bryozoans, and hybroids. Within six months to a year after a rig is initially placed on the sea floor, it will be a thriving reef ecosystem completely covered with marine life. When it is toppled, the newly created reef attracts additional mobile invertebrates and other fish species and an even more complex food chain develops.

The rigs-to-reefs approach saves the industry millions of dollars a year and also yields economic benefits for States:

- Generally 50 percent of the industry savings is donated to a host State's artificial reef program.
- Commercial and recreational fishing and recreational scuba diving prosper from the conversion, in turn increasing local tourism.
- Commercial divers are used for nearly all phases of the conversion.

Oilfield pits and pads... changing eyesores to assets

Caliche, the crust of calcium carbonate that forms on the stony soil of arid regions, is common in drilling pads and pits in many oil fields in Texas. A program recently initiated by the University of Texas converts these pits and pads into no-maintenance wildlife habitats. In the program, the pads and pits are recontoured to a depth of 18 inches, shrubs, grass, and forbs are planted, and a functional hydrologic cycle is reestablished. Natural recovery processes following drilling and production are accelerated and can quickly transform sites into desirable habitats.

Drill cuttings to create or restore wetlands

With assistance from DOE's National Petroleum Technology Office, Southeastern Louisiana University is exploring whether drill cuttings can be safely used to restore and create wetlands. Using unique temperature-controlled mesocosm greenhouse

facilities to simulate a wetland's full range of tidal fluctuations, researchers found that processed drill cuttings generally exhibited low levels of toxicity and appeared capable of supporting healthy wetlands vegetation. In some cases, the elemental composition of restored drill cuttings was found to be very similar to dredge spoil currently in use as a wetlands creation substrate.

New approaches to reclaiming and remediating abandoned well sites

The Oklahoma Energy Resources Board (OERB), with support from the U.S. Department of Energy, has been evaluating and restoring abandoned and orphaned drilling and production sites with no current owner or operator. Since 1995, OERB has restored more than 1,000 sites across 52 counties, and restoration is in process at an additional 500 sites. Under the OERB program, oil and gas producers and royalty owners in Oklahoma voluntarily finance the site clean-up—the landowner pays nothing, and OERB is not reimbursed from any other source. The OERB effort was the Nation's first industry-funded environmental cleanup and education program. Today, similar programs have been adopted in several other States.

Road mix from nonhazardous oilfield waste

In road building, native soils are typically excavated to prepare a road base and then used as aggregate (course binding material) in the on-site mixing process. For roads in oil and gas operations, a recently developed approach uses recycled crude oil tank residuals and other nontoxic wastes as an aggregate. Although this practice has limited application, it has proven effective in reducing particulate matter from unpaved roads and other road dust emissions. Roads of these materials provide all-weather access to remote exploration and production sites, improve driving conditions, and decrease dust generation in production areas.

Case Study

From Oil Fields to Housing

Here are two illustrations of how effectively exploration and production sites and their wastes can be adapted for reuse:

California (United States)

When the West Coyote oil field was discovered in 1909 near La Habra, California, it was 10 miles from the nearest town. By 1980, the field was nearly depleted and was surrounded by housing developments. Since then, Chevron's real estate management group has converted the field from a potential liability into a prime real estate asset through careful abandonments of tank farms, oil wells, and multiple surface facilities, and subsequent site restoration—all in line with very strict environmental regulations and constraints. The rolling hills are now the site of premium homes.

Colombia (South America)

In looking at options for disposing of drill cuttings from its Colombian operations, BP Amoco staff came up with a new answer: using the cuttings as a raw material for bricks. The deceptively simple idea has met a vital need in the local community, where building materials had been scarce and expensive. The approach has also eliminated the environmental impacts of traditional disposal methods, which involved placing lime-fixated cuttings in lined pits. Today, the bricks are manufactured by local companies, using a combination of cement and water-based drill cuttings. Cuttings produced from drilling just one well can make up to 700,000 new bricks.

Beyond the Oil Patch

Developments resulting from the restoration of oil and gas E&P sites have been adapted and applied to the restoration of a wide variety of industrial facilities.

Operations in Sensitive Environments

From the tundra of Alaska to the wetlands of Louisiana, a host of advanced technologies enable the oil and gas industry to produce resources far beneath sensitive environments.

Smaller Footprints, Less Waste, Lower Impact

A GROWING PROPORTION OF THE Nation's remaining untapped resources exist in sensitive environments—which are as varied as the mountains and tundra of Alaska, offshore California, the deepwater Gulf of Mexico, and the wetlands of coastal Texas and Louisiana—and even in the midst of bustling urban centers. Moreover, many of these fragile areas reside on our Nation's public lands, requiring industry and government to work collaboratively as stewards of these treasures. Industry simply cannot afford failures in these fragile settings. Over the last four decades, the industry has developed increasingly innovative technology and approaches for conducting operations in sensitive areas, improving not only environmental performance, but economic performance and resource recovery as well.

Technology that enables safe and efficient exploration and production beneath sensitive environmental areas includes new 3-D seismic and 4-D time-lapse imaging, satellite imaging, aeromagnetic sensing, and ground-penetrating radar. New acoustical and vibration devices have also replaced explosives for generating seismic signals onshore and offshore, reducing noise and protecting marine and animal life. And new directional drilling, extended-reach drilling, and multilateral drilling technology, coupled with measurement-while-drilling systems, allow industry to safely produce resources far beneath sensitive environments with less surface disturbance.

arctic environments

From Alaska's North Slope to Kenai . . . Greater Protective Measures

Photo: The Stock Market

Established by President Theodore Roosevelt, southern Alaska's Kenai National Wildlife Refuge is home to moose, Dall sheep, mountain goat, caribou, coyote, wolf, grizzly bear, black bear, lynx, wolverine, beaver, small mammals, birds, and salmon. It is also home to the Swanson River oil field. Unocal, operator of the field since 1992, received the "National Health of the Land" award in 1997 from the U.S. Department of the Interior for environmental excellence at Swanson River.

To ensure that its oil and gas operations within the refuge are conducted in an environmentally responsible manner, Unocal has implemented state-of-the-art practices. Plastic pipeliners have been installed on 28,000 linear feet of metal gathering lines and flow lines to avoid the potential for leaks. Specially trained dogs are used for the early detection of underground pipeline leaks. A water filtration and treatment system collects and processes runoff to prevent problems that may arise from the leakage of hydrocarbon compounds from old petroleum storage facilities. And groundwater-monitoring wells ensure that if contamination of groundwater occurs, it is quickly detected. Together, these measures protect a habitat that will be a refuge to wildlife and an inspiration to visitors for many generations to come.

Source: Unocal Corporation, 1996–97 Health, Environmental, and Safety Report

Logistical barriers—posed by extremely low temperatures, freezing and thawing of the tundra, and remote locations—once limited drilling in arctic environments. Today's operators not only cope successfully with these challenges, but also institute protective measures appropriate to sensitive environments. Improvements over the past 40 years have dramatically reduced industry's footprint on the fragile tundra, minimized waste produced, and protected the land for resident and migratory wildlife. Environmental advances have also dramatically reduced costs of conducting oil and gas activities. Industry innovations include:

Ice pads and roads

As ice construction technology and equipment have improved in recent years, bitter-cold temperatures have been turned to good use. Ice-based roads, bridges, drilling pads, and airstrips have become the standard for North Slope exploration projects. Not only is ice-based fabrication cheaper than gravel, it leaves virtually no footprint on the tundra; ice structures simply thaw and melt in the spring. In recent years, this approach has been further improved: BP Exploration (Alaska) Inc. (BPXA) has successfully built insulated ice pads for drill rigs, permitting the company to extend its exploratory drilling season significantly and to reduce both seasonal mobilization of equipment and drilling footprints, as well as operating costs.

Low-impact exploration approaches

When exploratory wells are too far from existing infrastructure to build ice roads cost-effectively, alternate means of transportation are now used almost exclusively. Large all-terrain vehicles with huge, low-pressure, balloon-like tires carry substantial equipment loads across the tundra, leaving practically no tracks. To protect the North Slope's fragile tundra, exploratory operations are now conducted exclusively during the winter.

Advanced drilling technology

Advances in drilling technology have played a major role in increasing North Slope productivity and in benefiting the environment. Horizontal drilling, introduced in 1990, now accounts for 90 percent of the wells drilled in Prudhoe Bay. Whereas early horizontal wells in Prudhoe penetrated only 500 to 800 feet of reservoir laterally, technology advances

recently enabled a North Slope operator to penetrate 8,000 feet of reservoir horizontally, greatly increasing contact with oil-bearing sands. If the bay were developed today using horizontal drilling, only 11 drill sites would be needed, compared to the 42 required in the 1970s. The area's first multilateral well was drilled less than two years ago; today there are 10 multilateral wells in the area, two of which used coiled tubing rigs.

A technology recently introduced jointly by ARCO-Alaska and BPXA is truly revolutionary. Called through-tubing rotary drilling, it allows an operator to drill a new well through the existing production tubing of an older well, saving both time and money. Another recent North Slope breakthrough is "designer wells" technology, an advanced form of directional drilling, where wells curve around and behind geological barriers to reach small pay zones. Extended-reach drilling is also greatly improving resource recovery and environmental protection in the area. Using extended-reach drilling, North Slope operators expect to develop the area's newest giant field, the 1-billion-barrel Alpine field, with 100 wells from only two drill sites, minimizing the drilling footprint. At Niakuk, operators have used extended-reach drilling to tap many offshore locations from a single drill pad on Heald Point.

By increasing resource recovery and reducing drilling costs, all these advances have benefited the economics of North Slope operators. By minimizing the number of wells drilled, drilling footprints, and waste volumes, they have benefited the environment as well.

Reduced footprint

Significant reductions in the size of production-related facilities have shrunk the footprint of North Slope operations. ARCO-Alaska's Kuparuk field, for example, uses a 55-acre facility as an operations base for contractor support, compared with a similar 1,000-acre facility in the original Prudhoe Bay field. If the entire Prudhoe Bay oil field were built with today's technology, its footprint would be 64 percent smaller than its current size—the area impacted by drilling pads would be 74 percent smaller, roads would cover 58 percent less surface area, and oil and gas separating facilities would take up 50 percent less space. Today, new production pads are up to 70 percent smaller than the original Prudhoe pads, and spacing between wellheads has been reduced dramatically. In addition, facilities are now built more quickly than previous ones, further reducing construction costs and disturbances to the environment.

Improved methods for site restoration and enhancement

In the fragile North Slope ecosystem, site restoration and habitat enhancement are a vital part of post-production. As North Slope operators continue their search for advanced environmental solutions, new technology and practices have been developed to restore areas affected by E&P activities. For example, at a number of abandoned gravel mining sites in floodplains, BPXA and ARCO-Alaska flooded the sites to create large pools and lakes that serve as overwintering habitats for fish and predator-free nesting sites for waterfowl, a practice encouraged by the Alaska Department of Fish and Game.

Revegetation of areas affected by gravel construction and drilling is also an important restoration technique. Between 1985 and 1989, BPXA and the U.S. Department of Fish and Wildlife worked jointly to restore the habitat along the 10-mile-long Endicott road. Researchers found that transplanting arctic pendant grass successfully revegetated disturbed aquatic sites. In 1988, BPXA began restoring its BP Pad, an exploratory drilling site first used nearly 20 years earlier. After equipment and debris were removed, the well was plugged and construction gravel was excavated from the site. BPXA seeded the wellsite and surrounding tundra with three types of native grasses and fertilized the area. A snow fence was erected to create snowdrifts that would increase moisture levels at the site. Within three years, the area's native vegetation had been restored.

wetlands, coastal, and offshore

Wetlands and Coastal Operations . . . Ecosystems Preserved

Growing national awareness of the environmental significance of wetlands and coastal areas has inhibited E&P operations in certain areas. Where operations are conducted, the industry takes extreme care to minimize all associated risks. Technology such as directional drilling is critical in minimizing surface disturbance in wetlands and coastal areas. Advanced site restoration methods for these sites are also a vital industry pursuit.

Today, operators employ a variety of advanced drilling and production technologies to operate safely in sensitive wetlands and coastal areas. In the wetlands of south Louisiana, for example, ARCO Oil and Gas Co. employed innovative drilling technology to conduct operations that were both environmentally safe and cost-effective. By utilizing an efficient closed loop solids control system, ARCO reduced both its drilling footprint and its waste volumes.

A recent drilling operation on Padre Island National Seashore on the Gulf Coast of Texas, the longest remaining undeveloped barrier island in the world and one of our Nation's most treasured Federal lands, also demonstrates this commitment to environmentally responsible operations. In drilling an exploratory well near the seashore's Malaquite Beach, Bright & Co. undertook extensive cooperative planning and regulatory compliance efforts with Federal and State agencies, while utilizing state-of-the-art drilling and site restoration technology to minimize impacts. For example, drilling operations were conducted with a diesel-electric rig, which operated at extremely low noise levels. Most of the rig's components were wheel-mounted, reducing the number of equipment loads moved across the beach. The drilling system's mud pumps and draw works were powered by electric motors—using electric motors not only reduced air emissions from the site, it minimized the possibility of harmful oil leaks.

Since the targeted pay zone was located under a large wetlands area, directional drilling was employed to drill beneath the sensitive area, greatly reducing environmental impacts. During its operations, Bright & Co. utilized an advanced polycrystalline diamond compact bit in order to maintain the well's angle and direction. Finding no productive zones in the well, Bright & Co. plugged and abandoned the well, restored the site to its original contours, and reseeded with native grass.

These are but two examples that represent the oil and gas industry's commitment to operate responsibly in sensitive wetland and coastal areas. This commitment is recognized outside the industry as well. Robert J. Potts, State Director of The Nature Conservancy's Texas office, recently noted, "The Nature Conservancy of Texas has a long history of cooperative partnerships with the oil and gas industry. Several of our preserves are home to ongoing oil and gas operations while at the same time providing excellent habitat for wildlife."

Offshore Operations...Operating Safer, Smarter, and Deeper

From the Gulf of Mexico's subsalt plays, to the hostile North Sea, to offshore West Africa and Brazil, as the offshore oil and gas industry moves into deeper and more remote settings in search of new resources, operators are utilizing a variety of advanced technologies to protect the environment, enhance worker safety, and increase recovery. Offshore operations, which occur in the midst of complex underwater ecosystems consisting of hundreds of aquatic species and flora types, require extreme care and planning. Today, advanced technology is meeting these challenges.

Advanced 3-D seismic and 4-D time-lapse data processing and imaging technologies, coupled with satellite-derived bathymetry and gravity data, enable offshore operators to locate oil and gas resources far more accurately than only one decade ago, resulting in fewer dry holes, less drilling, and greater resource recovery. For example, the Gulf of Mexico's subsalt play, completely undeveloped 10 years ago, is now one of the world's hottest offshore settings, thanks to state-of-art subsalt imaging technology such as Full Tensor Gradient (FTG) imaging and marine magnetotelluric surveys.

Not only is the industry finding and developing resources in more remote and challenging settings, it is significantly enhancing worker safety and pollution control in the process. Today, nearly all Outer Continental Shelf operators are collaborating with the Minerals Management Service and other Federal agencies to implement Safety and Environmental Management Programs (SEMP), voluntary, nonregulatory strategies designed to identify and reduce risks and occurrences of offshore accidents, injuries, and spills. As a result, this commitment to safer and smarter operating practices has enabled the offshore industry to practically eliminate oil spills from offshore platforms.

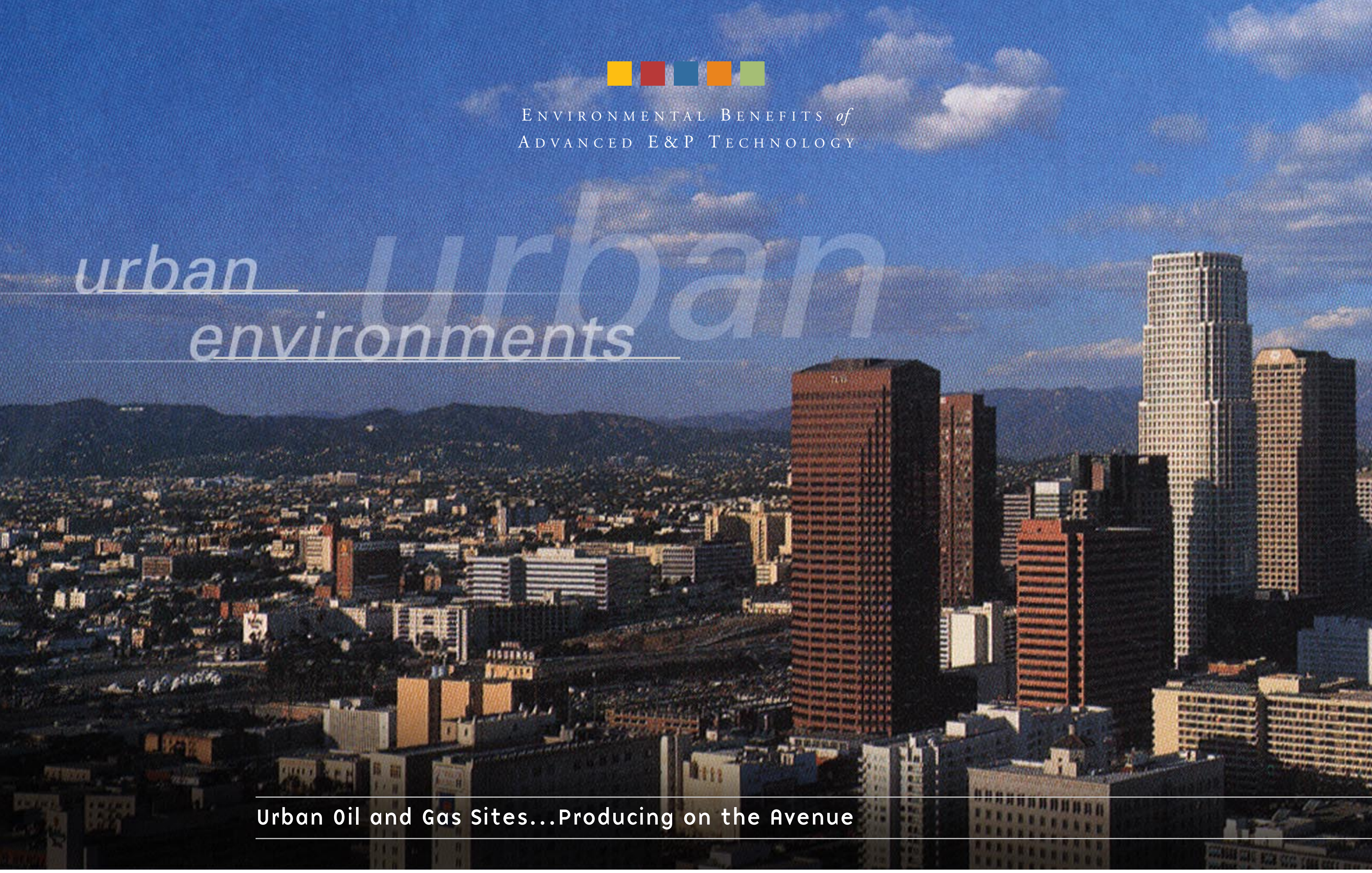
Today's advanced subsea drilling and completion technology also enables the industry to operate effectively and safely as it moves into deeper and more hostile areas. For example, advanced subsea blowout preventers (BOPs) maintain well control in deepwater environments. Current deepwater BOPs, located on the sea floor instead of at the platform level, continuously monitor subsurface and subseabed conditions.

In the event of a well control emergency, advanced "intelligent" subsea trees allow live wells to be shut in quickly under a variety of well conditions and operational circumstances. Moreover, current measurement-while-drilling technology enables drillers to accurately steer a deepwater relief well to regain well control if necessary.

Other recent advances in subsea technology are permitting operators to access more remote deepwater resources with minimal disturbance to the surface and subsea environments. Subsea production systems, aided by new-generation remotely operated vehicles, all-electric subsea monitoring and

control systems, and minimally sized umbilicals, are now able to connect remote subsea satellite wells to host production facilities tens of miles away. For example, Shell Exploration and Production's Mensa subsea production system, located in over 5,000 feet of water in the Gulf of Mexico, produces natural gas from three subsea wells connected to a subsea manifold sitting on the sea floor, which is then tied back to an existing shallow water production platform (West Delta 143) over 60 miles away via a 12-inch carbon steel flowline. At West Delta 143, a computer-based system monitors the operational status of the wells and other subsea equipment, with the capability to open and close the wells if necessary.

On the whole, these technologies are allowing the offshore industry to venture into deeper waters than ever before, while protecting marine life and subsea habitats. As a result of these advances, operators are able to locate and produce more offshore resources, with less drilling, fewer dry holes, less waste, and minimal impact.



urban environments

Urban Oil and Gas Sites...Producing on the Avenue

> "Hundreds of visitors from all around the world visit our islands every year, many of whom come here specifically to learn about this model of oilfield development in a sensitive, urban environment. I haven't met a person yet who doesn't come away impressed."
>
> James M. Davis
> *President of ARCO Long Beach, Inc.*

Diverse images come to mind when one envisions oil and gas exploration and production sites: scorching hot deserts; windblown, tumbleweed-strewn prairies; vast frozen tundra; 20-foot-high waves and churning whitecaps; and distant mountain ranges. But few people realize that the petroleum industry also explores for and produces oil and gas in the midst of our Nation's largest cities. In recent decades, the industry has successfully met the unique challenges posed by these urban environments, where operations are frequently visible for all to see. Advanced technology has been a key to meeting the challenges.

Urban operations are as varied as the cities in which they are located. For example, visitors to Oklahoma City are greeted with the sight of pumpjacks and other production equipment and facilities—Oklahoma City's Will Rogers World Airport is located in the heart of an active oil field. The Los Angeles Downtown oil field, located in the shadow of the Santa Monica Freeway and near the Los Angeles Civic Center, has produced nearly 14 million barrels of oil and 21 billion cubic feet of natural gas over the past 30 years. State-of-the-art fire prevention and gas leak detectors ensure the safety of the surrounding community. In the Southern California beach community of Huntington Beach, oil and gas development occurs both onshore and in State offshore waters. Onshore, production equipment located on the beach operates as runners and bicyclists enjoy a nearby boardwalk. Offshore, extended-reach drilling technology has permitted operators to tap nearshore reserves from onshore deviated wells.

Perhaps the most remarkable story of urban operations today is ARCO Long Beach, Inc.'s 43,000-barrel-per-day operation at the East Wilmington unit, located in the City of Long Beach's scenic harbor. The East Wilmington unit is part of the giant Wilmington field, one of the Nation's largest. Production at East Wilmington occurs from four manmade islands—built on 640,000 tons of boulders and 3.2 million cubic yards of sand dredged from the harbor, and concealed by palm trees, flowers, concrete sculptures, waterfalls, and colorful

nighttime lighting. These islands represent the centerpiece of a collaborative solution between the industry and the City of Long Beach to tap the harbor's resources without harming its natural beauty.

Daily operations at East Wilmington are a testament to advanced technology and its success in protecting the environment. Rather than using relatively noisy and polluting diesel engines for drilling and pumping, operations make use of quiet and clean electric power. To shelter operations from public view, drilling rigs are covered by structures built to resemble high-rise buildings, and wellheads and other support facilities are located below ground.

In recent years, advanced technology has played a critical role in expanding the field's production and maintaining a high level of environmental performance. In 1996, ARCO implemented the largest waterflood in California's history at the field. This oil recovery technique, combined with advanced hydraulic fracturing and horizontal drilling technology, has increased daily oil production by approximately 30 percent. Moreover, ARCO is expecting a recently conducted 3-D seismic survey to further boost production.

ARCO is now using chemical treatment for final separation of produced water and oil rather than gas-fired heated vessels, reducing air emissions by 60 percent. The thousands of tons of sand and shale removed during operations are now reinjected into a dedicated well on one of the production islands, rather than hauled to a landfill. Moreover, ARCO is currently testing the viability of using treated sewage effluent in its waterflood operations in order to reduce the amount of fresh water currently needed.

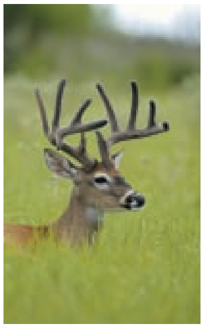
Advanced technology has enabled the petroleum industry to increase recovery of oil and gas resources wherever they may occur—including urban environments. As a result, oil and gas development operations are able to coexist, even thrive, in urban surroundings, as operators successfully minimize noise pollution, air emissions, and surface and visual disturbances.

Oilfield development in Long Beach harbor is a model urban operation.

public lands

public lands public benefit

Joint Stewardship Protects Our Public Treasures



Stewardship of public lands requires close collaboration of industry and government.

Many of our Nation's oil and gas resources are located on public lands, over which the Federal government has management and resource protection responsibilities. These public lands range from wildlife refuges to national parks and seashores to the Outer Continental Shelf. Operating in these national treasures entails complex logistical, organizational, and operational challenges. The industry, in collaboration with the Department of the Interior and other Federal and State agencies, has employed a variety of advanced technologies and creative solutions to operate effectively in these areas, thus providing the environmental stewardship necessary.

In the Aransas National Wildlife Refuge on Texas' Gulf Coast, for example, Conoco has worked collaboratively with the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and the Texas Parks and Wildlife Park for 60 years to ensure that ongoing operations do not harm the refuge's whooping crane population. Once one of the rarest species in North America, the refuge's whooping crane population has increased in number from 15 to approximately 200 over the last half century. Today, Conoco performs seismic and drilling operations only when the cranes are summering in Canada, avoids the marshlands inhabited by cranes, and protects the wolfberry plants on which they feed.

In Alaska's Kenai National Wildlife Refuge, Unocal Alaska won the Department of Interior's "National Health of the Land" award in 1997 for environmental excellence in its Swanson River field operations. Employing advanced pipeline maintenance, leak detection, and water filtration/treatment technologies, Unocal continues to operate successfully in this beautiful, yet fragile, environment.

Chevron USA Production Company's recent exploratory drilling operation at the Hunter Creek site in Lincoln County, Wyoming, further demonstrates advanced

technology's positive impact on industry performance in sensitive public lands. The Hunter Creek site is located in the Bridger-Teton National Forest—approximately 20 miles from Grand Teton National Park and within the Greater Yellowstone Ecosystem—and is home to a wide variety of sensitive wildlife species, from black bears to bighorn sheep to peregrine falcons. Chevron worked closely with the U.S. Forest Service, the Department of the Interior, the Wyoming Fish and Game Department, and other Federal and State agencies to design and conduct operations with minimal impact on the surrounding habitat and wildlife. Although the site's exploratory well was not a commercial success, Chevron's goal of reducing environmental impacts was achieved.

To minimize surface impacts of equipment mobilization on the area's main access road, the Hunter Creek operation became only the second well in the lower-48 States to be drilled utilizing a helicopter to transport the drilling rig and other heavy equipment to and from the site. The drilling pad was designed to blend in with the surrounding meadows and clearings by carefully locating the site, contouring the area cleared of trees, and leaving some of the site's trees intact.

To enhance site restoration activities, Chevron stockpiled snags, boulders, and stumps so that the site could eventually be returned to its natural state.

To manage drilling wastes, a semi-closed-loop solids removal system was employed, minimizing mud volumes and thus enabling smaller reserve pits. To reduce sedimentation impacts from runoff contact with exposed soil near the pad, the drilling location was enclosed by drain canals, drainage ditches, berms, and containment pit, and capped with four inches of gravel. To further manage operations, Chevron implemented surface and groundwater quality protection plans to ensure protection of surrounding creeks and underground water supplies.

These operations demonstrate the petroleum industry's commitment to environmentally responsible operations on our Nation's public lands. By collaborating with the numerous Federal and State agencies with stewardship responsibilities over these valued areas, the oil and gas industry is today fulfilling its role as protectors of the environment—and advanced technology is playing a large part in this success.

Beyond the Oil Patch

Research and demonstrations of the restoration of sensitive environments have advanced the state of knowledge and understanding of a wide variety of sensitive ecosystems.

The Future

Until now, in every aspect of the oil and gas business — from satellite sighting of under-earth resources, to production, to refining, to product formulation — technological progress has transformed the ability of the oil and gas industry to meet the imperatives of both the environment and the marketplace. • Now the bar is being raised. The new century brings an array of environmental, economic, and political challenges that will inevitably stretch the resources and test the will of the industry. Strategic issues currently facing the industry include remaining successful in an evolving and volatile marketplace; sustaining science and technology

Exploration

Drilling and Completion

Production

Site Restoration

Operations in Sensitive Environments

Photo: The Stock Market

Remaining Successful in an Evolving and Volatile Marketplace

As this report goes to press, oil prices at wellhead in the United States have increased approximately 80 percent since December 1998, when prices were at their lowest levels since the Great Depression. Although low prices enabled energy consumers and the United States economy to reap tremendous savings, low prices also threatened the economic viability of the domestic oil and gas industry and our Nation's longer-term oil and gas production capacity and energy security.

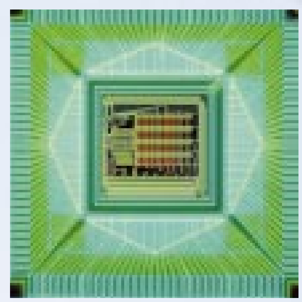


Photo: Corbis Images

Sustaining Science and Technology Progress

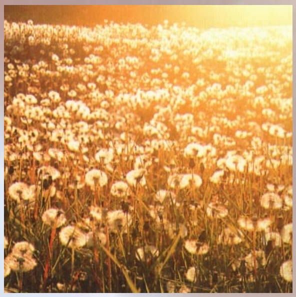
On the domestic E&P front, oil and gas resources will become increasingly difficult to find and produce. Although significant new resources remain to be discovered in previously unreachable areas, low oil prices will constrain E&P investments. If these domestic resources are to be developed, industry will be challenged to develop and apply E&P technologies that are even more productive and innovative than today's best. Ongoing R&D will be vitally important.

Challenges

progress; minimizing and controlling greenhouse gases; and ensuring responsible development. • In the longer term, worldwide demand for oil and gas is projected to increase significantly, possibly raising competitive tensions, particularly between the developed and developing nations. Increased productivity in E&P will be essential if the industry is to keep pace with demand. • If the past is prologue, further advances in science and technology can enable these challenges to be met. Technology innovations, stimulated by shared societal objectives for a sustainable future and enabled by a flexible, responsive government regulatory and policy framework, can ensure a brighter tomorrow.

Minimizing and Controlling Greenhouse Gases

Concerns about global climate change are expected to drive reductions in greenhouse gas emissions associated with the production and use of fossil energy. Scientists cite such phenomena as the melting of the polar ice caps and increases in weather volatility as evidence that climate change is already under way, and consensus is growing among both political and industry leaders that actions must be taken to reduce greenhouse gas emissions to prevent far-reaching consequences. The oil and gas industry will be challenged to minimize and control these emissions on many fronts, including in E&P.



Ensuring Responsible Development

Environmental challenges for the exploration and production of oil and gas will intensify. Industry will face increased concerns and pressures related to land, air, and water quality issues, environmental justice, preservation of indigenous plants, animals, and people throughout the world, and protection of the earth's ozone layer. Continued improvements in efficiency, waste minimization, ecology-sensitive solutions, and societal interactions in E&P will be required.

DAUNTING CHALLENGES DEMAND NEW SOLUTIONS

Remaining Successful in an Evolving and Volatile Marketplace

MOST INDUSTRY EXPERTS PROJECT that worldwide demand for oil and gas will grow considerably over the longer term. As a result, the international petroleum industry will face intensified pressure to provide increased volumes of crude oil and natural gas at reasonable prices. Industry success will depend on continued improvements to productivity and efficiency.

The global oil and gas industry is struggling to survive in the increasingly competitive and volatile marketplace. Mergers and acquisitions, such as the BP-Amoco and Exxon-Mobil mergers, are unprecedented in both scale and pace. Moreover, the industry is going through a fundamental transformation —many countries with traditionally government-operated national petroleum companies are divesting assets and opening their borders to international investment and development.

The petroleum industry has in the past and must continue in the future to be able to withstand change in the marketplace. The industry has a long record of success in assessing and managing risk, and in handling the cyclic oil prices that have been a hallmark of the petroleum business. By most accounts the year 1998 was considered one of the worst the industry has ever experienced. Adjusting for inflation, world oil prices reached the lowest level in 25 years. Throughout 1999, however, world oil prices have rebounded considerably, increasing nearly 50 percent in the first six months of the year.

Increased productivity in E&P is vital to meeting future demand growth.

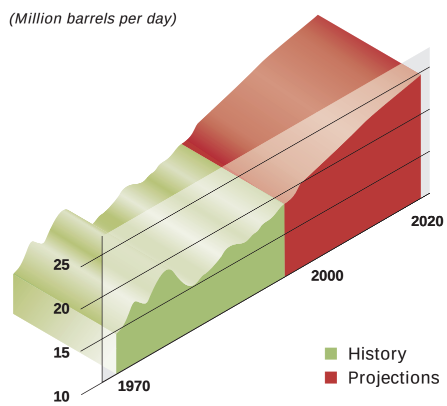
Low oil prices: What's at stake?

While low oil prices, such as those in 1998, enable energy consumers to reap significant savings, they also threaten the viability of the domestic petroleum industry. The number of rigs drilling in the United States in 1998 was 60 percent lower than the year earlier. Upstream employment dropped to levels not seen in decades, to an annual average of almost 326,000, the lowest level in 25 years —nearly 55 percent lower than the record employment levels of the early 1980s. And U.S. imports of crude oil reached an all-time high of 8.6 million barrels per day.

Low prices make marginally producing wells (especially those producing fewer than 10 barrels per day) particularly susceptible to premature abandonment. In 1997, approximately 436,000 oil wells in the United States produced fewer than 10 barrels per day. With 353 million barrels produced, these wells accounted for almost 15 percent of domestic oil production.

In 1998, company budgets for exploration and development expenditures were dramatically reduced from previous years. Finding capital for new projects and preserving the existing infrastructure—including leases, wells, drilling and service equipment, transmission pipelines, and a skilled workforce—became increasingly difficult. Although industry is breathing easier these days, the pain of low oil prices has not faded. Despite months of recovering prices, rig activity remains near historic lows. Some analysts predict that domestic E&P spending will decrease 20 percent in 1999.

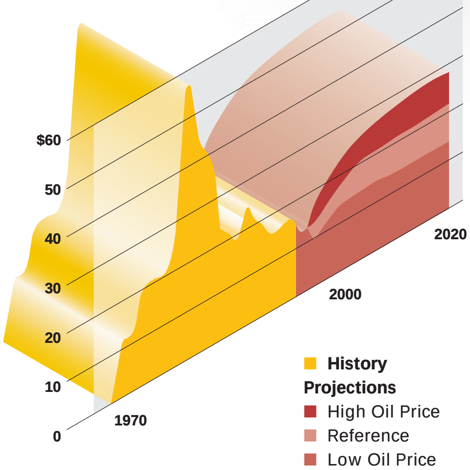
U.S. Consumption of Petroleum Products, 1970–2020
(Million barrels per day)



Source: Energy Information Administration, 1998

U.S. Crude Oil Prices, 1970 – 2020

(1997 dollars per barrel)



Source: Energy Information Administration, 1998

Low oil prices pose a particular threat to smaller domestic companies, those of insufficient size, diversification, or worldwide presence to "weather the storm." In the United States, the vast majority of oil and gas companies are smaller independent firms with fewer than 20 employees. These independents drill 85 percent of all new oil and gas wells in the country and produce 40 percent of the crude oil and 65 percent of the natural gas.

Americans enjoying the low prices at the gasoline pump may ask, "So what?" The answer: this short-term windfall may well come at the expense of longer-term economic and national security. If American wells are prematurely plugged and abandoned and American producers go out of business, we lose jobs, tax revenues, royalty income to land and mineral owners, access to domestic resources, in some cases never to return, and increase our dependence on foreign oil and gas. Such changes could also hurt our environment — reducing the capability of industry to meet projected natural gas demand in the United States, increasing tanker traffic and the possibility of spills in the marine environment, and reducing industry's capacity to develop and deploy new technologies for improving productivity and environmental performance.

> United States dependence on imported oil has increased to record levels during the last 25 years. Net imports provide almost 50 percent of U.S. oil consumption. Oil imports could grow to as much as 71 percent in 2020 depending on world oil prices, as the gap between domestic oil production and consumption widens.

A formidable task for industry and government

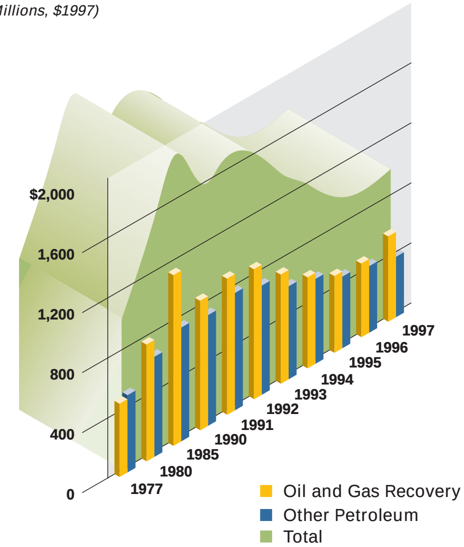
At this challenging time in the industry's history, government and industry must work together to preserve America's longer-term oil and gas production capacity and energy security. An array of actions by States as well as the Federal government may periodically be necessary to assist the industry, especially small businesses, in surviving low oil prices, and to enable them to provide a foundation for the future. Industry itself plays the greatest role in its future survival. Companies must reassess their corporate strategies and be prepared to articulate to others outside the industry why oil and gas E&P is a prudent longer-term economic and energy investment.

Sustaining Science and Technology Progress

Research and development (R&D) is America's investment in its future, providing a science and technology base for international competitiveness and leadership. In the oil and gas industry, however, both public and private investment in R&D have been declining over the past decade. The 24 largest E&P companies report that they spent less than $500 million in 1995 on research and development, only about 45 percent (in real dollars) of its 1985 peak. A decline in basic research is particularly apparent. Two-thirds or more of the investments made supported field service activities rather than the advance of the basic science that generates dramatic new technology.

Petroleum Industry R&D Expenditures, 1977 – 1997

(Millions, $1997)



Source: Energy Information Administration, Form EIA-28 (Financial Reporting System)

Photo: Corbis Images

Additional causes for concern are trends in corporate downsizing and restructuring, as well as a phase-out of consumer subsidized financing by 2005 at the Gas Research Institute, the Nation's largest natural gas research and technology development organization. Some experts believe these trends foreshadow a shrinking population of scientists and engineers and reduced opportunities for new generations of technologists.

Other factors provide reason for hope. From the vantage point of three decades, both the E&P industry and government have climbed a steep learning curve. Industry and government relationships over the environment have progressed markedly, from confrontation toward dialogue, from conflict to far more collaborative, win-win problem solving. Technology partnerships have become more widespread. To meet cost pressures and leverage resources, companies increasingly are working with each other, with academic groups, and with government in new and creative technology research, development, and deployment efforts. More efforts of this kind will be required in the future, to enable essential technological advances.

Continued need for leadership

Energy experts from industry, academia, and the research community have recommended that the Federal government continue to provide leadership, focus, and substantial financial support for energy research and development. This Federal role can ensure the achievement of national goals of U.S. energy security, economic strength, environmental quality, and leadership in science and technology.

Building Awareness of Smarter Technology

Organizations fostering oil and gas technology transfer range from universities, to States, to professional societies, to advocacy groups. These groups are also instrumental in articulating geoscience principles, and standards for more efficient oil and gas operations, environmental protection, and professional conduct. A representative—but not comprehensive—list of these organizations includes:

- American Association of Petroleum Geologists
- American Association of Professional Landmen
- American Geological Institute
- American Institute of Professional Geologists
- American Petroleum Institute
- Association of American State Geologists
- Completion Engineering Association
- Drilling Engineering Association
- E&P Forum
- Federal agencies
- Gas Research Institute
- Geological Society of America
- Ground Water Protection Council
- Independent Petroleum Association of America
- International Association of Drilling Contractors
- International Petroleum Institute Environmental Conservation Association
- International Marine Contractors Association
- Interstate Oil and Gas Compact Commission
- National Ocean Industries Association
- National Association for Black Geologists and Geophysicists
- Offshore Operators Committee (Gulf of Mexico)
- Oil and gas service companies (e.g. drilling and equipment service suppliers)
- Petroleum Technology Transfer Council (addressing the needs of independent producers)
- Society of Exploration Geophysicists
- Society of Independent Petroleum Earth Scientists
- Society of Petroleum Engineers
- Society of Petroleum Evaluation Engineers
- Society of Professional Well Log Analysts
- State and national environmental professionals associations
- State and private universities, including Historic Black Colleges and Universities
- State and regional industry trade associations
- State geological surveys and societies
- State regulatory agencies
- U.S. Oil and Gas Association

To lower carbon dioxide emissions and decrease oil imports, the Department of Energy has been called on to increase collaborative government and industry R&D on natural gas as the transition fuel in the 21st century. For example, investments would be made to conduct R&D in natural gas production and processing technologies, including a science-based program to understand the potential of methane hydrates worldwide. Collaborative investments also would be continued for technology transfer and cost-effective technology demonstrations, to maintain production from mature and marginal domestic oil and gas regions.

"The United States' research and development enterprise is in transition, shaped by the end of the Cold War, increasing competitive pressures in the private sector, realignments at research universities, and shifting priorities in Federal spending. . . . The headlights are being lowered in the private sector, where 'long term' is now only five years—and sometimes three."

Secretary of Energy Advisory Board Task Force on Strategic Energy Research and Development, 1995

Fostering technology transfer

Demonstrations of advanced technology concepts and information exchange are critical to accelerating the deployment of smarter technologies. As new technologies are developed to improve economics or productivity, their introduction into the marketplace can vary significantly due to such factors as cost, performance, applicability, adherence to government regulations or policies, and regional availability. The advanced technologies described in this report range from technologies commonplace today, such as 3-D seismic, to those gaining wider use domestically and internationally, such as horizontal drilling, to very promising technologies yet to be fully demonstrated, such as separating oil and water downhole within the reservoir.

Minimizing and Controlling Greenhouse Gases

The rise in greenhouse gas emissions from fossil fuel combustion and industrial and agricultural activities has aroused international concern about the impacts of these emissions on climate. Greenhouse gases—mostly carbon dioxide, but also some methane, nitrous oxide, and other trace gases—are emitted to the atmosphere, enhancing an effect in which heat reflected from the earth's surface is kept from escaping into space, as in a greenhouse. Concerned scientists believe that the earth's surface temperature may rise enough to cause global climate change. They cite such phenomena as the melting of the polar ice caps and increases in weather volatility as evidence that climate change is already under way. And while scientific uncertainty remains on the extent of the potential climate change, nonetheless, consensus is growing among both political and industry leaders that actions must be taken to reduce greenhouse gas emissions to prevent potentially far-reaching consequences.

> "Technological progress plays a critical role in the modern economy."
>
> *Presidents Council on Advanced Science and Technology, 1998*

On a per capita basis, the United States is the world's largest source of greenhouse gas emissions. With 4 percent of the world's population, our Nation emits 23 percent of the world's greenhouse gases.

Approximately 90 percent of United States greenhouse gas emissions from human activities come from energy production and use, most emissions a by-product of the combustion of fossil fuels. Concerns about global climate change are expected to drive reductions in greenhouse gas emissions related to the production and use of fossil energy. The oil and gas industry will be challenged to minimize and control these emissions on many fronts, including in E&P.

The Kyoto Protocol, negotiated by more than 160 nations in December 1997, is intended to reduce net emissions of certain greenhouse gases significantly by the 5-year period between 2008 and 2012. Each participating developed country has established emission reduction or limitation targets under the negotiated treaty. The ground rules for how these reductions can be achieved, reported, and verified continue to be negotiated.

Uncertainties and constraints

Many believe that significant economic burdens could result from implementing the requirements agreed to under the Kyoto protocol. The extent of these burdens is highly uncertain, however, and is the source of significant disagreement. Some factors contributing to this uncertainty include:

- The availability and cost of new and improved technologies, and the pace at which existing capital stock can be replaced.
- Consumer acceptance of more advanced or efficient technologies, as well as the increased use of nuclear and renewable electric generation technologies.
- The identification and implementation of successful, cost-effective fiscal and monetary policies to moderate economic impacts, and a diverse range of cost-effective mechanisms to encourage actions to reduce greenhouse gas emissions.
- The adjustment of the electricity, natural gas, and renewable energy industries to new requirements and the possible changes in industrial and energy sector composition that would likely result.
- The timing and phase-in of the necessary transitions.

The Birth of the Kyoto Protocol

- **In 1988, the World Meteorological Organization and the United Nations Environment Programme established the Intergovernmental Panel on Climate Change (IPCC) to assess the available scientific, technical, and socioeconomic information regarding climate change.**
- **The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992, in which Parties agreed in a nonbinding pledge to voluntarily reduce greenhouse gas emissions to 1990 levels by 2000. The United States was one of the first countries to ratify this treaty.**
- **In 1995 and 1996, the first and second Conference of the Parties agreed to address greenhouse gas emissions for the period beyond 2000, and began negotiating a protocol establishing legally binding emissions limitations and reductions for developed countries.**
- **At the third Conference of the Parties—held in December 1997 in Kyoto, Japan—the Kyoto Protocol was finalized, committing participating developed nations to specific, binding emissions targets.**
- **The fourth Conference of the Parties, which was held in Buenos Aires, Argentina, in November 1998, agreed to a 2-year plan for implementing the Kyoto Protocol. The United States signed the Kyoto Protocol on November 12, 1998. Although signing affirms the United States' commitment to work with other nations to meet the treaty's goals, it does not impose an obligation on the United States to implement the Protocol. (The treaty cannot become binding without approval of the United States Senate.)**

"For the oil and gas industry the dominant issue of public policy is climate change. . . . Our goal [at BP Amoco] is to reduce our emissions of greenhouse gases by 10 percent from a 1990 baseline over the period to 2010. . . . That target will now sit alongside our financial targets. . . . [It] has been developed . . . in close cooperation with the Environmental Defense Fund, whose help and support has been tremendously valuable. I want to pay a tribute to them."

Sir John Browne, Group Chief
Executive, BP Amoco p.l.c., 1998

The opportunity: the critical role of natural gas

Because of the higher relative carbon content of coal and petroleum products, any strategy to reduce greenhouse gas emissions would encourage the decreased use of these fuels and the increased use of lower-carbon fuels. This implies more reliance on renewable energy, perhaps on nuclear energy, and, especially in the nearer term, on natural gas.

Most projections envision a dramatic rise in natural gas consumption to meet the needs of a greenhouse gas constrained world, which in turn will require substantial increases in natural gas development and production to meet growing market demands. To minimize potential negative economic impacts of climate change constraints, the domestic industry must be able to continue to hold costs down while delivering increasing volumes of natural gas. To accomplish this, technological advances must continue, and a supportive policy and regulatory environment must encourage increased natural gas development and production.

The response: policy and technology dimensions

To meet the challenges posed by climate change, industry and government must work collaboratively. Government must provide a policy and regulatory environment for the industry that encourages action, without posing unnecessary economic burdens or penalizing in the future those that act today. Governments must identify and evaluate the full range of options available to encourage greenhouse gas emission reductions, allowing the maximum amount of flexibility possible to capture the innovation and entrepreneurial creativity that has always characterized the petroleum industry. All possible policy instruments—including, but not limited to, economic incentives, emissions trading, technology controls, energy efficiency initiatives, and product changes—should be debated, evaluated, and, where appropriate, implemented.

Industry must be proactive in addressing demands upon it to reduce greenhouse gas emissions. It must participate in multi-stakeholder forums to constructively develop effective mechanisms to address climate change issues and ensure that industry's concerns and recommendations are represented. Industry must carefully examine its own operations, policies, and procedures, and identify all possible options for cost-effectively and voluntarily reducing emissions of greenhouse gases and improving efficiency of operations. In many instances, considerable cost reductions and economic advantages can be achieved in conjunction with emissions reductions. And responding to concerns about climate change can provide marketplace opportunities for those in industry willing to act decisively.

The oil and gas industry currently possesses many of the tools and basic understandings needed to mitigate carbon emissions. Technologies now available, and under development, may be used to separate and capture carbon dioxide emissions from fossil-fueled power plants, oil and natural gas processing facilities, and other industrial processes for injection into geologic formations. Three principal formations—inactive and uneconomical gas reservoirs, aqueous formations, and deep and unmineable coal reservoirs—are widespread and have the potential for sequestering large amounts of carbon dioxide. In the case of carbon dioxide injection for enhanced oil recovery or enhanced coalbed methane recovery, the benefits of oil and gas extraction may partially or totally offset the cost of carbon dioxide separation and capture.

> "Natural gas has the potential to make a significantly larger contribution to both this Nation's energy supply and its environmental goals. Achieving that potential will take a commitment of innovation, leadership, and resources by the industry to overcome challenges that arise."
>
> *National Petroleum Council, The Potential for Natural Gas, 1992*

For the industry and the Nation to address climate change, continued improvements in technology are critical. Technology opportunities in the 21st century to reduce United States greenhouse gas emissions are possible only with sustained government and industry R&D efforts. Future technologies for deployment in the oil and gas industry to reduce greenhouse gas emissions may include:

- Increasing energy efficiency in crude oil refining.
- Converting natural gas to liquid fuels.
- Increasing natural gas production to help fuel industry and generation of electric power.
- Pumping carbon dioxide captured from industrial and electric power generation into oil reservoirs to enhance oil recovery, into coal seams to recover methane efficiently, and into natural gas storage fields to maintain subsurface pressures necessary for gas deliverability (carbon sequestration).
- Minimizing fugitive gas emissions from pipelines and other oil and gas equipment.

While holding significant promise, the development and deployment of such technologies is not certain, given the decline in R&D investment.

Ensuring Responsible Development

Environmental quality will be a continuing issue for the oil and gas industry. America's oil and gas industry must find the means, including new technology, to meet its future challenges, both in lowering costs to maintain competitiveness and in protecting the environment. A rational regulatory framework, reasonable access to resources in the United States and abroad, and communication are also critical to meeting these objectives.

Reinventing government

A more flexible and responsive policy and regulatory framework is critical to the U.S. oil and gas industry's ability to provide reliable and affordable energy supplies in a manner reflecting shared societal concerns for environment, health, and safety. Government must continue to improve its approach to regulation—emphasizing sound science and cost-benefit and goal-oriented mechanisms—and to improve coordination of policies affecting the industry. States and Federal agencies, including the United States Environmental Protection Agency, the Department of the Interior, and the Department of Transportation, have increasingly come to understand effective roles of government in enabling industry to improve its environmental performance. These roles include providing educational assistance and fostering, not stifling, technology innovation and voluntary efforts to protect the environment.

Moving beyond conflict to consensus

Access to oil and gas resources domestically and abroad will increasingly depend on industry's ability to demonstrate its commitment to responsible development. Industry has a responsibility to improve its credibility and an opportunity to lead in the resolution of contentious issues. Oil companies, in particular, have been viewed by many as lacking a concern for the environment and the commitment to protecting it. For this perspective to change, industry must improve and expand communication with stakeholders outside the industry. Such communication will be crucial for resolving the economic and environmental issues the oil and gas industry will face. Enhanced communication must be championed by industry leaders to show the commitment to real change in relationships with stakeholders. Effective dialogue can enable consideration of the positions of all stakeholders, resulting in a more realistic basis of action. Great strides have been made, but more opportunities remain.

"A better dialogue between the oil industry and the environmental movement is imperative. There is a lot of misunderstanding, and an opportunity for constructive action exists."

Participant in the National Petroleum Council's 1995 Report on Future Issues: A View of U.S. Oil and Natural Gas in 2020

A Vision for the Future

Innovation in E&P technology continues well into the 21st century, providing further environmental benefits. Successive generations of technology pioneers ensure that E&P trends are progressively smarter, more protective of the environment.

In the fields of the future:

- **Advanced earth imaging pinpoints the location of valuable oil and gas resources.**
- **Downhole sensors ensure peak drilling efficiency.**
- **Multiple completion wells and reduced surface footprints are the norm.**
- **Improved reservoir management and recovery processes ensure maximum oil and gas recovery.**
- **Subsurface waters remain in situ or are separated downhole, and produced waters are minimized.**
- **Air emissions approach zero as particulates are effectively captured, gases are reinjected, and leak detection and control strategies become more effective.**
- **Production wastes are minimized and/or recycled.**
- **Impacts of drilling and resource recovery on sensitive environments, including wildlife habitat, are minimal.**
- **Exploration and production sites are restored to original conditions or beneficially improved.**

In the Nation:

- **Maximum recovery of the Nation's valuable domestic oil and gas resources is achieved, respecting the environmental and other societal objectives.**
- **Natural gas serves as a transition fuel to lower carbon-based greenhouse gas emissions and to decrease oil imports.**
- **Affordable and abundant supplies of energy enhance our national security.**
- **The United States sustains its E&P technology leadership worldwide.**
- **International cooperation expands to address global economic, security, and environmental concerns.**

Better communication between industry and the public will improve public understanding of the industry and its value to the country. Education in the principles of science and economics is key to comprehending energy and environmental issues facing the industry. Though industry has a strong history of supporting educational programs, it must focus its efforts to better understand public and customer concerns, and to encourage science, economic, and energy education.

Stewardship of public lands

In the United States, vast quantities of oil and gas resources underlie Federal lands, including forests, deserts, rangelands, wetlands and marine environments, to be managed for public benefit. Today, onshore Federal lands annually yield approximately 5 percent of our Nation's crude oil production and nearly 10 percent of its natural gas. Offshore, Federal lands account for approximately 19 percent of annual crude production and 25 percent of annual natural gas production. About 50 percent of the remaining untapped technically and economically recoverable crude oil and gas reserves are on Federal lands, excluding wilderness areas. More than 80 percent of these properties are offshore. Public opinion on access to Federal lands for resource exploration and production remains divided. Advanced oil and gas technology will play a critical role in the continued debate regarding access to Federal lands, both onshore and in the Outer Continental Shelf. Public dialogue on the need for energy and the need for protection of the environment, particularly our most fragile ecosystems, will contribute to improved resolution of the issues.

ENABLING NEW GENERATIONS OF TECHNOLOGY PIONEERS

"Folks were impressed with the pluck and enterprise of the two guys and decided to give them a hand. . . . The story of Wilcox Oil Company [the dream of two young geologists fresh out of college] is one of generosity, mentoring, giving the lessons of a lifetime, and furthering the best of human character."

Richard S. Bishop
President
American Association of Petroleum Geologists, 1998

Looking to the Future

As we approach the 21st century, oil and gas scientists and engineers, through professional organizations such as the American Association of Petroleum Geologists, the American Geologic Institute, and the Society of Petroleum Engineers, are looking to the future. Key organizations have strengthened their commitment to fostering ethical behavior and professional conduct, to applying scientific principles and data for addressing basic environmental issues, and to working actively to encourage responsible exploration and production of the world's oil and gas resources.

These organizations have long stimulated professional development in the oil and gas industry, as the hub of information exchange on geologic, engineering, and biological sciences, and as the source of career and corporate mentoring. Increasingly, these organizations are also looking outward. They are stepping up outreach efforts to communicate the technology and practices used today to minimize environmental impact. They are partnering across scientific disciplines. They are partnering with land management agencies to understand the impact of oil and gas operations on sensitive ecosystems, and to develop industry guidelines and policy for future operations in these areas. And they are encouraging members to become more involved in public policy and promoting a scientific approach in solving environmental problems.

The development of new oil and gas technologies—and the environmental benefits that come from them—will be constrained only by the limits of our Nation's drive and imagination. With sustained vision, leadership, and the commitment of both the public and private sectors, new technologies will be developed, American oil and gas resources can be utilized, and the environment will be served.

Technology

Exploration

	Technology	Fewer Wells or Dry Holes	Smaller Footprint	Protection of Habitats, Wildlife, and Cultural Resources	Better Wellbore Control
①	3-D Seismic	■		■	
②	4-D Visualization	■		■	
③	Remote Sensing	■		■	
④	Subsalt Imaging	■			

Drilling and Completion

	Technology	Fewer Wells or Dry Holes	Smaller Footprint	Protection of Habitats, Wildlife, and Cultural Resources	Better Wellbore Control
⑤	CO_2-Sand Fracturing				
⑥	Coiled Tubing		■	■	■
⑦	Horizontal Drilling	■		■	
⑧	Hydraulic Fracturing	■			
⑨	Measurement-While-Drilling	■			■
⑩	Modern Drilling Bits				■
⑪	Multilateral Drilling	■	■	■	
⑫	Offshore Drilling			■	
⑬	Pneumatic Drilling		■	■	■
⑭	Slimhole Drilling		■	■	■
⑮	Synthetic Drilling Muds			■	■

Production

	Technology	Fewer Wells or Dry Holes	Smaller Footprint	Protection of Habitats, Wildlife, and Cultural Resources	Better Wellbore Control
⑯	Acid Gas Removal and Recovery				
⑰	Artificial Lift Optimization				
⑱	Coalbed Methane Recovery				
⑲	Freeze-Thaw/Evaporation				
⑳	Gas-to-Liquids Conversion				
㉑	Glycol Dehydration				
㉒	Advanced Data Management				
㉓	Improved Recovery Processes	■			
㉔	Leak Detection and Measurement Systems				
㉕	Low-Bleed Pneumatic Devices				
㉖	Offshore Platforms		■	■	
㉗	Downhole Oil/Water Separation	■	■		
㉘	Safety & Environmental Management Programs			■	
㉙	Vapor Recovery Units				

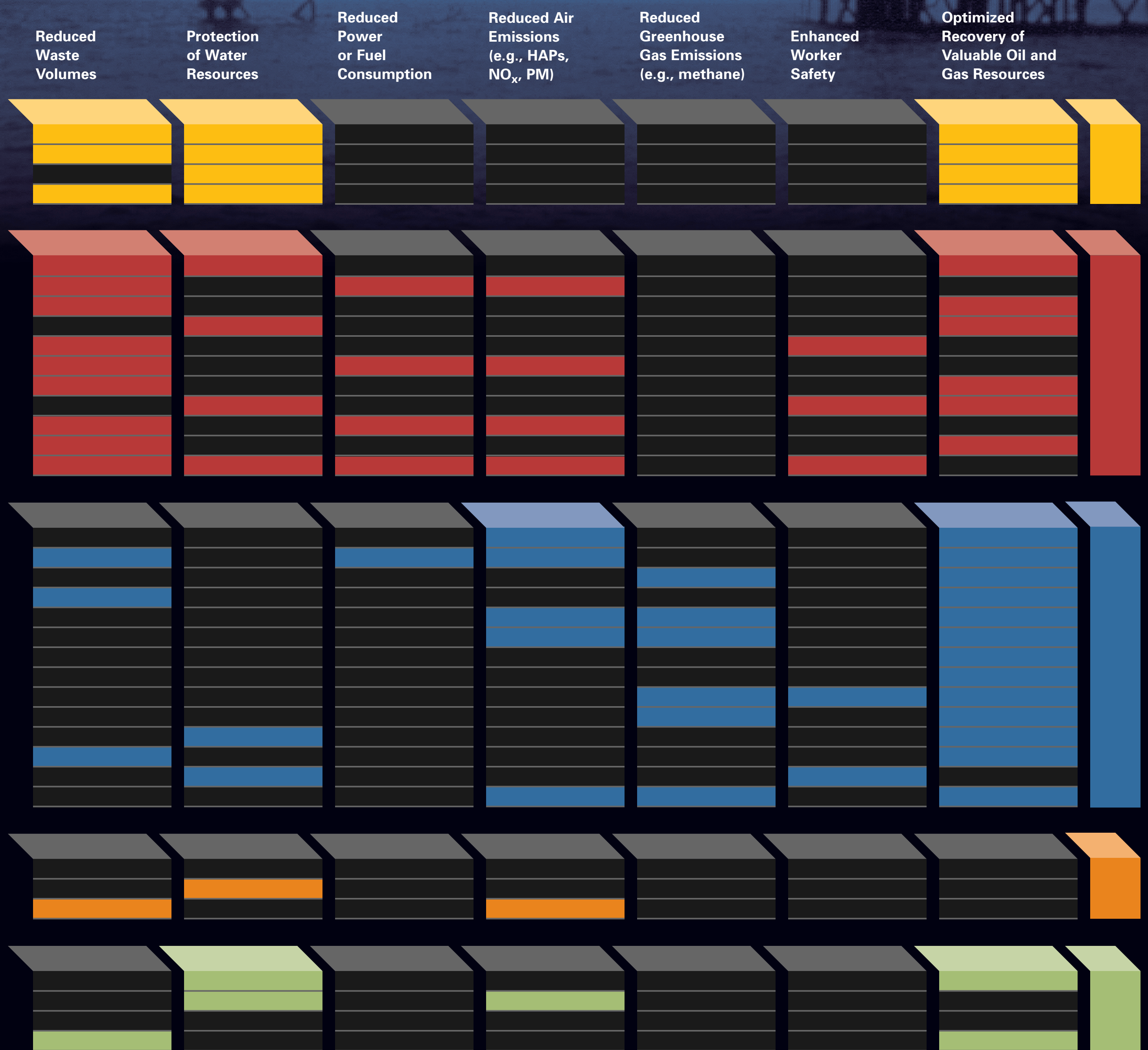
Site Restoration

	Technology	Fewer Wells or Dry Holes	Smaller Footprint	Protection of Habitats, Wildlife, and Cultural Resources	Better Wellbore Control
㉚	Advanced Approaches to Site Restoration			■	
㉛	Rigs to Reefs			■	
㉜	Road Mix and Roadspreading				

Sensitive Environments

	Technology	Fewer Wells or Dry Holes	Smaller Footprint	Protection of Habitats, Wildlife, and Cultural Resources	Better Wellbore Control
㉝	DOE-BLM Partnership			■	
㉞	Coastal and Nearshore Operations		■	■	
㉟	Insulated Ice Pads		■	■	
㊱	North Slope Operations	■	■	■	

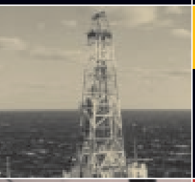
FACT SHEETS



The technologies described in these Fact Sheets are merely representative of the numerous advances in exploration and production technology over the last three decades and, as such, are not intended as an exhaustive inventory of these advances.

Technology Fact Sheets

Contents



TECHNOLOGY Locations: Worldwide, onshore and offshore

3-D Seismic

SUMMARY

Advances in 3-dimensional (3-D) seismic technology over the past 25 years have enabled oil and gas producers to evaluate prospects more effectively, drill fewer exploratory wells, and develop fields more efficiently. The result is decreased environmental impact and increased profit. To establish a visual orientation of the subsurface without drilling, energy waves directed downward through the earth's strata are reflected off the rock layers and sent back to the surface. The resulting data undergo complex processing and interpretation and provide explorationists with a 3-D visual characterization of the subsurface's geological features. This allows detailed assessment of the opportunities and risks of developing a reservoir, an increasingly important capability as the search for resources pushes into new exploration frontiers, such as deepwater and subsalt formations.

BLUEPRINT ON TECHNOLOGY

Two decades of successively better geologic interpretation demonstrate tangible results and environmental benefits

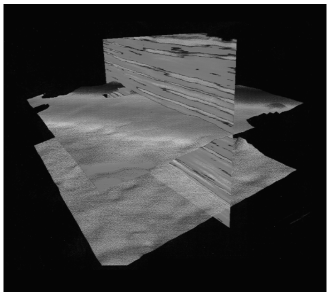
From 2-D to 3-D technology

UNTIL THE 1960S, developers had to rely on inaccurate, low-resolution analog data in planning their exploration investments. In the 1970s, improved 2-D seismic techniques enabled explorers to characterize subsurface opportunities with greater effectiveness. Now, with 3-D seismic, they can establish more accurate 3-D characterization of geologic structures. Reservoir characterization is key across all stages of a hydrocarbon field's life. Seismic information, critical during the exploration and appraisal phase, is now used for development until the field is abandoned. In the last 20 years, the discovery cost has decreased from $20 per barrel with 2-D seismic to just under $5 per barrel with 3-D seismic. Better geologic representations, coupled with advanced drilling and production technologies, also lead to increased recovery efficiencies.

Several major improvements in 3-D surveying occurred during the 1990s, in seismic data acquisition, processing, computer hardware, and interpretation and display. Particularly remarkable have been the hardware improvements. Within the last five years, recording systems have increased capacity from 48 to 2,000 channels, as many as 32 seismic data lines can be recorded in a single pass, and satellite navigation systems have evolved to pinpoint accurate positioning of sources and receivers. At the same time, technological improvements have reduced computing time and lowered costs. 3-D stack-time migration can now be performed in a few hours on massively parallel processors, and between 1980 and 1990, costs dropped from $8 million to $1 million for a 50-square-mile survey using 3-D post-time depth migration. By 2000, costs for an equivalent survey are expected to be near $90,000.

ECONOMIC BENEFITS
Helps explorers to better identify oil and gas prospects
More effective well placement improves development of resources
Fewer dry holes ultimately reduces drilling and exploration costs
Can substantially improve project economics by reducing overall drilling costs
Exploration time relative to successful production is cut

ENVIRONMENTAL BENEFITS
More accurate exploratory well-siting reduces the number of dry holes and improves overall productivity per well drilled
Less drilling waste is generated
Better understanding of flow mechanics produces less water relative to oil and gas
Overall impacts of exploration and production are reduced because fewer wells are required to develop the same amount of reserves



3-D seismic has now gained widespread acceptance. Whereas by 1980 only 100 3-D seismic surveys had been done, by the mid-1990s an estimated 200–300 3-D seismic surveys were being conducted annually. Offshore growth has been tremendous: in 1989, only 5 percent of the wells drilled in the Gulf of Mexico were based on 3-D seismic data; by 1996, nearly 80 percent used 3-D seismic. Onshore, 75 percent of all surveys were conducted with 3-D seismic by 1993.

Answering environmental and safety challenges

Today, producers are working to assess and minimize the impact of 3-D seismic equipment and crews on sensitive environments. Explosives used to generate sound waves recorded by a seismograph can now be replaced where necessary by vibrating technology that sends an acoustic signal. Offshore seismic surveying now relies on the use of compressed air guns to ensure protection of marine life. Depending on the kind of information needed, the geology expected, the nature of the field, and the costs, 3-D seismic exploration can be customized to protect the specific terrain. For example, in mountainous terrains, standard seismic techniques (2-D) required densely gridded surveys for accurate geologic descriptions. 3-D acquisition techniques allow for more widely spaced, less invasive surveys while providing better quality data.

Advancements in 3-D data processing also allow for survey acquisition in areas congested with urban or industrial noise sources.

CASE STUDIES

Success in the Field

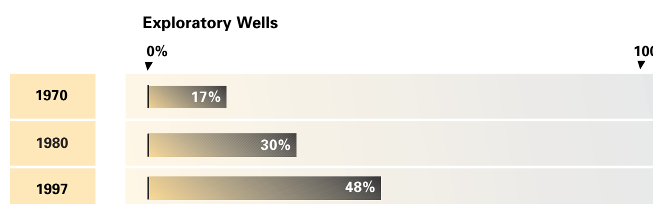
3-D seismic highly effective for portfolio management at Amoco

Amoco Corporation established an exploration drilling success rate of 48 percent for its 3-D seismic exploration activities between 1990 and 1995. By contrast, its exploration success rate for wells drilled without the benefit of 3-D seismic was only 13 percent. To evaluate the effectiveness of using 3-D, data were collected on 159 seismic surveys and a control group of 15 other prospects. 3-D proved extremely valuable at defining geometries, particularly in the North Sea and Gulf of Mexico. Where conventional surveying turned up eight prospects, 3-D narrowed these down to two. In addition, while all eight had been given an economic success probability of between 22 and 53 percent, 3-D seismic correctly predicted that the two selected had a potential success rate of 60 percent.

METRICS

Exploration success in the United States

Advances in 3-D seismic and drilling and completion technology dramatically increased drilling successes.



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TECHNOLOGY Locations: Worldwide, onshore and offshore

4-D Visualization

SUMMARY

Three-dimensional (3-D) seismic technology has revolutionized oil and gas exploration and served as a springboard to visualization technology. Now emerging visualization and 4-D time-lapse monitoring technologies are improving interpretation of the data 3-D seismic imaging provides. Invaluable in locating bypassed reserves in existing formations and discovering new resources, seismic reservoir characterization can now incorporate perceptual cues such as projection, lighting and shading, depth, motion, and transparency. This technology enables a more consistent, detailed picture of a complex formation. 4-D monitoring goes one step further, providing a dynamic picture of hydrocarbon flows and other reservoir changes over time, information valuable for both exploration and reservoir management of existing resources.

BLUEPRINT ON TECHNOLOGY

Evolving seismic technologies improve accuracy and interpretation, allowing operations to be tailored to protect the environment

Adding a fourth dimension—time

PETROLEUM ENGINEERS, geologists, and planners have a far better understanding of the geologic structures of potential hydrocarbon-bearing formations now that reservoir images are projected in three dimensions. Four are better still, largely due to DOE-supported research. A reservoir's fluid viscosity, saturation changes, temperature, and fluid movements can be analyzed by time-lapse monitoring in three dimensions. The time-lapse picture is built out of data re-recorded at intervals, compared and plotted by computer onto a 3-D model. Engineers can view changes occurring over time and link these to static and dynamic reservoir properties and production techniques. They can then follow the consequences of their reservoir management programs and make predictions as to the results of future activities. 4-D monitoring is an offshoot of the computer processing techniques developed for 3-D seismic interpretation.

With improved visualization techniques, petroleum engineers, geologists, and geophysicists are integrating many types and ages of data (well logs and production information, reservoir temperatures and pressures, fluid saturations, 2-D and 3-D seismic data) into time-lapse imagery and reservoir performance modeling. As this time-dependent tool is c orrelated with physical data acquisition, more accurate characterization of subsurface reservoirs will be possible, pushing maximum recovery efficiencies.

Geologists and planners are better able to understand the structure of promising formations. As computing science advances, further gains will be made. Already, audio technology is being added, both for controlling images and presenting complex geological data so that scientists can share data in real time from remote locations.

ECONOMIC BENEFITS
Improved recovery due to precise placement of injector wells and infill drilling
More efficient operations due to better identification of drainage patterns
Lowered operating costs because of improved program timing and fewer dry holes
Increased identification and ultimate recovery of as yet untapped resources

ENVIRONMENTAL BENEFITS
Reduced drilling due to more successful siting of wells, with greater recovery from existing wells
Less drilling waste through improved reservoir management
Lower produced water volumes through better well placement relative to the oil/water interface in the formation
Increased ability to tailor operations to protect sensitive environments

CASE STUDIES

Success in the Field

4-D seismic in Indonesia

The Duri field in central Sumatra was the first 4-D project of its kind. Today over 60 time-lapse projects follow its lead. Producing 300,000 barrels of oil per day, the PT Caltex Pacific Indonesia project is the largest steamflood in the world. In 1992, Caltex began 4-D recording in a series of eight surveys to determine whether time-lapse could successfully monitor a steamflood. The goal: to improve oil recovery and cut energy use. The data generated helped direct the injection process and identify both swept and unswept zones. Due to the project's success, Caltex started baseline surveys in six new areas, and other companies are also initiating use of time-lapse monitoring.

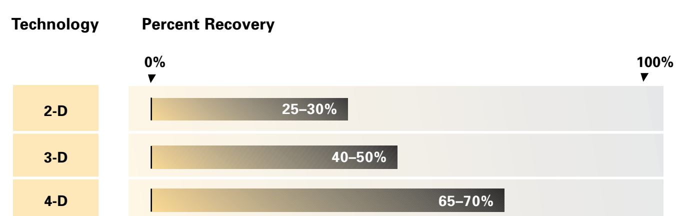
Immersed in 3-D visualization at ARCO

The ultimate formation viewing experience is to be immersed in a walk-in virtual reality cube that replicates geophysical features. In ARCO's Immersive Visualization Environment, images from projectors and mirrors outside the cube are projected onto three 10-foot walls of seamless screens. An electromagnetic tracking system orients the viewer's perspective, and stereoscopic goggles use alternate left- and right-eye images and infrared timing devices to create 3-D effects.

ARCO's exploration teams have used the facility to study data from the North Sea, Alaska's North Slope, and a project near the Philippines, using its superior visualization capabilities to produce solutions to drilling problems. In the North Sea's Pickerill field, for example, drilling plans for a multilateral hole were complicated by pressure changes among the reservoir's different compartments and drilling hazards above the reservoir. Adjustments to the original drilling plan were dictated by judgments made in the Visualization Environment, avoiding potential problems.

METRICS

Estimated recovery for oil-in-place at BP Amoco/Shell's Foenhaven field in offshore U.K.



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TECHNOLOGY Locations: Worldwide (especially deepwater)

Remote Sensing

SUMMARY

Used in conjunction with other exploratory techniques, such as 3-D seismic imaging, remote sensing systems detect and map concentrations of hydrocarbons with greater accuracy than other technologies alone, and with less environmental impact. Technologies such as satellite imagery, aeromagnetic surveys, and gravimetry are now being applied by the largest exploration companies to attempt to detect the vertical or near-vertical migration of oil and gas to the earth's surface and help identify promising geologic structures. These systems measure gases, solids, and liquids, using their physical properties to attenuate or reflect beams of electromagnetic energy. Resulting geophysical data are processed into easily understood images and maps, and form an integral part of current onshore and offshore programs throughout the world.

BLUEPRINT ON TECHNOLOGY

Remote exploration helps pinpoint hydrocarbon resources, pollution sources, and sensitive environments

Enhanced satellite imaging systems

OPTICAL SATELLITE imagery has been the predominant source of data for identifying and mapping onshore geology since the early 1970s, when the first Landsat Earth Observation satellite was launched. Today, satellite imagery, onshore and offshore, is also provided by radar satellites very sensitive to the earth's surface contours. For example, various types of satellites can see through 70 feet of clear water and up to 20 feet beneath the surface. Early optical satellites depended on visible or near-infrared light to collect energy reflected from the earth's surface. By contrast, radar satellites emit energy at microwave frequencies, enabling them to acquire imagery under nearly any atmospheric condition. Sophisticated digital image processing systems can now convert and sort raw satellite data into thematic maps that point to the location of productive formations, even detecting oil and gas seepages that indicate migration pathways from undrilled traps. Similarly, remote sensing techniques can also identify hydrocarbon spills and leaks in remote areas, such as along pipelines.

Current multispectral satellites such as the Landsat Thematic Mapper create images by gathering up to seven bands of light spectra in prism-like fashion. In 2000, when the U.S. Navy plans to launch its Navy EarthMap Observer satellite, an exciting new satellite technology called hyperspectral analysis, accessing upwards of 200 bands of light, will further increase imaging accuracy.

Improved aeromagnetic surveys

Initially developed for military applications, aeromagnetic surveying has evolved into a productive exploration technology that can recognize the magnetic signature of potential hydrocarbon-bearing basins from altitudes over 10,000 feet. Using a

ECONOMIC BENEFITS

- Increased exploratory success rates
- Dramatically reduced exploratory costs
- Access to geological data otherwise unobtainable
- Increased recovery of resources from frontier basins
- Identification of hydrocarbon "seeps" as distinguished from oil spills or pollution

ENVIRONMENTAL BENEFITS

- Accurate identification of fragile ecosystems, enabling care when drilling
- Increased ability to address environmental needs
- Fewer dry holes and nonproductive exploratory wells are drilled
- Improved characterization of earth's natural systems
- Identification of spills and leaks in remote areas

magnetometer mounted on a magnetically cleaned aircraft, explorers are successfully mapping sedimentary anomalies critical to oil and gas exploration, detecting salt/sediment contact, mineralized shear zones, and intrasedimentary markers.

Recent improvements in magnetometer design, digital signal processing techniques, and electronic navigation technologies, in combination with faster sampling of the magnetic field and the use of more detailed survey grids, allow mapping of subtle magnetic signatures. These advances improve the interpretation and visualization of geological data.

Measuring gravity to gauge resources

Gravimetry measurement is now derived from both satellite and airborne observations. Gravity anomalies can be measured and mapped to give geoscientists an idea of the size and depth of the geological structures that caused them.

Satellite gravity imaging uses radar to measure undulations in the sea surface that reflect density variations in the earth's upper crust. This technology enables mapping of areas of mass deficit, where sedimentary deposition is likely to have occurred. Identification of such areas gives explorers a better idea of where hydrocarbons may be located.

Putting it all together

Exploration companies like BP Exploration, Exxon, Mobil, Texaco, Unocal, and RTX are tailoring their remote sensing programs to combine technologies as needed. Recent advances in radar imaging and sophisticated image-processing packages, combined with satellite-derived gravity and bathymetry data, for example, present new opportunities to use remote sensing for deepwater exploration. Remote sensing is now considered critical to such operations. It is also extraordinarily cost-effective.

CASE STUDIES

Success in the Field

Satellites help explore in the Caspian Sea

After water-level changes along the shallow coast of the Republic of Kazakhstan made their bathymetric maps obsolete, Oryx Energy and its exploration partner, Exxon, turned to remote sensing to gauge depths. Water depth fluctuations caused by wind can make movement of seismic and drilling equipment challenging. With satellite image processing technology, the team created new bathymetric maps (e.g., the 12,200 square km Mertvyi Kultuk block, some 30 km south of the giant Tengiz field) and used these maps to position a successful new drilling program in one of the world's most productive oil exploration areas.

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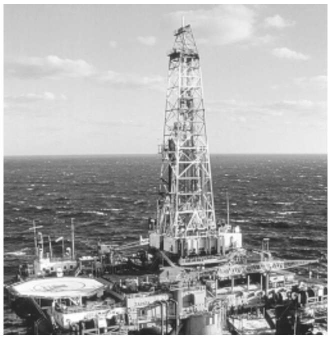


TECHNOLOGY Locations: Gulf of Mexico, West Africa, and other salt formations

Subsalt Imaging

SUMMARY

Now that most easily accessible domestic resources have been discovered, oil and gas explorers are investigating the promising but more inaccessible resources beneath saltsheet formations in the Gulf of Mexico. Large, irregular saltsheets may cover 60 percent of the slope beneath the Outer Continental Shelf in the Gulf and are found throughout the world. Advances in 3-D imaging technologies are crucial to providing reliable images of what lies below the thick layers. A 3-D prestack depth migration method of seismic data processing and an advanced marine magnetotellurics technique are now making it possible to image the structure and thickness of subsalt sediments. Together, these technologies provide sufficient information to help locate new oil or gas deposits, estimated at 15 billion barrels of oil equivalent in the Gulf of Mexico alone.

BLUEPRINT ON TECHNOLOGY

Interpretation of formations hidden under layers of salt allows more accurate siting of new reserves

Getting under the salt

DEVELOPING IMAGES of subsalt structures poses a critical challenge to exploration. Seismic imaging is based on the transmission of sound waves and analysis of the energy that is bounced back. But large amounts of energy are lost when sound waves pass through salt; thus, an extremely strong seismic source is required. Often seismic data are incomplete, preventing explorers from obtaining accurate readings of a structure's shape and thickness. Traditional imaging methods cannot deliver accurate readings when seismic sources are blocked by salt squeezed into sheets between sediment layers from an underlying salt base. The oil and gas sandwiched between the salt layers can only be imaged by a combination of advanced seismic source technology, complex mathematical modeling simulations, and improved data processing and imaging techniques. DOE's public/private Natural Gas and Oil Technology Partnership has helped develop several such technologies, among them improvements to the speed and reliability of 3-D prestack depth migration, which creates a coherent image by processing as many as 25 million records.

Using electromagnetic resistance

As a part of this DOE partnership, the National Laboratories and industry are currently investigating the feasibility of marine magnetotellurics, which is ideal for subsalt exploration since it is based on electrical resistance. Because salt's resistivity is 10 times greater than that of surrounding sediments, the contrast between salt and sediment resistance to low-frequency electromagnetic radiation from the earth's ionosphere makes it easier to map the extent and thickness of salt structures.

Stealth imaging breakthrough

The latest technology used to enhance seismic data is 3-D full tensor gradient (FTG) imaging, originally developed by the U.S. Navy during the Cold War for stealth submarines. A 3-D gradiometer survey takes real-time measurements of very small changes in the earth's gravity field, each relaying information directly related to mass and geometry of subsurface

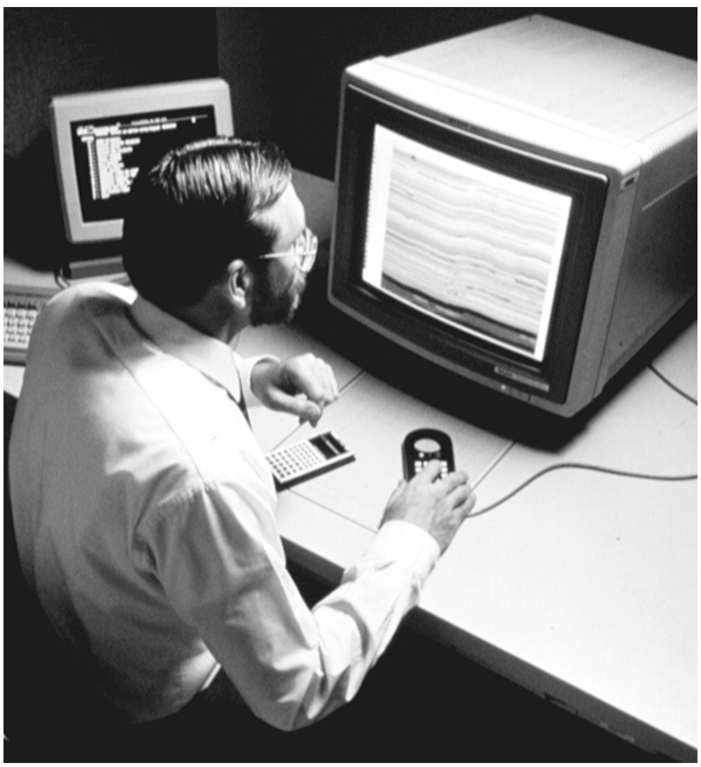
ECONOMIC BENEFITS

- More efficient exploration to pinpoint new oil and gas, reducing the financial risks
- Cost-effective exploration: an average 30-image seismic survey costs $500,000, while an MT survey covering the same area costs about $50,000

ENVIRONMENTAL BENEFITS

- Increased resource recovery due to better reservoir characterization
- Better, more careful siting of new drilling operations
- Reduced drilling wastes as fewer wells are drilled

geological bodies. FTG provides the depth and shape of almost any geological structure, independent of seismic velocities, allowing geoscientists to develop more complete images of complex salt formations. Two field tests have demonstrated a significantly improved view of the Gulf's subsalt geology, and FTG promises to be an affordable tool with which to enhance existing 3-D seismic imaging technology in salt formations around the world.



CASE STUDIES

Success in the Field

Beneath the Mahogany field salt

Drilling beneath the salt formations of the Gulf of Mexico, an exploration play spanning 36,000 square miles south of the Louisiana coast, began in the 1980s. A decade of unsuccessful exploration followed, and it took advanced subsalt technologies to break through the visual block. Nine subsalt discoveries were drilled in the play from 1990 to 1996, representing a phenomenal success rate of 35 percent. The centrally located Mahogany field (the Gulf's first commercial subsalt play) was discovered in 1993, and four wells were completed by 1997, now flowing at a daily rate of 15,000 barrels of oil and 35 million cubic feet of gas. Mahogany field's total reserves are estimated at 100 million barrels of oil-equivalent, and total recovery from this and the Gulf's other subsalt discoveries is estimated to be 650 million energy equivalent barrels, resources that would have remained inaccessible without advanced subsalt imaging technology. A new discovery, the Tanzanite field, is estimated to hold reserves of 140 million barrels of oil-equivalent. Due to the size of this discovery, subsalt exploration in the Gulf is likely to remain active. Future subsalt technology advances may be the key to discovering other large untapped fields. As technology progresses, so will resource recovery.

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TECHNOLOGY Locations: Canada (commercial) and United States (demonstration only)

CO_2-Sand Fracturing

SUMMARY

Fracturing has been widely used since the 1970s to increase production from formations with low permeability or wellbore damage. Unlike conventional hydraulic and acid fracturing techniques, CO_2-sand fracturing stimulates the flow of hydrocarbons without the risk of formation damage and without producing wastes for disposal. A mixture of sand proppants and liquid CO_2 is forced downhole, where it creates and enlarges fractures. Then the CO_2 vaporizes, leaving only the sand to hold the fracture open—no liquids, gels, or chemicals are used that could create waste or damage the reservoir. Any reservoir that is water-sensitive or susceptible to damage from invading fluids, gels, or surfactants is a candidate. The process has had widespread commercial success in Canada, and recent DOE-sponsored field tests have demonstrated commercial feasibility in the United States.

BLUEPRINT ON TECHNOLOGY

In widespread use in Canada, a stimulation technique now successfully demonstrated in the U.S. has outstanding results without formation damage

Using CO_2 to fracture oil and gas reservoirs

Recompleting and fracturing an existing oil or gas well to stimulate production that has declined over time is significantly less costly than drilling a new well. First used in the mid-1930s, fracturing treatments inject fluids under high pressure into the formation, creating new fractures and enlarging existing ones. "Proppants" (usually large-grained sand or glass pellets) are added to the fluid to support the open fractures, enabling hydrocarbons to flow more freely to the wellbore. Fracturing is widely used to stimulate production in declining wells and to initiate production in certain unconventional settings. More than one million fracturing treatments were performed by 1988, and about 35 to 40 percent of existing wells are hydraulically fractured at least once in their lifetime. More than eight billion barrels of additional oil reserves have been recovered through this process in North America alone. Yet conventional fracturing technology has drawbacks. The water- or oil-based fluids, foams, and acids used in traditional fracturing approaches can damage the formation—for instance, by causing clay in the shale to swell—eventually plugging the formation and restricting the flow of hydrocarbons. Conventional fracturing also produces wastes requiring disposal.

An advanced CO_2-sand fracturing technology overcomes these problems, and is proving a cost-effective process for stimulating oil and gas production. First used in 1981 by a Canadian firm, the process blends proppants with 100 percent liquid CO_2 in a closed-system-pressurized vessel at a temperature of 0°F and a pressure of 300 psi. Nitrogen gas is used to force the resulting mixture through the blender to the suction area of the hydraulic fracture pumping units and then downhole, where it creates and enlarges fractures. The CO_2 used in the process

ECONOMIC BENEFITS

- Eliminates hauling, disposal, and maintenance costs of water-based systems
- Can significantly increase well productivity and ultimate recovery
- CO_2 vaporization leads to fast cleanup, whereas water-based fluids sometimes clean up slowly, reducing cash flow
- Recovery of valuable oil and gas is optimized

ENVIRONMENTAL BENEFITS

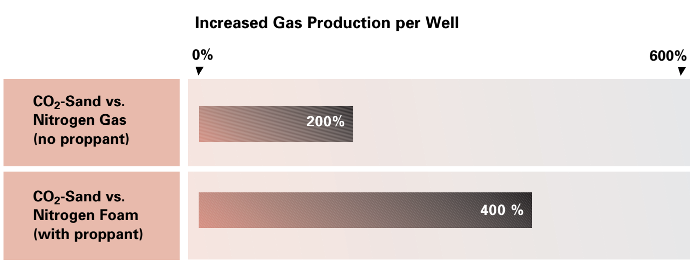
- Using liquid CO_2 creates long, propped fractures without formation damage
- No wastes requiring disposal are created
- Conventional fracturing gels and chemicals, which may damage the flow path between wellbore and formation, are not used
- Groundwater resources are protected

vaporizes, leaving behind a dry, damage-free proppant pack. The technology has gained widespread commercial acceptance in Canada, where it has been used some 1,200 times. In the United States, use has been limited to demonstrations—many sponsored and cofunded by DOE—taking place over the last two years in about 50 wells in Kentucky, Ohio, Pennsylvania, Tennessee, Texas, New York, Colorado, and New Mexico.

CO_2-sand fracturing treatments average from $30,000 to $50,000, depending on well depth and rock stresses. While often higher-cost than conventional methods, these costs are offset by savings realized through eliminating both swab rigs and the hauling, disposal, and maintenance costs associated with water-based systems. As in conventional fracturing, CO_2-sand treatments can significantly increase a formation's production and profitability.

METRICS

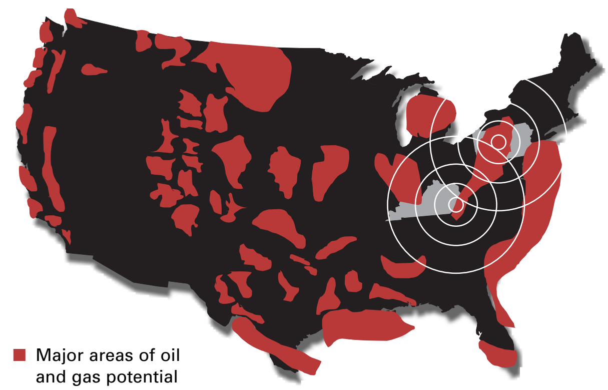
Results of fracturing technique tests in Devonian Shales wells after 37 months



Source: Arnold, Hart's Petroleum Engineer International, January 1998

CASE STUDIES

Success in the Field



Successful DOE-sponsored field tests

The U.S. Geological Survey estimates that 200 to 400 trillion cubic feet of natural gas resources exists in unconventional settings in the United States. Developing cost-effective advanced fracturing techniques is crucial in our quest to recover these resources. A number of field-test fracturing projects sponsored by DOE recently evaluated and proved CO_2-sand technology's effectiveness in gas recovery. In the Devonian Shales in Kentucky, four of 15 gas wells were stimulated with CO_2-sand mixture, seven with nitrogen gas and no proppant, and four with nitrogen foam and proppant. After 37 producing months, wells stimulated with the CO_2-sand process had produced four times as much as those treated with foam, and twice as much as those stimulated with nitrogen gas. In central Pennsylvania, three gas wells were stimulated using CO_2-sand fracturing. Immediately after fracturing, two of the wells exhibited production increases of 1,000 percent and 600 percent. Over a year and a half later, production from the wells had increased 620 percent, 300 percent, and 240 percent, respectively.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Coiled Tubing

SUMMARY

Continuous coiled tubing can dramatically increase the efficiency, profitability, and productivity of drilling for oil and gas. Whereas in conventional drilling operations, the drilling pipe consists of several jointed pieces requiring multiple reconnections, a more flexible, longer coiled pipe string allows uninterrupted operations. A cost-effective alternative for drilling in reentry, underbalanced, and highly deviated wells, coiled tubing technology minimizes environmental impacts with its small footprint, reduced mud requirements, and quieter operation. Quick rig set-up, extended reach in horizontal sidetracking, one-time installation, and reduced crews cut operating costs significantly. For multilateral and slimhole reentry operations, coiled tubing provides the opportunity for extremely profitable synergies.

BLUEPRINT ON TECHNOLOGY

Successively better coiled tubing technologies drive improvements in cost, productivity, and efficiency of drilling operations, while reducing environmental impact

A strong portfolio of benefits

Particularly valuable in sensitive environments such as Alaska's North Slope, coiled tubing technology has far less impact on a drilling site than conventional equipment, in addition to performing drilling operations more efficiently and cost-effectively. Although the first coiled tubing units were built in the 1950s, only after rapid technological advances in the late 1980s did the technology start to gain industry-wide recognition. From 533 operating units in 1992, usage has grown to some 730 units in 1998, and many drilling companies are now revising their rig portfolios.

In a variety of drilling applications, coiled tubing eliminates the costs of continuous jointing, reinstallation, and removal of drilling pipes. It is a key technology for slimhole drilling, where the combination can result in significantly lower drilling costs—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.

Reduced working space—about half of what is required for a conventional unit—is an important benefit, as are reduced fuel consumption and emissions. A significant drop in noise levels is also beneficial in most locations. The noise level at a 1,300-foot radius is 45 decibels, while at the same radius a conventional rig has a 55-decibel level.

ECONOMIC BENEFITS

- Increased profits, in certain cases, from 24-hour rig set-up and faster drilling
- Smaller drilling infrastructure and more stable wells
- No interruptions necessary to make connections or to pull production tubing
- Reduced waste disposal costs
- Reduced fuel consumption
- Increased life and performance from new rig designs and advanced tubulars, reducing operating costs

ENVIRONMENTAL BENEFITS

- Reduced mud volumes and drilling waste
- Cleaner operations, as no connections to leak mud
- Reduced operations noise
- Minimized equipment footprints and easier site restoration
- Reduced fuel consumption and emissions
- Less visual impact at site and less disturbance, due to speedy rig set-up
- Reduced risk of soil contamination, due to increased well control
- Better wellbore control

Technology advances in the '90s

Dramatic advances have recently brought new coiled tubing technology to market. For example, new designs from leading drilling service companies have eliminated coiled tubing rigs' guide arches; in these new designs, eliminating the bending in the tubing at the guide arch has significantly increased its life. The newest advance is an electric bottomhole assembly offering immediate data feedback on bottomhole conditions, reduced coiled tubing fatigue, maintenance of bit speed independent of flow rate, and improved reliability. New materials like advanced titanium alloys and advanced metal-free composites have improved the reliability, performance, corrosion-resistance, weight, and cost-effectiveness of coiled tubing assemblies. In certain cases, titanium tubing offers an estimated reeling cycle life 5 to 10 times greater than steel.

Photo: WZI, Inc.

CASE STUDIES

Success in the Field

At Lake Maracaibo field

Advanced coiled tubing drilling is helping operators optimize resource recovery at Venezuela's Lake Maracaibo field. Baker Hughes INTEQ's first-of-its kind Galileo II hybrid drilling barge, containing 2⅜-inch coiled tubing and slimhole drilling measurement-while-drilling tools, drilled its first well at the end of 1997. It was the first time an underbalanced well had been drilled on Lake Maracaibo, and it promises good results. Galileo II's unique design is also expected to significantly increase the life of its coiled tubing, ultimately reducing operating costs. Operating in a fragile lake ecosystem presents unique waste management challenges, and all drill cuttings and waste mud are transported back to shore for disposal.

METRICS

Field trials in the Netherlands demonstrate environmental benefits

Fuel Consumption and Gas Emissions:
Coiled Tubing vs. Conventional Rigs

		Med Workover Rig	Land Drilling Rig	Coiled Tubing Drilling Unit
Diesel m³/month			35	160 25
Gas Emissions kg/day	CO_2	3,293	15,055	2,122
	CO	3.7	16.8	2.5
	NO_x	4.6	21	2.1
	HC	3.9	17.8	2.8
	HC (Gas)	1.8	8.4	1.1
	SO_2	4.2	19.4	2.2

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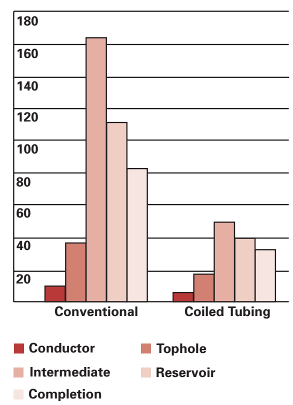
Conventional drilling fluids volume compared with coiled tubing volumes (m3)



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TECHNOLOGY Locations: Worldwide, onshore and offshore

Horizontal Drilling

SUMMARY

Horizontal drilling targets oil or gas in thin, tight reservoirs, reservoirs inaccessible by vertical drilling, and reservoirs where horizontal wellbores significantly increase flow rates and recovery. Horizontal wells maximize utilization of drilling sites and infrastructure. While vertical wells drain oil from a single hole and have limited contact with oil-bearing rock, horizontal wells penetrate a greater cross-section of the formation, allowing substantially more oil to drain. A horizontal well is drilled laterally from a vertical wellbore at an angle between 70° and 110°. It can tap the hydrocarbon supplies of a formation without further environmental disturbance, of particular value in sensitive areas.

BLUEPRINT ON TECHNOLOGY

Without any increase in environmental impact, horizontal drilling allows developers to reach reserves beyond the limits of conventional techniques

Breaking geologic barriers

The current boom in horizontal drilling is due to rapid developments in technology over the past two decades. Although several horizontal wells were successfully drilled between the 1930s and 1950s, these were limited to expensive 100- to 200-foot forays. Interest waned in such onshore applications after the development of hydraulic fracturing technology made vertical wells more productive. The offshore industry continued to pursue horizontal drilling, but the limitations of the available equipment often resulted in ineffective, expensive, and time-consuming drilling operations.

In the mid-1970s, several significant technology advances started breaking down these barriers. Steerable downhole motor assemblies, measurement-while-drilling (MWD) tools, and improvements in radial drilling technologies were the breakthroughs needed to make horizontal drilling feasible. Short-radius technology had been developed in the 1930s, the earliest curvature technique used to drill laterals; in the 1950s, long-radius technology allowed lateral displacement away from the rig to penetrate the reservoir. Then, in the 1970s, medium-radius techniques permitted re-drilling horizontal intervals from existing wellbores, and with this advance producers could build rapidly to a 90° angle. Today, horizontal wells are being drilled longer and deeper, in more hostile environments than ever before.

Horizontal drilling is now conventional in some areas and an important component of enhanced recovery projects. At any given time, horizontal drilling accounts for 5 to 8 percent of the U.S. land well count. The Austin Chalk field has been the site of over 90 percent of the onshore horizontal rig count since the late 1980s, and still accounts for the majority of horizontal permits and rig activity in the U.S. today. Thirty percent of all U.S. reserves are in carbonate formations, and it is here that 90 percent of horizontal wells are drilled.

ECONOMIC BENEFITS

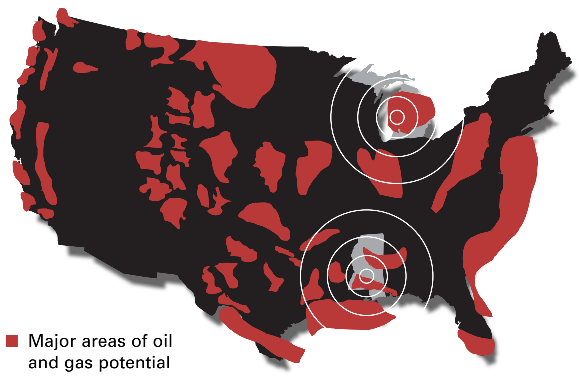
- Increased recoverable hydrocarbons from a formation, often permitting revitalization of previously marginal or mature fields
- More cost-effective drilling operations
- Less produced water requiring disposal and less waste requiring disposal
- Increased well productivity and ultimate recovery

ENVIRONMENTAL BENEFITS

- Less impact in environmentally sensitive areas
- Fewer wells needed to achieve desired level of reserve additions
- More effective drilling means less produced water
- Less drilling waste

CASE STUDIES

Success in the Field



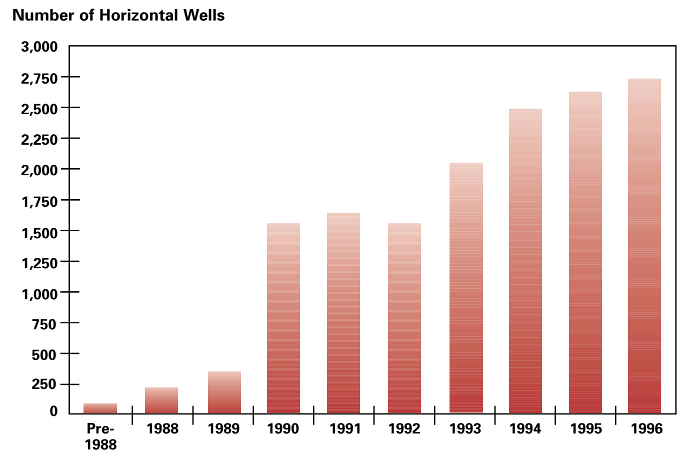
Success in the Black Warrior Basin

In 1993, after six years of production, the Goodwin gas field in the Black Warrior Basin was converted to gas storage by the Mississippi Valley Gas Co. Only conventional vertical wells had been drilled in the thin (10 feet), tight, abrasive formation. The operator successfully drilled and completed the first horizontal well in only 23 days, utilizing MWD and gamma ray tools, a short radius motor, and a polycrystalline diamond bit. Overall costs approached twice that of a conventional well in the field, but the deliverability of the horizontal well was six times that of a vertical well. Since one horizontal well is producing the equivalent of six vertical wells, maintenance and operating costs are lower, and fewer meter runs, flowlines, and other facilities are required.

New reserves in the Dundee Formation

Only 15 percent of the known oil located in the Michigan Basin's Dundee Formation had been produced when a DOE co-sponsored horizontal drilling project brought new life to the formation's exhausted Crystal field. The new horizontal well now produces nearly 20 times more than the best conventional well in its field—100 barrels of oil a day—and boasts estimated recoverable reserves of 200,000 barrels. Success has spawned the drilling of nine other horizontal wells here, and nearly 30 others in geologically similar fields in the basin. If successful in other depleted Dundee fields, horizontal wells could produce an additional 80 to 100 million barrels of oil, worth about $210 million in tax revenues alone.

Worldwide Horizontal Wells



Source: Oil & Gas Journal, November 23, 1998

METRICS

In the United States, according to a recent DOE study, horizontal drilling has improved:

Potential reserve additions—by an estimated 10 billion barrels of oil equivalent, nearly 2% of original oil-in-place

The average production ratio—now 3.2:1 for horizontal compared to vertical drilling based on field data, even though the average cost ratio is 2:1

Carbonate numbers are even better—production is nearly 400% greater than vertical wells, yet costs are only 80% more

Source: U.S. Department of Energy and Maurer Engineering, Inc., 1995

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Hydraulic Fracturing

SUMMARY

Routinely applied to over half of U.S. gas wells and a third of oil wells, hydraulic fracturing has been proven to enhance well performance, minimize drilling, and recover otherwise inaccessible resources. It makes the development of some low-permeability, tight formations and unconventional resources economically feasible. When the flow of hydrocarbons is restricted by formation characteristics, injecting pressurized fluids and solid additives can stimulate wells to increase production. Fluids are pumped into the formation at pressure great enough to fracture the surrounding rock. A proppant slurry follows, biodegrading to sand proppant that holds the fractures open, allowing free passage of fluids to the wellhead. So successful has this technology been that the industry currently spends a billion dollars annually on hydraulic fracturing.

BLUEPRINT ON TECHNOLOGY

Assisting operators to bring new life to mature fields and make unconventional fields commercially viable

Stimulating wells to deliver more

First introduced in 1947, hydraulic fracturing quickly became the most commonly used technique to stimulate oil and gas wells, ultimately enabling production of an additional eight billion barrels of North American oil reserves that would otherwise have been unrecovered. By 1988, fracturing had already been applied nearly a million times. Each year, approximately 25,000 gas and oil wells are hydraulically fractured.

Fracturing is generally used to regain productivity after the first flow of resources diminishes. It is also applied to initiate the production process in unconventional formations, such as coalbed methane, tight gas sands, and shale deposits. Improvements in fracturing design and quality control have enabled operators to successfully apply fracturing techniques in more complex reservoirs, hostile environments, and other unique production settings.

New advances

The DOE-led Natural Gas and Oil Technology Partnership has promoted many of this decade's fracturing advances. These include the use of air, underbalanced drilling, and new fracturing fluids to reduce formation damage and speed well cleanup. Improved log interpretation has improved identification of productive pay zones. Improved borehole tools help map microseismic events and predict the direction and shape of fractures. New 3-D fracture simulators with revised designs and real-time feedback capabilities improve prediction of results.

Advanced breakers and enzymes that minimize the risk of formation plugging from large-volume hydraulic stimulations are the latest advances to protect the environment and increase ultimate recovery. In addition, emerging technologies developed by DOE and the Gas Research Institute, such as microseismic fracture mapping and downhole tiltmeter fracture mapping, offer the promise of more effective fracture diagnostics and greater ultimate resource recovery.

ECONOMIC BENEFITS

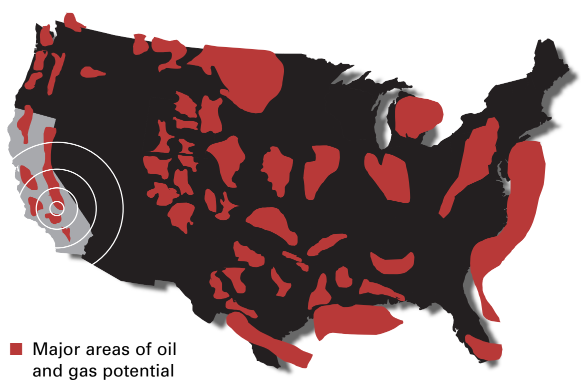
- Increased well productivity and ultimate recovery
- Significant additions to recoverable reserves
- Greatly facilitated production from marginal and mature fields

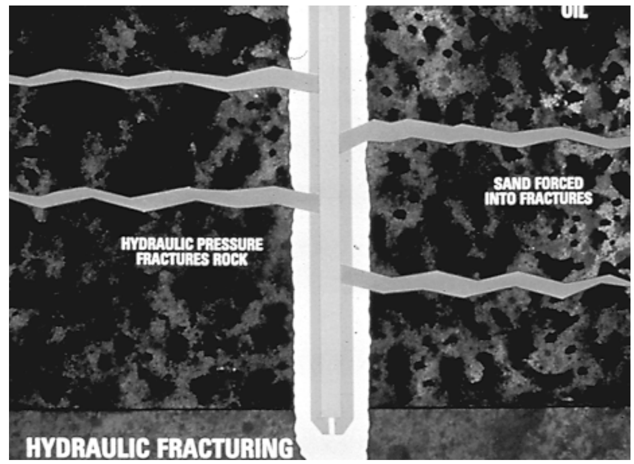
ENVIRONMENTAL BENEFITS

- Optimized recovery of valuable oil and gas resources
- Protection of groundwater resources
- Fewer wells drilled, resulting in less waste requiring disposal

Case Studies

Success in the Field





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Increased profits from the once declining Lost Hills field

Refined fracturing methods and improved quality control have brought increased productivity and profitability to a field that once resisted development. The Lost Hills field in California contains an estimated two billion barrels of oil-in-place, but since its discovery in 1920 it has produced only a fraction of its potential. The field has very low permeability and it lacks a strong natural fracture network, which restricts the flow of resources. This makes the field difficult to produce at acceptable rates without fracture stimulation.

Although hydraulic fracturing began in Lost Hills during the '60s and '70s, completion results were poor because of small proppant volumes and inefficient fracture fluids. Between 1987 and 1990, Chevron initiated massive hydraulic fracture stimulation. Although productivity increased significantly, costs were high and the work was not as profitable as anticipated.

In 1990, Chevron and Schlumberger Dowell formed a partnership aimed at improving fracturing efficiency, reducing costs, and increasing productivity. One result is that multiple wells are now stimulated from fixed equipment locations. Since its implementation in late 1992, this central site strategy has been used to fracture more than 100 wells, using some 200 million pounds of proppant. The strategy has lowered costs by reducing personnel, well completion time, and equipment mobilization, while improving environmental management and safety controls. Along with fracture design changes, this has reduced overall fracturing costs by 40 percent since 1988. These efforts played a large part in the field's 250 percent production increase between 1989 and 1994—from 6,000 barrels to more than 15,000 barrels of oil per day.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Measurement-While-Drilling

SUMMARY

Measurement-while-drilling (MWD) systems measure downhole and formation parameters to allow more efficient, safer, and more accurate drilling. These measurements can otherwise be obtained only by extrapolation from surface measurements. MWD systems calculate and transmit real-time data from the drill bit to the surface, avoiding the time-lag between occurrence and surface assessment and significantly improving drilling safety and efficiency. Without this analysis of bottomhole conditions, it is sometimes necessary to abandon a hole for a new start. MWD reduces both costs and environmental impacts because measurements and formation evaluation occur before formation damage, alteration, or fluid displacement have occurred. Of particular use in navigating hostile drilling environments, MWD is most frequently used in expensive exploratory wells, and in offshore, horizontal, and highly deviated wells.

BLUEPRINT ON TECHNOLOGY

High-tech tools that deliver real-time bottomhole data prevent excessive formation damage and make drilling significantly more precise and cost-effective

More information for better drilling

MWD TECHNOLOGY is critical as operators seek to reach deeper and farther for new hydrocarbon resources. A real-time bit navigation and formation evaluation aid, MWD uses tools such as triaxial magnetometers, accelerometers, and pressure sensors to provide vital downhole data concerning directional measurements, pore pressures, porosity, and vibration. This provides for more effective geosteering and trajectory control, and safer rig operations. Novel equipment transmits bottomhole information to the surface by encoding data as a series of pressure pulses in the wellbore's mud column or by electromagnetic telemetry. Surface sensors and computer systems then decode the transmitted information and present it as real-time data.

In normal drilling environments, MWD is used to keep the drill bit on course. MWD is also valuable in more challenging drilling environments, including underbalanced, extended-reach, deviated, and high-pressure, high-temperature drilling. In underbalanced directional drilling, MWD monitors the use of gas injected to maintain safe operating pressure. In deviated and horizontal wells, MWD can be used to geologically steer the well for maximum exposure in the reservoir's most productive zones.

Evaluating the formation

Prior to the spread of MWD systems in the late '70s, bottomhole conditions were monitored by time-consuming analysis of cuttings and gas intrusion, and by after-the-fact wireline steering measurement that necessitated frequent interruptions for pipe removal. Today, the continuous flow of MWD information improves formation evaluation efforts as well as drilling progress. Over successive periods, MWD data can reveal dynamic invasion effects, yielding information on hydrocarbon mobility, gas-oil-water contact points, and formation porosity. Future advances in MWD technology, such as MWD acousticalipers with digital signal processing

ECONOMIC BENEFITS

- Improved drilling efficiency and accuracy
- Timely formation evaluation
- Reduced operating costs and financial risks
- Improved rig safety

ENVIRONMENTAL BENEFITS

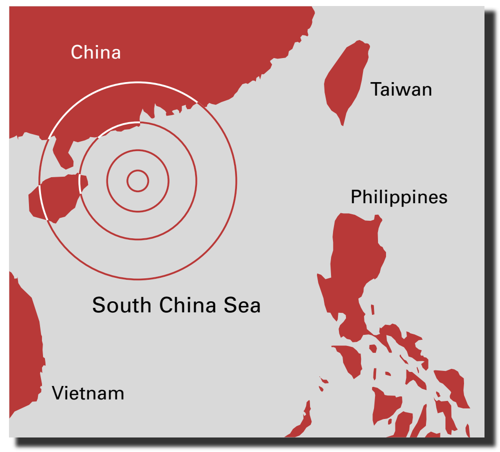
- Less formation damage
- Reduced possibility of well blowouts and improved overall rig safety
- Reduced volume of drilling waste as fewer wells drilled overall
- Better wellbore control

and DOE-sponsored research into ultra-deepwater MWD technologies, promise to enhance operations even further.

Contributing dramatically to operational safety
Operators seeking to control drilling operations and enhance rig safety in difficult environments such as deepwater drilling find MWD a valuable tool. In combination with advanced interpretive software applications, MWD is helping deepwater operators better forecast and measure a formation's pore and fracture pressures. More accurate geopressure estimates can prevent dangerous well blowouts and fires. In the unlikely event of a deepwater blowout, MWD equipment is a crucial tool in assisting operators to drill and steer a relief well to regain control of the well.

CASE STUDIES

Success in the Field



Extended reach in the South China Sea
In the South China Sea, MWD technology was critical in helping operators drill a 5-mile extended-reach well to a then world-record horizontal displacement of nearly 26,500 feet, at a true vertical depth of approximately 10,000 feet. It effectively "steered" the well to access the most productive zones at a final hole angle of 54°. In combination with other advanced drilling and completion technologies, MWD technology permitted operators to access this otherwise uneconomical, remote offshore field, completing the project in approximately 100 days at a cost of $24 million. As of June 1997, this once-bypassed field was producing 7,000 barrels of oil per day.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Modern Drilling Bits

SUMMARY

Dramatic advances in drill bit technology have improved drilling performance significantly while cutting wastes and environmental impacts. Although the choice of bit represents only 3 percent of the cost of well construction, bit performance indirectly affects up to 75 percent of total well cost. Faster rates of penetration and greatly extended bit life, the result of advances in materials technology, hydraulic efficiency, cutter design, and bit stability, now allow wells to be drilled more quickly, more profitably, and with less environmental impact. The improvement to an operator's cost-efficiency from these advances is striking. Today, selection of the appropriate bit has become critical both in establishing the overall economics of field development and in minimizing the environmental impacts of drilling.

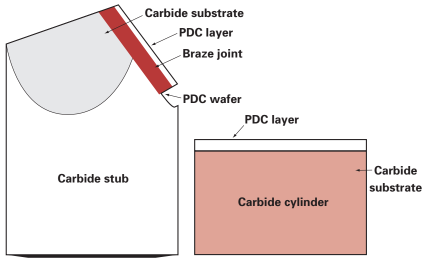
BLUEPRINT ON TECHNOLOGY

Evolving bit technology allows operators to drill wellbores more quickly and with less environmental impact

The diamond success story

FROM USE IN ONE percent of total worldwide drilling in 1978, to an estimated 25 percent in 1997, diamond drill bits, which use cutters consisting of a thick layer of tungsten carbide permeated with bonded diamond particles, have been one of the success stories of the last 25 years. Natural diamonds, synthetic diamonds, and diamond composites are now routinely used within insert-bit cutting structures, and, although originally developed for hard formations, polycrystalline diamond compact (PDC) bits have proved their value in soft- and medium-hard formations too. Today, PDC bits are most applicable in areas with relatively soft formations or where drilling is expensive, such as offshore locations and remote wells. In parallel with PDC development, roller cone bits have also been improved. The National Petroleum Council estimates that improvements in drilling efficiency from advances such as those in bit technology have reduced underlying drilling costs by about 3 percent annually over the last 50 years. As materials technology, hydraulics, and bit stability continue to improve, so will drilling performance and environmental protection.

PDC Cutter Components



Source: Petroleum Engineer International, 1993

Matching the bit to the formation

By helping operators choose the best bit for the job, computerized drill bit optimization systems have improved the way bits are being selected and used. These systems match an individual formation to the most effective milled-tooth, tungsten carbide insert and PDC bit to complete the job for the least cost per foot. They also prescribe other design parameters such as hole gauge and hydraulic requirements to help determine optimal cutting structure.

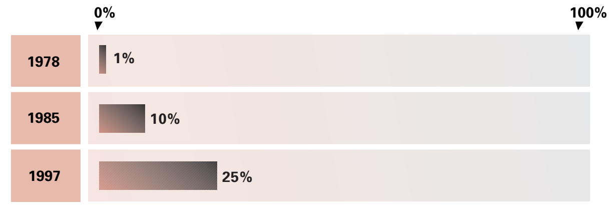
ECONOMIC BENEFITS
Increased rates of penetration
Fewer drilling trips due to greater bit life
Reduced power consumption
Improved drilling efficiency and hence viability of marginal resources

ENVIRONMENTAL BENEFITS
Reduced power use and resultant emissions
Less drilling waste
Reduced equipment mobilization and fewer rigs
Less noise pollution
Better wellbore control and less formation damage

METRICS

Increases in diamond bit drilling

In 1978, approximately 1 percent of the total footage drilled worldwide was drilled with diamond bits; in 1985, it was approximately 10 percent; by 1997, that figure was an estimated 25 percent. Also, between 1988 and 1994, advances in PDC technology increased the average footage drilled by over 260 percent, from approximately 1,600 feet to 4,200 feet per PDC bit.



Source: Rappold, Oil & Gas Journal, 8/14/95

CASE STUDIES

Success in the Field

Switching to new drill bits saves time and money

Using a specialized bit optimization system, Anadarko Petroleum has demonstrated significant efficiency improvements. For example, drilling time was reduced by 8 to 12 days in Algeria, with savings of $250,000 to $350,000; and a Mississippi project saved 15 days and $200,000. Ultimately, impacts on the environment were appreciably lessened.

Petroleum Development Oman found that rates of penetration dropped from 26 feet per hour to under 10 feet per hour when drills using tungsten carbide inserts hit the hard Khuff Formation. Switching to a new generation PDC bit with carbide-supported edge cutters resulted in a new rate of 23.6 feet per hour in the Khuff. The entire section was drilled in one run, at half the cost of the same section in a similar well. Another well drilled in the comparable Zauliayah field resulted in a rate of 34 feet per hour at a cost of $34 per foot, nearly half the cost of drilling a comparable well in the area with an earlier-generation bit.

When Chevron switched to new generation polycrystalline bits at its Arrowhead Greyburg field in New Mexico, the rate of penetration increased more than 100 percent. Chevron had been experiencing problems using 3-cone bits and thermally stabilized diamond bits. Switching to PDC bits with curved cutters significantly increased drilling efficiency, while reducing environmental impacts.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Multilateral Drilling

SUMMARY

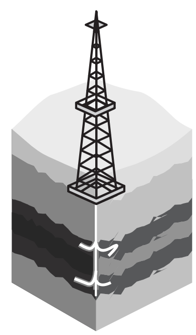
Multilateral drilling creates an interconnected network of separate, pressure-isolated, and reentry-accessible horizontal or high-angle wellbores surrounding a single major wellbore, enabling drainage of multiple target zones. In many cases, this approach can be more effective than simple horizontal drilling in increasing productivity and enlarging recoverable reserves. Often multilateral drilling can restore economic life to an aging field. It also reduces drilling and waste disposal costs. Today, in a wide variety of drilling environments, both onshore and offshore, from the Middle East to the North Sea and from the North Slope to the Austin Chalk, multilateral completions are providing dramatic returns for operators.

BLUEPRINT ON TECHNOLOGY

New lateral drilling developments provide dramatic returns for operators, with less waste, smaller footprints, and increased site protection

From horizontal to multilateral branching wellbores

HORIZONTAL DRILLING provoked a surge of interest in the 1980s as a way to contact more oil reserves, penetrating a greater cross-section of the oil-bearing rock with a single wellbore and intersecting repeatedly the fractures that carry oil to a producing well. Today, declining production, flat prices, and heightened environmental awareness have led the exploration and production industry to develop advanced drilling and completion technologies that permit wells to branch out multilaterally, in certain cases saving both time and money compared to horizontal drilling. In many cases, such as deep reservoir production, it is more efficient to create a connected network than to drill multiple individual horizontal wellbores.



Multilateral drilling is of greatest value in reservoirs that:

- Have small or isolated accumulations in multiple zones
- Accumulate oil above the highest existing perforations
- Have pay zones that are arranged in lens-shaped pockets
- Are strongly directional
- Contain distinct sets of natural fractures
- Are vertically segregated, with low transmissibility

ECONOMIC BENEFITS
Improved production per platform
Increased productivity per well and greater ultimate recovery efficiency
New life for marginally economic fields in danger of abandonment
Reduced drilling and waste disposal costs
Reduced field development costs
Improved reservoir drainage and management
More efficient use of platform, facility, and crew

ENVIRONMENTAL BENEFITS
Fewer drilling sites and footprints
Less drilling fluids and cuttings
Protection of sensitive habitats and wildlife

CASE STUDIES

Success in the Field

"[With advanced re-entry multilateral technology] we are seeing the potential to reduce by half the costs associated with subsea developments. In some cases, this will make what were previously marginal or non-economic discoveries economical."

Ali Daneshy
Vice President, Halliburton

Norsk demonstrates the future of offshore drilling

A highly successful offshore project in Norway is showcasing the reduced environmental impacts and increased economic benefits of multilateral completions. In March 1997, Norsk Hydro a.s. and Halliburton Energy Services drilled the world's first subsea multilateral with reentry access in Norsk's Troll field. The companies estimate that the economic benefits will be 50 percent greater than those from fixed platforms. By reducing the systems required to access the subsea reservoir, the project cuts both costs and impact on the environment and leads the way for subsequent offshore drilling operations.

New life for old wells: pentalateral drilling in the Middle East

Mounting evidence demonstrates that multilaterial drilling can bring new life to old wells. In the Arabian Gulf recently, a significant reduction in production that may have spelled well closure in the past was instead the stimulus to drill five lateral branches into new pay zones. The lateral wells were drilled in only 19 days, reaching some 5,000 feet of new producing formations. Since the new zones consisted of relatively soft limestone layers separated from each other by dolomites, drilling presented few problems. Dramatically increased production rates covered costs in just six days. In all, production increased 2.7 times as a result of the multilateral completions.

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TECHNOLOGY

Locations: Deepwater—Gulf of Mexico, West Africa, North Sea, Brazil, others

Offshore Drilling

SUMMARY

Recent exploration successes in deepwater plays in the Gulf of Mexico are of crucial importance in providing a vital new domestic resource. Technological advances are increasing operators' ability to take advantage of these finds, while reducing the dangers and uncertainty inherent in deepwater operations. Without such progress, much of the Gulf's resources may remain undeveloped. A major concern for operators is the safety of deepwater exploratory operations, especially as the industry moves toward depths of 10,000 feet. To ensure stability and efficiency at such depths, advanced dynamic positioning technology is now being used. This includes thruster units and sophisticated computer and navigation systems to hold a new generation of drillships, floating production, storage, and offloading systems, and survey vessels on location without anchors or mooring lines.

BLUEPRINT ON TECHNOLOGY

Technology advances in dynamic positioning expand opportunities for deepwater drilling with reduced environmental impact

Deepwater opportunities

The Gulf of Mexico's deepwater reservoirs have become America's new frontier for oil and gas exploration. Production potential from proved and unproved reserves in deepwater areas is estimated to be roughly 1.8 billion barrels of oil and 5.8 trillion cubic feet of natural gas. Consequently, drilling in the Gulf's Outer Continental Shelf has increased greatly over the last 10 years. Today, deepwater drilling from permanent structures and wildcat wells is at an all-time high. In October 1997, a record 31 temporary and permanent deepwater rigs were drilling in water depths greater than 1,000 feet, as compared to only nine in 1990.

Production from deepwater wells is increasing too. In 1985, for example, less than 2 percent of the Gulf's total oil production was from deepwater wells. By 1996, over 17 percent of the Gulf's oil production came from deepwater wells. Natural gas production from deepwater areas in the Gulf has also increased—from less than 1 percent of total production in 1985—to nearly 6 percent in 1996.

Improving station keeping

Dynamic positioning systems compensate for the effects of wind, waves, and current, enabling mobile offshore drilling units to hold position over the borehole, maintaining within operational limits lateral loads on the drill stem and marine riser. Improved dynamic positioning systems, in combination with improved onboard motion compensation systems, are expanding the range of water depths and environmental conditions within which drilling operations can be safely conducted.

Azimuthing thruster units, often retractable so as to enable shallow water maneuvers, are the backbone of the dynamic positioning system. Ship-based computers and satellite-linked navigation units control the vessel's rudder, propellers, and thrusters using input from various monitoring systems, such as gyrocompass wind sensors, real-time differential global positioning systems, micro-wave positioning systems, underwater sonar

ECONOMIC BENEFITS

- Minimized positioning and transit times for deepwater exploration
- Reduced operating costs in deepwater exploration operations
- Improved access to deepwater and ultra-deepwater resources that might otherwise have remained undeveloped

ENVIRONMENTAL BENEFITS

- Less disruption to seafloor ecosystem
- Reduced environmental impacts due to increased operational stability
- Enhanced deepwater operational safety

beacons, and hydro-acoustic beacons. If the wind or tide swell moves the ship from its desired station, guided thrusters can automatically hold the vessel's orientation and position. They can also move it to a new position in the event of extreme weather.

A new equipment market
The trend toward long-term, ultra-deepwater exploratory operations has substantially increased demand for dynamically positioned vessels. The harsher environments of deeper offshore plays has accelerated demand for dynamically positioned drillships, semisubmersible rigs, seismic survey vessels, floating production, storage, and offloading systems, pipelayers, shuttle tankers, and standby support vessels. The benefits of dynamic positioning include:

Cost-effectiveness
When permanent or disconnectable moorings become excessively difficult or expensive, or when low-cost fuel is available, dynamically positioned systems may be highly cost-effective. Given today's technology, it would be practically impossible to conduct ultra-deepwater exploratory operations without dynamic positioning technology.

Operational flexibility
These systems allow vessels to move readily from one location to another during exploratory operations, eliminating the cost and time of setting and removing mooring lines. Such flexibility, vital during hurricane season, may ultimately reduce operating costs.

Safety
The precise positioning afforded by these systems contributes significantly to both environmental protection and worker safety during offshore operations. The safety of operations involving diving support vessels, deepwater drillships, or shuttle tankers, for instance, is often enhanced by the degree of operational precision provided by dynamic positioning systems.

The forces of wind, waves, and ocean currents cause exploration and drilling support vessels to sway, yaw, and move off course. To counter this, dynamic positioning technology stabilizes deepwater site equipment, allowing exploratory operations in waters too deep for conventional mooring systems.

METRICS

Steady drilling from dynamic positioning

Today's advanced dynamic positioning technology enables drillships to maintain station with maximum excursion levels below 1% of total water depth. At a water depth of 5,000 feet, for example, these advanced systems are able to keep a 200-yard-long, 30-story-high drillship within 50 feet of station.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Pneumatic Drilling

SUMMARY

Pneumatic drilling is an underbalanced drilling technique in which boreholes are drilled using air or other gases as the circulating agent. In certain cases this air drilling technique offers the promise of mudless drilling. By using nitrogen, air, or natural gas in place of oil- or water-based muds, producers can both eliminate drilling fluids that need disposal and ensure that drill cuttings are not tainted by chemicals or oil. Although it is suitable only for certain formation types and lithologies and can create potentially explosive downhole conditions—and is not therefore likely to become widespread—this technique is a very attractive environmental prospect, offering significant operational benefits.

BLUEPRINT ON TECHNOLOGY

Unlike conventional mud-based drilling, air drilling significantly reduces or eliminates drilling fluid additives and prevents formation damage

Protecting low-pressure formations and maximizing production

UNDERBALANCED drilling offers significant advantages over conventional systems in low-pressure or pressure-depleted formations. Pressure overbalances in conventional drilling can cause significant fluid filtrate invasion, and lost circulation in the formation. Expensive completions, decreased productivity, and high mud and mud-removal costs can then plague drilling operations, but these can be avoided by using underbalanced conditions. By lowering downhole pressure using a noncondensable gas in the circulating fluid system, underbalanced pneumatic drilling can prevent difficulties commonly encountered when reservoir pressures are lower than the hydrostatic pressure exerted by traditional water-based drilling fluids. Depending on the environment, gas may be used alone or with water and additives. When drilling fluid is needed for well control, gas is mixed with lightweight drilling fluids.

In general, pneumatic drilling is used in mature fields and formations with low downhole pressures, in open-hole completions, and in fluid-sensitive formations. It is an important tool in drilling horizontal wells, which must expose a large amount of reservoir face to be productive, and have minimum damage from fluids invasion. As horizontal drilling increases in popularity, underbalanced pneumatic drilling will become more widespread, because it can penetrate the reservoir without damaging the formation or its productive capacity.

Air drilling techniques to suit

Air dust drilling is a dry technique that relies on the annular velocity of air to

ECONOMIC BENEFITS

- Substantially less fluid and waste requiring disposal
- Increased rates of penetration and longer drill bit life
- Indication and evaluation of productive zones and more effective geosteering of the well by monitoring flow of produced fluids
- Potential elimination of waste pits gives access to restricted areas

ENVIRONMENTAL BENEFITS

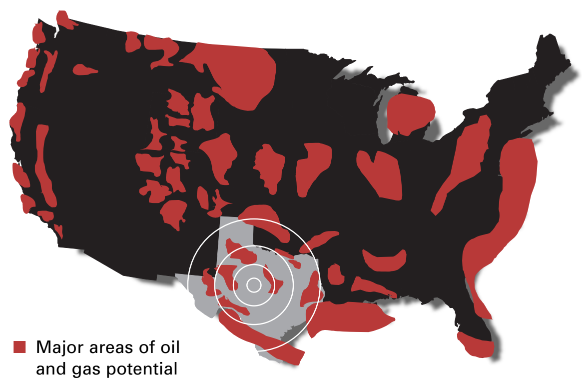
- Greatly reduced drilling fluids and chemical-tainted cuttings
- Decreased power consumption and emissions
- Better wellbore control and less damage to formations
- Fewer workover and stimulation operations needed
- Potential for smaller drilling footprints and less impact on habitats, wildlife, and cultural resources

transport cuttings. It is typically employed in drilling dry formations, or when any water influx is low enough to be adsorbed by the air stream. If excessive water influx precludes its use, *air-mist drilling* is employed instead, using an air-injected mud that returns to the surface as mist. Sometimes *foam-drilling* is required, using a stable mixture of water and compressed air with detergent and chemicals. When the water influx is too great to be removed through mist or foam, *aerated mud drilling*, a technique in which air is injected into viscosified fluid or mud in order to reduce the weight of the fluid column on the formation, combines the best properties of conventional and air drilling to provide an effective solution.

A new waste management technology enables operators to eliminate the earthen waste pits used to catch effluent created while drilling with an air- or air-mist system. Liquids and solids in the effluent are separated and treated, and gases are exhausted. By eliminating the environmental risks associated with pits, drillers can operate in otherwise restricted areas, such as State parks and within city limits. Initial field tests indicate that this technology can handle continuous liquid volumes of 90 barrels per hour and solid volumes of 14 barrels per hour.

CASE STUDIES

Success in the Field



Accessing new supplies in the Carthage field

Selected as the most viable technique to prevent damage to an extremely low-pressure reservoir, pneumatic drilling made history as the first air-drilled horizontal well in the Carthage field in Texas. Air drilling successfully increased gas recovery from depleted zones without wellbore skin damage, which would have restricted the reservoir's productive flow. Drilled in December 1995, the Pirkle 2 well had by the end of April 1997 produced 530 million cubic feet of gas at a rate of 1.1 million cubic feet per day. The well was drilled with compressed nitrogen into the Cretaceous Frost "A" zone at 6,000 feet true vertical depth; it produces through a 1,400-foot lateral well with bottomhole pressure of 185 psi. The operation successfully met the economic criteria of producer OXY USA Inc., which had determined that the well's production rate would have to at least double that of a standard vertical well to be economically viable.

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TECHNOLOGY

Locations: Worldwide, onshore and offshore

Slimhole Drilling

SUMMARY

Improved slimhole drilling technology brings the twin advantages of environmental protection and economical results to oil and gas exploration and production. (For example, a conventional well drilled with a 12.25-inch bit and a 5-inch drill pipe becomes a slimhole when using a 4-inch bit and a 3.7-inch drill pipe.) Slimhole rigs are defined as wells in which at least 90 percent of the hole has been drilled with a bit six inches or less in diameter. Slimhole rigs not only boast a far smaller footprint and less waste generation than conventional operations, they can also reduce operating costs by up to 50 percent. The technique is proving a low-cost, efficient tool with which to explore new regions, tap undepleted zones in maturing fields, and test deeper zones in existing fields.

BLUEPRINT ON TECHNOLOGY

Technology advances in less invasive slimhole drilling increasingly valuable in exploration and production

Narrow boreholes prove highly effective

POTENTIALLY APPLICABLE to more than 70 percent of all wells drilled, slimhole drilling holds promise for improving the efficiency and costs of both exploration and production. Although the technique was first used in the oil and gas industry in the 1950s, its acceptance has been hampered until recently by concerns that smaller boreholes would limit stimulation opportunities, production rates, and multiple completions. Advances in technology, coupled with a growing record of success, have dispelled these concerns, making slimhole an increasingly attractive option for reservoir development. Today, slimhole drilling is employed throughout the lower-48 States and the Gulf of Mexico, especially in the Austin Chalk fields of South Texas. Globally, slimhole drilling has been used in a wide range of onshore and offshore settings.

As an **exploration** tool, slimhole drilling for stratigraphic testing provides geologists with a clearer picture of the local geography, refining seismic interpretation. Such testing, combined with other technologies such as continuous coring, yields valuable information for increasing success rates in exploration.

In the **production** arena, improved slimhole drilling offers a viable means of recovering additional reserves from existing reservoirs, including economically marginal fields. Resources in pay zones bypassed in the original field development can be cost-effectively accessed through the existing wellbores, thereby extending the productive life of the field.

ECONOMIC BENEFITS

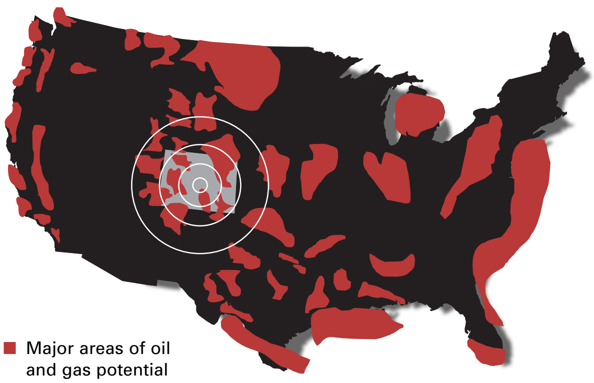
- Smaller drilling crews and less drilling time mean up to a 50 percent reduction in costs
- Slimhole drilling is critical for adding millions of barrels of oil to the Nation's reserves
- Slimhole is feasible in a wide range of operations and capable of reducing exploration and development costs around the United States

ENVIRONMENTAL BENEFITS

- A slimhole rig occupies far less space than a conventional rig—the entire footprint including site access can be up to 75 percent smaller
- The rig requires far less drilling fluid and produces far fewer cuttings for disposal
- Reduced volume and weight of equipment favors use in sensitive environments, such as rainforests and wetlands, particularly in helicopter-supported campaigns
- Better wellbore control

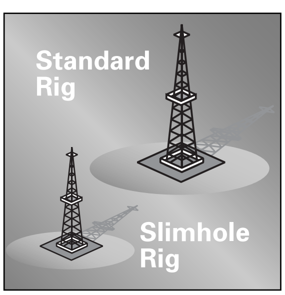
CASE STUDIES

Success in the Field



In Wattenberg field

An eight-well field test conducted by HS Resources Inc. in 1996 in the Denver-Julesburg Basin's Wattenberg field successfully demonstrated that slimhole lateral wells could be drilled from inside an existing 4.5-inch cased producing vertical well. These lateral wells with 2.375- and 2.875-inch liners are considered the first lateral cementing operations of this size liner in the Rocky Mountain region and the first reported lateral drilling in Colorado using coiled tubing. The project's success led HS Resources to begin additional slimhole drilling in 1997 and is significant for several reasons. First, this approach allows production of additional reserves with minimal impact on an active agricultural area. Second, it reduces operating costs by commingling production from both vertical and lateral wellbores.



At the Austin Chalk fields

More than 100 horizontal slimhole well reentries have been drilled by Slim Dril International, demonstrating a successful way to discover and tap otherwise inaccessible reserves of domestic oil. The company also used slimhole to deepen a conventional well to a depth of 22,000 feet, using mud motors to test a producing field. This advancing technology is extending the life of wells both at Austin Chalk in south Texas and in the Gulf of Mexico, and could potentially add millions of barrels of oil to our Nation's reserves.

METRICS

A Head-to-Head Comparison

At a drilling depth of 14,000 feet, here is how a slimhole rig with a 4-inch diameter performs versus a conventional drilling operation with an 8.5-inch diameter:

Fuel consumption	75% less
• Installed power	1,350 vs. 4,000 kilowatts
• Mud-pump power	330 vs. 3,200 horsepower
Drillsite area	75% smaller
Mud cost	80% less
• Active mud volumes	50 vs. 1,500 barrels
Rig weight	412,000 vs. 3,400,000 pounds
	150 vs. 500 helicopter lifts
	12 vs. 65 Hercules loads
	18 vs. 55 truckloads
	Drillstring weight: 37 vs. 150 tons
Drilling crew size	Staff of 3 or 4 vs. 6
Camp size	Staff of 30 vs. 80

Bottom Line:

Potential well cost-savings of 50%

Source: Nabors Industries

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TECHNOLOGY Locations: Worldwide, deepwater

Synthetic Drilling Muds

SUMMARY

Drilling fluids are essential to carry cuttings to the surface, maintain pressure balance and stability in the borehole, lubricate and clear the drillstring and bit, and prevent the influx of other fluids. Today's advanced offshore drilling practices include the use of synthetic-based muds (SBMs), which combine the higher performance of oil-based muds (OBMs) and the lower toxicity of water-based muds (WBMs). SBMs are a high-performance, environmentally friendly choice for complex offshore drilling environments. Management of fluids and cutting wastes is a significant responsibility for the industry, and in remote offshore areas can entail significant expense. Compared with OBMs, drill cuttings from SBMs can be safely discharged in many offshore areas, significantly reducing disposal costs and environmental impacts.

BLUEPRINT ON TECHNOLOGY

New synthetic drilling muds combine the performance of oil-based muds with the easier, safer disposal of water-based muds

Conventional versus new muds

NEARLY ALL WELLS less than 10,000 feet and 85 percent of deeper wells are drilled with water-based muds (WBMs), making them the most commonly used muds both onshore and offshore. With a 90 percent water base, WBMs and associated cuttings can typically be discharged on-site. However, they are often not technically feasible or cost-effective in complex drilling situations. As such, oil-based muds (OBMs) are often the drilling fluids of choice in deep, extended-reach, high-angle, high-temperature, and other special drilling environments, greatly outperforming WBMs. But their diesel or mineral oil base means that although they effectively minimize drilling problems, OBMs cannot be discharged on-site. At remote offshore sites, operators must incur the expense, logistical problems, and environmental risks of shipping OBM wastes back to shore for disposal.

The development of synthetic-based muds (SBMs) was driven by industry's need for a drilling fluid with lower

ECONOMIC BENEFITS

- Improved drilling speeds, lower operating costs, and shorter completion times (versus WBMs)
- Reduced downtime from common drilling problems (versus WBMs)
- Minimal to no waste hauling and disposal costs (versus OBMs)
- Reduced drilling costs as SBMs can be reconditioned and revised (versus WBMs)
- Increased access to resources by high-angle, extended-reach, and horizontal wells (versus WBMs)

ENVIRONMENTAL BENEFITS

- Lower concentration of inherent contaminants, such as complex hydrocarbons (versus OBMs)
- Safe discharge of drill cuttings (versus OBMs)
- Less waste than WBMs, as SBMs are reusable
- Faster drilling, so reduced power use and air emissions (versus WBMs)
- Smaller footprint, as SBMs facilitate extended-reach and horizontal wells (versus WBMs)
- Increased worker health and safety—volume and toxicity of irritating vapors lower than OBMs
- Reduced air pollution because SBMs are not transported to shore for disposal (versus OBMs)
- Reduced landfill usage
- Increased wellbore control (versus WBMs)

disposal costs than OBMs and higher levels of performance than WBMs. In general, SBM performance is comparable to that of OBMs, and in some cases superior. They are manufactured by chemical synthesis from basic building blocks of relatively pure materials, forming highly uniform products. By varying the components and manufacturing conditions, different SBMs can be created that exhibit varying rheological properties and environmental performance parameters. Current synthetic fluids fall into several groups: polyalphaolefins (PAOs), linear alpha olefins (LAOs), internal olefins (IOs), fatty acid esters, and others.

Comparing costs

Although more expensive on a per-barrel basis, SBMs can reduce overall drilling expenses. When measured against WBMs, SBMs can shorten drilling time. Compared with OBMs, SBMs offer lower disposal costs.

METRICS

Advantages of synthetic muds as demonstrated by Marathon Oil in the Gulf of Mexico

Footage Drilled	Footage per Day	Mud Cost in $ Millions	Cost $ per Foot	Total Well Cost in $ Millions	Total Days
WBM Wells					
17,981	138	1.3	74	11.6	163
16,928	63	2.5	150	18.3	326
17,540	82	–	–	9.6	214
17,142	101	1.6	90.4	12.7	197
17,381	215	–	–	10.1	77
SBM Wells					
16,842	301	0.8	48	5.0	50
18,122	275	1.7	94	7.8	75
17,250	431	0.8	45	3.7	33

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CASE STUDIES

Success in the Field

Proof in the Gulf

A set of Gulf of Mexico wells with similar characteristics were the scene for a comparative study of the relative merits of SBMs and WBMs. Marathon Oil drilled five wells with WBMs and three with SBMs, and found that SBM performs with greater overall efficiency. For example, the SBM wells averaged 336 feet per day and 53 days per well, compared to 120 feet per day and 195 days per WBM well. Despite higher per-barrel costs, SBM resulted in lower total drilling mud costs and downtime costs. Overall, total drilling and completion costs for the SBM wells were in the range of $3.7 to $7.9 million per well, compared with $9.6 to $18.3 million for WBM wells. Combined with significant increases in productivity and decreased environmental impacts, these results proved that SBM was the better performer for these wells.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Acid Gas Removal and Recovery

SUMMARY

Before natural gas can be transported safely and economically, hydrogen sulfide (H_2S), a highly poisonous acid gas, and other acid compounds such as carbon dioxide (CO_2) must be removed from the raw gas stream in order to meet pipeline sales contract specifications. Sulfur recovery plants are used in tandem with acid gas removal (sweetening) operations to avoid emitting unacceptable quantities of sulfur compounds to the atmosphere. Improvements in gas sweetening, in conjunction with advanced sulfur recovery technologies, make it possible to practically eliminate noxious emissions and recover nearly all the acid gas stream's elemental sulfur for later sale or disposal.

BLUEPRINT ON TECHNOLOGY

Improved technology and practices "sweeten" sour gas for pipeline use and achieve nearly 100 percent sulfur recovery, greatly reducing air emissions

Sweetening natural gas

A RECENT GAS RESEARCH Institute survey concluded that approximately 24 percent of the raw natural gas produced in the lower-48 States contains unacceptable quantities of H_2S, CO_2, or both. To sweeten the high acid content "sour" gas, it is first prescrubbed to remove entrained brine, hydrocarbons, and other substances. The still sour gas then enters an absorber, where lean amine solution chemically absorbs the acid gas components, as well as a small portion of hydrocarbons, rendering the gas ready for processing and sale. An outlet scrubber removes any residual amine, which is regenerated for recycling. Hydrocarbon contaminants entrained in the amine can be separated in a flash tank and used as fuel gas or sold. Process efficiency can be optimized by mixing different types of amine to increase absorption capacity, by increasing the amine concentration, or by varying the temperature of the lean amine absorption process.

Recovering sulfur

Once acid components have been removed from the gas stream, sulfur recovery plants can minimize sulfur emissions and maximize recovery of elemental sulfur—environmental regulations commonly require sulfur recovery levels well over 99 percent. The Claus sulfur recovery process, first developed over 100 years ago, is still the most widely used process today. Between 90 and 95 percent of the total sulfur recovered worldwide uses a variation of this process. Typically, the acid gas feed is partially oxidized to produce SO_2, which is then catalyzed with the remaining H_2S to produce elemental sulfur, of which approximately 94 to 97 percent is recovered for sale. Most Claus plants contain two or three catalytic stages to enhance recovery. To reach higher recovery levels, a sub-dewpoint Claus process is employed, which operates at a lower temperature, causing sulfur condensation and higher recovery. A tailgas cleanup unit is required to obtain sulfur recovery levels as high as 99.9 percent. This converts the sulfur compounds in the tailgas back to H_2S, then transfers it to a low-pressure amine sweetening unit, which recycles the H_2S with some CO_2 to the

ECONOMIC BENEFITS

- Increased access to sour natural gas resources
- Sale of recovered sulfur as a commodity

ENVIRONMENTAL BENEFITS

- Improved air quality through increased sulfur recovery

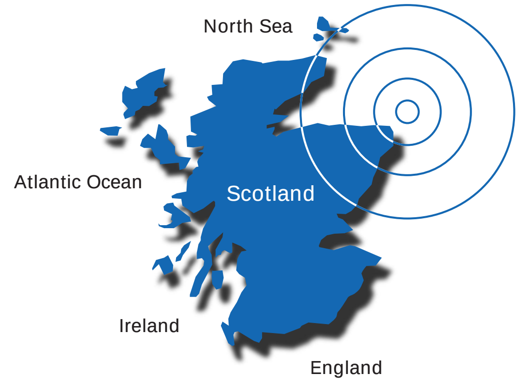
Claus unit for reprocessing. In most sulfur recovery processes, a tailgas thermal oxidizer incinerates nearly all remaining sulfur compounds and other contaminants before venting it to the atmosphere.

Alternative acid gas disposal methods
In cases in which it is not economically feasible to recover elemental sulfur for sale, industry is developing advanced acid gas disposal techniques. In Canada, for example, where operators have typically flared recovered acid gases if unable to recover sulfur economically, acid gas is now being dissolved in oil field produced water at the surface and injected into subsurface formations. This practice, although still being demonstrated, potentially offers producers a low-cost, environmentally sound acid gas disposal technique when sulfur recovery is not economic.

Aerial view of pipeline transporting recovered sulfur to market

CASE STUDIES

Success in the Field



The Scott field experience

Scott field, 130 miles northeast of Aberdeen, Scotland, is the United Kingdom's largest offshore project this decade. Recoverable reserves are estimated at 450 million barrels of oil and 287 billion cubic feet of associated gas. In addition to subsea facilities, the development has twin connecting steel platforms, including a process/drilling platform, drilling and gas treatment modules, and a flaring unit.

Developer Amerada Hess Ltd. realized that offshore production could begin several months before availability of permanent onshore gas processing facilities at Mobil North Sea Ltd.'s St. Fergus terminal, which was scheduled to come on-line on April 1, 1994. To permit early production, temporary gas sweetening equipment was installed in April 1993 to attain pipeline specifications. A single, fixed-bed reactor sweetening unit enabled H_2S content to be reduced by nearly 95 percent. By the middle of October, the Scott field development was producing, treating, and exporting gas, approximately five months ahead of schedule.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Artificial Lift Optimization

SUMMARY

As reservoir pressure declines, natural processes no longer push the oil to the surface. Artificial lift technology, which includes sucker-rod pumps, electrical submersible pumps, hydraulic jet pumps, plunger lifts, progressing cavity pumps, and gas lift systems, is now used to produce some 65 percent of all oil. Performance of artificial lift systems has been optimized through recent innovations in artificial lift equipment, improved operational design and parameters, and real-time data collection, automation, and control technologies. System optimization not only maximizes production efficiency, but can also decrease on-site power use and extend equipment life. Results include improved profitability, reduced workover wastes, and lower air emissions.

BLUEPRINT ON TECHNOLOGY

Reduced emissions during production and increased productivity result from increasing the efficiency of the systems that raise oil to the surface

Practical measures with attractive environmental and productivity paybacks

SUCKER-ROD PUMPS, the most prevalent form of artificial lift, use arm-like devices to provide up-and-down motion to a downhole pump. Such rod pumping, most effective in relatively shallow and low-volume wells, can be optimized to increase lifting efficiency and minimize energy consumption. Surface and downhole energy losses can be reduced by adjusting key design parameters like pumping mode selection, counterbalancing (to balance loads on the gear box during the pumping cycle), and rod string design.

A number of other advanced artificial lift technologies and practices have improved efficiency in recent years. Real-time data collection, automation, and control techniques now allow operators to monitor pumping performance and downhole conditions continuously, and to control operations accordingly. Variable-speed motors tailor pumping operations to changing conditions. New low-profile rod pumps are attractive options in sensitive urban, residential, and agricultural areas, as well as on crowded offshore platforms.

Gas lift, another common form of artificial lift, pumps natural gas down the well's annulus and injects the gas into the production tubing near the bottom of the well. The gas expands within the production tubing stream, allowing liquid hydrocarbons to be carried to the surface. Gas lift is commonly used when natural gas is readily available, and is especially prevalent offshore. Each gas lift well has an optimum injection rate and pressure. Since the injected gas raises the back pressure in the flow line leading to the field's separation and processing facilities, back pressure in one well affects all wells sharing common flow lines. Using advanced modeling techniques to develop models of multiflow characteristics and to optimize parameters, operators today can design complex gas lift systems that maximize production from all wells in a network, given the system's constraints.

ECONOMIC BENEFITS

- Enhanced efficient production from existing wells
- Lower equipment maintenance costs
- Lower on-site power consumption and costs

ENVIRONMENTAL BENEFITS

- Increased equipment life and fewer failures result in less workover and recompletion operations, reducing the volume of workover fluids and other wastes
- Reduced air emissions due to lower power consumption

CASE STUDIES

Success in the Field

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Optimization of sucker-rod pumping can increase production efficiency and minimize energy consumption.

Optimizing artificial lift in Oman

For Petroleum Development Oman (PDO), real-time automation and optimization software was the key to increasing production by some five percent, while saving $7 million annually. Power consumption was reduced and the mean time between pump failures was increased by 35 percent.

PDO used the Shell Oil Foundation System (SOFS) to monitor, control, and optimize over 1,200 wells and production facilities, including both beam-pump and gas lift operations. It collected load, position, and operational data from 900 individual beam pumps and then modeled downhole conditions. The system enabled pumps to be remotely started, stopped, and adjusted, providing an on-line tool to evaluate and optimize pump designs and predict pump performance.

PDO also applied the SOFS to gas lift wells in the Yibal field, creating gas lift performance models for each of 320 wells, matching them to actual field measurements, and using the resulting performance curves to calculate optimal production rates for given lift-gas availability. In a pilot demonstration, 52 wells in the Yibal field were also fitted with electronic instruments to measure lift-gas injection pressure and flow, and tubing-head and casinghead pressures. Ten months of data were used to adjust lift rates, valve settings, and completion strings as necessary. As a result, PDO optimized wells in real-time, achieving a five percent increase in oil production and a 10 percent reduction in the volume of lift gas used. So successful was the pilot effort that PDO decided to extend the program to the entire field.

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TECHNOLOGY Locations: Worldwide onshore

Coalbed Methane Recovery

SUMMARY

Only 30 years ago, coalbed methane was viewed primarily as a hazard by the mining industry. To ensure mine safety, ventilation and degasification systems emitted this gas to the atmosphere. Methane is now considered a potent greenhouse gas thought to contribute to global warming. It is also a valuable and significant resource with potential recoverable domestic quantities estimated at 40 to 60 trillion cubic feet. Since the 1970s, Federal tax credits, intensive government and industry R&D efforts, and rapid technology growth have motivated improvements in coalbed reservoir characterization, reservoir engineering, and completion technology. These advances have spurred coalbed methane production and reserve growth, making this unconventional resource a significant component of our domestic natural gas supply.

BLUEPRINT ON TECHNOLOGY

Technology has reduced greenhouse gas emissions by transforming coalbed methane into an energy resource

Producing coalbed methane

LARGE AMOUNTS OF methane are stored within coal's internal structure. Most coalbeds are aquifers, in which water pressure holds the gas in an adsorbed state. To produce the methane, water must be pumped from the coal seams to decrease reservoir pressure and release the gas. After desorption from the coal matrix, the gas diffuses through the coal bed's cleats and fractures toward the wellbore.

Some coal seams are too deep to be profitably mined, but methane production may be feasible. In these cases, operators drill into the coal seam, insert production piping, and then perforate opposite the target zone. Typically, the reservoir is then hydraulically fractured to enhance natural fractures or create new ones. Such "stand-alone" coalbed methane sites often require substantial initial dewatering to reduce reservoir pressure, although produced water tapers off as methane production increases. Produced water disposal presents major economic and environmental challenges for operators—these costs alone can determine the feasibility of coalbed methane projects. In areas such as Alabama's Black Warrior Basin, produced water can be used for irrigation or treated and discharged into surface waters. In regions where these waters are more saline, they are reinjected into subsurface geological formations, or in some cases recycled in fracturing applications. In the future, emerging technologies using evaporation, reverse osmosis, ion exchange, and wetlands construction promise more cost-effective water management.

Capturing coal mine emissions

Reduction in reservoir pressure during underground mining operations releases coalbed methane into the mine. To ensure mine safety, this methane is typically vented into the atmosphere in significant volumes—an EPA profile of 79 underground mines in 1996 indicated that they emitted an estimated 46 billion cubic feet of methane. But technological advances, along with utility industry restructuring, utility offset projects, and "green" pricing, are motivating operators to add methane recovery units to their ventilation and drainage systems. Also, the U.S. Environmental Protection Agency's voluntary Coalbed Methane Outreach Program is assisting coal mine operators to identify and exploit ways to recover and use or sell methane. As a result, coal mine methane

ECONOMIC BENEFITS

- Lower operating costs and increased profitability if recovered gas can be used to fuel on- or off-site facilities or to generate electricity for site use or sale
- Depending on quality, recovered gas can be marketed through pipeline sales

ENVIRONMENTAL BENEFITS

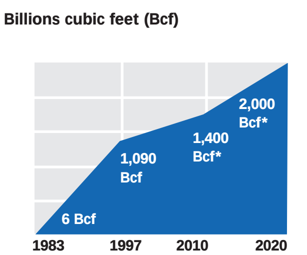
- Significantly reduced methane emissions
- Optimized recovery of valuable natural gas resource

recovery has risen more than 50 percent since 1990.

As technology improves, coal mine methane recovery is likely to increase. Several prototype technologies for using low and variable quality coal mine methane are under demonstration. In the UK, an operator is recovering methane from poorly sealed vent holes in abandoned mines. In the United States, DOE-sponsored field trials in recent years have focused on recovering gob gas.

METRICS

Coalbed methane production growth in the United States

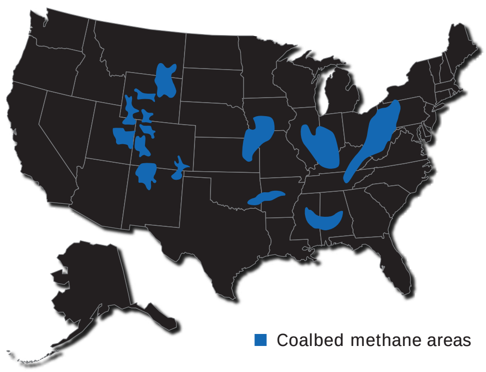


* Estimates assume high technology progress.

Source: Energy Information Administration; Kuuskraa; Gas Research Institute

CASE STUDIES

Success in the Field



Enhanced recovery in the San Juan Basin

Several advanced technologies are in use in the San Juan Basin of northwest New Mexico and southwest Colorado. In the overpressured, highly permeable San Juan Basin fairway, open hole cavitation completions are outperforming conventionally cased and fractured completions by factors of three to seven. In this technique, repeated high-rate, high-pressure injections of air-water mixtures into the coal seam are followed by rapid blowdown. This promotes sloughing of coal into the wellbore, which increases its radius and induces tensile and shear fractures.

San Juan operators are also field testing two new enhanced coalbed methane (ECBM) recovery technologies—displacement desorption with injected carbon dioxide (CO_2) and partial pressure reduction with injected nitrogen. Amoco successfully conducted the first nitrogen flooding field test in 1993 at its Simon 15U-2 well, increasing production fivefold in one year. At Amoco's Tiffany Project, 24 million cubic feet of nitrogen is injected daily into 13 injection wells—the largest commercial demonstration of this technology to date. Since full-scale injection began January 31, 1998, total gas production from 35 production wells has increased from 5 million cubic feet to 17 million cubic feet per day. Furthermore, Burlington Resources is testing CO_2 flood technology at a four-well project at its Allison Unit, with encouraging preliminary results.

In a recent study outlining promising technologies for reducing greenhouse gas emissions, U.S. National Laboratory directors concluded that coalbed sequestration technology is critical. For example, future technology could inject CO_2 from a powerplant stack into coal seams to enhance coalbed methane production, then cycle the methane back to fuel or co-fire the plant, thereby eliminating significant CO_2 emissions.

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TECHNOLOGY Locations: Rocky Mountains, Northern Great Plains, and Canada

Freeze-Thaw/Evaporation

SUMMARY

A new freeze-thaw/evaporation process purifies produced waters from oil and gas production operations by separating out dissolved solids, metals, and chemicals. These typically brackish waters can be made suitable for beneficial use, significantly lowering environmental risks and furthering resource management. Initial field tests indicate that, under specific climatic and operational parameters, the freeze-thaw/evaporation process is highly effective. In these cases, the volume of produced water can be reduced by 80 percent if it is frozen until its solids-laden brine separates, and the resulting purified water thawed and drained off for use or discharge. The isolated pollutants, which can include heavy metals and naturally occurring radioactive materials, are then disposed of separately. For volumes greater than 500 barrels per day, disposal costs and environmental risks can be cut dramatically.

BLUEPRINT ON TECHNOLOGY

New approach promises substantial reductions in produced water volume and associated environmental risks

From wastewater to beneficial by-product

PRODUCING WELLS generate an average of six or seven barrels of produced water per barrel of oil. This ratio generally increases as the field matures, and it may rise as high as 100:1 for marginally productive wells. Due to its sheer volume, the near 15 billion barrels of wastewater generated by exploration and production activities annually is a matter of potential environmental concern.

Produced water handling, treatment, and disposal are expensive. Class II wells for enhanced oil recovery or subsurface disposal wells cost from $100,000 to $1 million each. Water handling costs usually increase as a field matures, eroding profit margins. Most oil fields lose economic viability when the ratio is between 10:1 to 20:1, even if they still hold producible resources. Water-handling costs are often the main factor leading to well abandonment and may make development of unconventional resources, such as coalbed methane, economically unfeasible.

Although not considered hazardous waste under existing Federal legislation, produced waters are governed by Resource Conservation and Recovery Act nonhazardous waste provisions as well as by the Clean Water Act and the Safe Drinking Water Act. Through cost-effective freeze crystallization and evaporation processes, they can be separated into fresh water, concentrated brine, and solids.

Photo: Hart Publications, Inc., and Gas Research Institute

Start-up of freezing operations

ECONOMIC BENEFITS

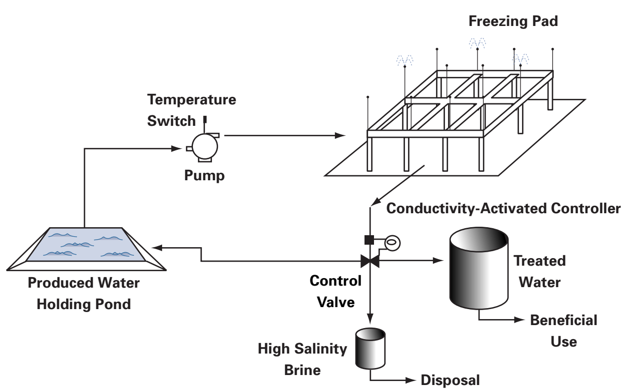
- A low-cost, energy-efficient method of purifying produced water volumes greater than 500 bbl/day
- Reduction of water treatment and disposal costs. DOE-supported field tests in the San Juan Basin estimate treatment costs of 25¢ to 60¢/barrel, compared to current disposal costs of about $1/barrel in New Mexico
- Extended life for mature fields in certain regions
- Improved economic feasibility of developing marginal or unconventional resources

ENVIRONMENTAL BENEFITS

- Produced water volume requiring disposal reduced by 80% in preliminary field tests
- Creation of fresh water to enhance agricultural development in the arid western United States

How the Technology Works

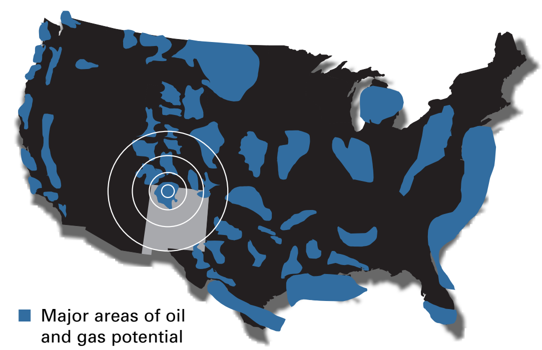
- **Produced water is placed in a holding pond.**
- **When ambient temperature drops below 32°F, water is sprayed on a freezing pad.**
- **Due to its higher density, brine with elevated concentrations of total dissolved solids separates from the ice.**
- **When ambient temperature rises above 32°F, ice on the pad melts and purified water drains.**
- **Brine is disposed of; purified water is discharged or stored for later beneficial use.**
- **In summer, natural evaporation from the holding pond is substituted for freezing cycles.**



Source: Hart Publications, Inc., and Gas Research Institute

Case Studies

Success in the Field



Successful DOE-sponsored tests in New Mexico

In 1996, a joint DOE-, Amoco-, and Gas Research Institute-sponsored project reported that the freeze-thaw/evaporation process could economically cut produced water disposal volumes by more than 80 percent and produce purified water suitable for beneficial use or surface discharge. Total dissolved solids concentrations at Amoco's Cahn/Schneider evaporation facility in the San Juan Basin, for example, were between 200 and 1,500 mg/l for the waters resulting from the process, compared with 11,600 mg/l in untreated waters. In addition to this near 92 percent reduction, organic and metal constituents were also significantly reduced in the processed water. In the winter of 1996–97, a more extensive evaluation conducted in more typical weather conditions resulted in almost identical outcomes. These field tests demonstrate the technology's commercial viability for high retention operations in areas with subfreezing winters and warm, dry summers, such as the Rocky Mountains and Northern Great Plains and much of Canada.

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TECHNOLOGY Locations: Stranded natural gas resources worldwide

Gas-to-Liquids Conversion

SUMMARY

Evolving gas-to-liquids (GTL) technology offers the promise of accessing our vast but remote and uneconomic natural gas resources in Alaska's North Slope and the deepwater Gulf of Mexico, significantly increasing our Nation's energy and economic security. GTL technology, on the brink of widespread commercial viability, chemically alters natural gas into stable synthetic liquid hydrocarbons that are far more environmentally friendly and efficient than conventional petroleum-based liquid fuels. Globally, the technology could bring some of the estimated 2,500 trillion cubic feet of known but currently untapped gas to market, accessing an abundant fuel source to produce liquid transportation fuels fully compatible with our existing transportation infrastructure.

BLUEPRINT ON TECHNOLOGY

Gas-to-liquids conversion taps remote sources of gas to produce cleaner transportation fuels and promote energy security

Developing and transporting remote gas resources

ROUGHLY HALF THE world's natural gas is unused because remote locations makes it too expensive to transport to market via conventional gas pipelines or as cryogenically generated liquefied natural gas, due to distance, climate, environmental concerns, political uncertainty, and the large capital investments required. On Alaska's North Slope alone, for example, approximately 25 trillion cubic feet of producible gas-in-place could be accessed with a cost-effective approach such as GTL technology, with the converted liquid transported through existing pipelines and tankers.

The promise of gas-to-liquids

In 1923, German scientists Franz Fischer and Hans Tropsch introduced the first GTL conversion process. The technology can produce a variety of chemicals and fuels—of particular interest is its ability to yield large volumes of sulfur-free diesel fuel. The process involves reforming natural gas into synthesis gas ("syngas") by combining the gas with steam, air, or oxygen, then converting the synthesis gas to liquid hydrocarbons through catalytic reaction, typically with an iron- or cobalt-based catalyst. The liquid products are hydrocracked and stabilized to create transportation fuels and chemicals. Until recently, this process has not been competitive in the petroleum marketplace, although it had been used for political reasons in noncompetitive economies such as Nazi-era Germany and apartheid-era South Africa. Dramatic recent advances in GTL technology focus on improved processes and catalysts, which are reducing costs enough to be more competitive with petroleum-based fuels, depending on gas costs and oil prices.

GTL's potential to fundamentally alter oil and gas markets worldwide has generated significant private sector research and development efforts, and sparked numerous small-scale and pilot studies. The Department of Energy is committed to a

ECONOMIC BENEFITS

- Access to remote uneconomic natural gas resources
- Prolonged access to Alaskan crude oil as a result of sufficient Trans-Alaska Pipeline System (TAPS) utilization
- Creation of a gas-to-liquids industry resulting in thousands of new domestic jobs and potentially billions of dollars in new investments

ENVIRONMENTAL BENEFITS

- Reduced emissions of greenhouse gases and other air pollutants compared with conventional petroleum-based fuels
- Optimized recovery of valuable gas resources
- Reduced flaring of associated gas in remote fields

goal of 200,000 barrels per day of GTL production by 2010 (assuming Alaskan North Slope gas is no longer required for reservoir repressurization), and it plays an active role in technology advances through support of a variety of research and assessment projects. It recently concluded an eight-year, $86 million cost-sharing agreement with a consortium of research and private sector parties. The consortium, led by Air Products and Chemicals, Inc., is working on a revolutionary ceramic membrane technology that promises to cut GTL production costs substantially.

Far-reaching impacts of commercial GTL application

GTL technology mounted on barges or offshore platforms could bring to market liquid transportation fuels from deepwater Gulf of Mexico sites without gas pipeline access. In Alaska, converted gas from the North Slope could be transported through the existing Trans-Alaska Pipeline System (TAPS), from Prudhoe Bay to Valdez, where tankers would deliver these liquids to market. This would have major ramifications for Alaska's oil and gas industry and the state's overall economy. Due to the approximate annual 10 percent decline in Prudhoe Bay oil production rates, pipeline flow may fall below the minimum volume required for cost-effective operations within the next two decades, eventually requiring that the pipeline be shut in. GTL technology could extend TAPS' life by more than 25 years and prevent shut-in of as many as 200,000 barrels per day of the last remaining North Slope crude, protecting valuable jobs and revenue.

Zero sulfur, zero aromatics, high cetane diesel fuel made by Rentech, Inc., a small fuel development company based in Denver, Colorado.

Photo: Rentech, Inc.

ENERGY EXPERTS

The GTL revolution

"GTL will revolutionize the gas industry the way the first LNG plant did...[w]e expect to see a 1-2 million barrels per day GTL industry evolving over the next 15-20 years to the tune of 25-50 billion dollars of investment."

- Arthur D. Little, Inc.

"We're looking to open the door to a vast resource of natural gas that is today beyond our economic reach. This research...could pioneer a way to tap that resource and convert it into valuable liquid fuels that America will need in the 21st century."

- Former Secretary of Energy Federico Peña

"The cost-effective conversion of natural gas to clean liquid transportation fuels...offers a significant potential for greenhouse gas emissions reduction while allowing greater use of domestic natural gas supplies."

- National Laboratory Directors, Department of Energy

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TECHNOLOGY

Locations: Worldwide, onshore and offshore

Glycol Dehydration

SUMMARY

The U.S. natural gas production sector operates some 37,000 glycol dehydration systems, which are designed to remove water from unprocessed gas production streams to produce pipeline quality gas. But during dehydration, these systems typically vent methane and other volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) into the atmosphere. Methane, a potent greenhouse gas, is thought to contribute to global warming, and reducing these emissions is of critical environmental importance. Better dehydration systems management, including optimization of glycol circulation rates and installation of flash tank separator-condensers, enables producers to capture up to 90 percent of methane and other emissions. These processes reduce greenhouse gas emissions, improve air quality, and recover substantial gas for on-site use or pipeline sale.

BLUEPRINT ON TECHNOLOGY

Effective management of dehydration systems reduces greenhouse gas emissions, improves air quality, and recovers substantial saleable natural gas

Improved practices and technologies

AFTER REMOVING water from a stream of wet natural gas, a typical dehydration system circulates triethylene glycol (TEG) through a reboiler unit to boil off the water and gaseous compounds so that the "wet" TEG can be recycled. At the reboiler, however, methane, and in some cases other VOCs, and HAPs such as benzene, toluene, ethyl benzene, and xylene (BTEX), are vented to the atmosphere. The amount of methane and other compounds vented is directly proportional to the rate at which the glycol circulates through the dehydration system. If the circulation rate is higher than needed to achieve pipeline quality gas, more methane and other compounds are emitted, with no real improvement in the quality of the gas stream.

Consequently, producers are reducing air emissions and recovering valuable methane by combining two advanced practices: first, by installing flash tank separators and condenser units at the reboiler to capture methane, VOCs, and HAPs before they are vented to the atmosphere; and second, by adjusting glycol circulation rates to optimal levels. Using a simple mathematical model, engineers can determine an optimal circulation rate, based on the characteristics of the particular gas stream, the pipeline's water content requirements, and the operator's production needs. These two processes, used in combination, yield significant environmental benefits for the producer in addition to attractive economic benefits, since the recovered methane can be used as on-site fuel or compressed and reinjected into the sales pipeline.

ECONOMIC BENEFITS

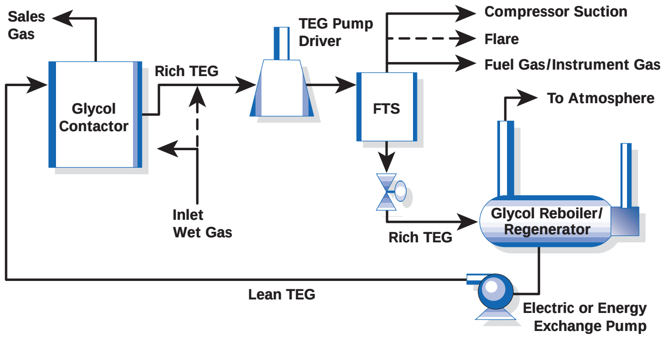
- Reduced energy consumption for circulation pumps and reboiler
- Lower operating costs if captured methane is used to fuel on-site equipment
- Increased saleable gas
- Potential for increased recovery of natural gas liquids

ENVIRONMENTAL BENEFITS

- Reduced greenhouse gas emissions
- Improved local air quality due to reduction in BTEX and VOC emissions
- Enhanced regulatory compliance for upcoming Federal E&P Maximum Achievable Control Technology (MACT) requirements

HOW THE TECHNOLOGY WORKS

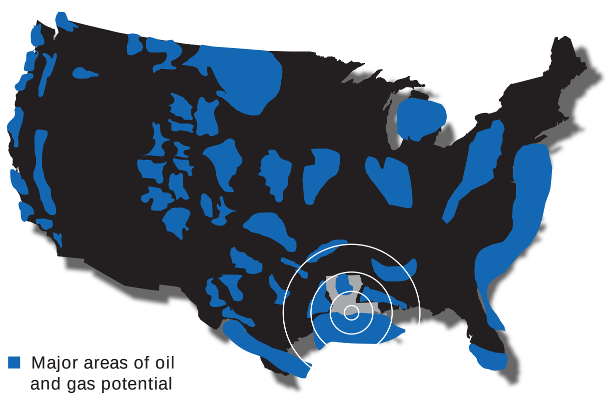
Flash Tanks produce a drop in pressure that causes the methane to vaporize ("flash") from the glycol stream.



In a dehydration process with a flash tank separator, "lean" TEG is sent to the contactor, where it strips water, methane, BTEX, and other compounds from the gas stream before entering the separator. Here pressure is stepped down to fuel gas system or compressor suction levels, allowing most of the methane and lighter VOCs to vaporize (flash). The flashed methane can be captured and used as fuel gas or compressed and reinjected into the sales line. The TEG flows to the reboiler, where water and remaining gases are boiled off, and it is recycled back to the contactor. To prevent discharge of HAPs and VOCs not recovered through the flash process, dehydration systems can also be fitted with air- or water-cooled condensers, which capture additional compounds as they move through the reboiler stack.

CASE STUDIES

Success in the Field



Lower emissions plus lower costs in Louisiana

In the early 1990s, Texaco retrofitted 26 of 27 field-based glycol dehydration systems with flash tank separator-condenser units to reduce emissions of VOCs and BTEX in response to the State of Louisiana's emission control program. In addition to greatly reducing these emissions, it soon became clear that the units also recovered substantial amounts of methane. To determine exactly how much, Texaco staff conducted empirical measurements and used a computer-based dehydrator emissions model developed by the Gas Research Institute. Additional tests analyzed the extent to which flash methane and condenser BTEX recoveries were affected by variances in separator temperature and pressure, and circulation rates.

Results showed methane capture of some 104 thousand cubic feet per day, nearly 38 million cubic feet per year. In total, methane emissions from these units were reduced by 95 percent, from 500 tons to less than 25 tons per year. Under a wide range of tested separator pressures and temperatures, flash methane recoveries ranged from 90 to 99 percent, and condenser BTEX recoveries ranged from 69 to 98 percent. Texaco also found that reducing higher than necessary circulation rates resulted in concomitant emission reductions, even without separator-condenser installation. As an added benefit, Texaco routed the captured gas into a low-pressure gathering system for recompression and subsequent use in its field operations, thus lowering total operating costs.

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TECHNOLOGY Locations: United States

Advanced Data Management

SUMMARY

The exploration and production (E&P) industry is among the most data intensive in the world; various data—from geological to technical to regulatory—must be managed by both industry and government. Advanced data management systems are key to increasing the efficiency of oil and gas recovery and making effective regulatory and policy decisions. With participation by industry, State regulators, and DOE, numerous efforts are under way, such as standardized data collection of State oil and gas statistics, risk-based decision making, detailed online digital atlases of oil and gas plays, and validation methodology for Area of Review (AOR) variances. Initiatives such as these reflect advanced computer technology capabilities, handling massive amounts of data more quickly and cheaply than ever.

BLUEPRINT ON TECHNOLOGY

Data management tools improve information access, increasing resource recovery efficiencies and informing regulatory and policy decisions

E&P data management

E&P DATA GENERALLY fall into five major categories: environmental, geologic, exploration and production, regulatory, and technology. Advanced data management techniques enable: (1) better regulatory, enforcement and compliance decisions; (2) more informed government program and policy decisions; and (3) more efficient oil and gas recovery. "Data management" has different meanings for different technologists. For example, geophysicists may want to interpret 3-D seismic data to locate oil and gas resources, and petroleum engineers may want to interpret production data to enhance recovery; whereas State regulators might use online permitting and compliance data to improve decision-making processes; versus environmentalists, who need habitat surveys and emission reports to inform policy debates. Both government and industry seek to improve their data management systems to support these goals.

Comprehensive State data facilitate decisions

States and DOE are collaborating to enhance State-level oil and gas data collection and management efforts. For example, with DOE support, the Interstate Oil and Gas Compact Commission (IOGCC) is cataloging State data collection efforts and management capabilities and devising uniform standards for State permitting, production, and well statistics. IOGCC and DOE are also bringing key E&P data online to facilitate decision making by industry and States. These efforts include DOE's *Environmental Compliance Assistance System*, which provides information regarding Federal E&P environmental regulations, and IOGCC's framework for helping States develop permitting and regulatory compliance assistance programs.

Enabling cost-effective regulation

Developed by the Ground Water Protection Council with funding from DOE, the Risk-Based Data Management System (RBDMS) was originally designed to manage data for underground injection control programs, enabling

ECONOMIC BENEFITS

- Better data access facilitates more effective business and investment decisions
- Risk-based regulatory decisions lower environmental costs and increase operational efficiency
- More efficient recovery of oil and gas resources, through improved prospect identification and targeting

ENVIRONMENTAL BENEFITS

- Better regulatory and policy decision-making processes, leading to enhanced environmental protection
- Risk-based regulatory structures focus industry and government activities on areas of greatest potential risk

more effective regulatory and operational decision making. The system has been so well received that it is being modified by individual States to include production, geological, and waste management data, as well as enforcement and permitting data. Initial RBDMS success has prompted more than 20 States to form a users' group to help each other implement the system.

Improving AOR verification

Under the Safe Drinking Water Act, operators are required to conduct quarter-mile AOR analyses of disposal and injection wells, but AOR variances may be granted in specific cases. With DOE and American Petroleum Institute support, the University of Missouri-Rolla has developed a scientific methodology for validating AOR variance requests that is expected to provide industry cost savings exceeding $300 million. DOE has also supported development of data management tools and Geographic Information Systems (GIS) to help regulators conduct AOR and variance analyses statewide.

Enhancing oil and gas recovery

Partnering with States and the Gas Research Institute, DOE is supporting both print and digital atlases of producing regions in the United States. For example, a DOE-supported consortium is using GIS technology to develop a digital atlas of oil and gas plays and fields specific to Kansas, Nebraska, the Dakotas, and parts of Montana and Colorado. In these mature regions, advanced technology and data management are seen as the best approaches to extend production and prevent premature well abandonment. To help operators recover more original oil-in-place, the atlas, which currently covers only Kansas, will provide extensive production, petrophysical, and geological data, sophisticated digital maps and imagery, as well as field-specific information on recovery technologies and engineering methods for identifying new or unswept zones.

Electronic permitting in Texas

Through a new DOE-sponsored pilot program, the Texas Railroad Commission is developing a paperless, digital on-line permitting system, which will save the State's operators and regulators millions of dollars and countless labor hours. This fully digital approach will soon enable operators to submit an electronic permit application via an Internet-linked computer, complete with supporting graphical or text attachments. The operator's identity will then be authenticated, and permit fees paid through a secure on-line transaction. Within hours—perhaps the same day, rather than the days or weeks now required—the producer will be notified electronically whether the application has been approved. Although the expected savings per permit application may be relatively small, overall cost savings are expected to be significant; annual savings from drilling permits alone are estimated at between $3 million and $6 million.

Advanced computing leads the way

The Oil and Gas Infrastructure Project—part of DOE's Advanced Computational Technology Initiative—has explored implementing inexpensive mechanisms for online access to well-level oil and gas data from Texas, California, and other States. Such mechanisms enhance producers' access to production and geological data, ultimately enabling more efficient resource recovery.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Improved Recovery Processes

SUMMARY

The goal of evolving oil recovery technologies is increased reserves with less drilling. Despite significant technology advances in primary and secondary production, much of a reservoir's original oil-in-place remains untapped after these phases of the production cycle. Coupled with advanced field management practices, new enhanced oil recovery (EOR) technologies—such as thermal, gas, and chemical techniques—can significantly increase production in some maturing fields. The United States leads the world in sophisticated EOR technology, which currently accounts for about 12 percent of domestic daily crude oil production, a 140 percent increase from daily EOR rates only 15 years ago. In addition to preventing premature abandonment of significant domestic oil resources, these technologies could potentially recover half of the Nation's 350 billion barrels of "discovered, but unrecoverable" original oil-in-place.

BLUEPRINT ON TECHNOLOGY

Thirty years of continuous improvement in enhanced recovery technology has led to significant reserve additions and less drilling

Getting more oil from existing fields

PRODUCTION AT MOST oil reservoirs includes three distinct phases: primary, secondary, and enhanced recovery. During primary recovery, which uses natural pressure or artificial lift techniques to drive oil into the wellbore, only about 10 percent of the oil-in-place is generally produced. Shortly after World War II, producers began to conduct secondary recovery techniques to extend the productive life of oil fields, increasing ultimate recovery to more than 20 percent. Gas injection, for example, can maintain reservoir pressure and keep fluids moving; waterfloods are used to displace oil and drive it to the wellbore. In recent decades, the development and continued innovation of EOR techniques has increased ultimate recovery to 30 to 60 percent of a reservoir's original oil-in-place. In the United States, three major categories of EOR technology—thermal, gas, and chemical—dominate EOR production.

Even though improved EOR technology can significantly extend reservoir life and has been successfully used since the 1960s, historically high costs have limited widespread application. In the last decade, however, dramatic improvements in analytic and assessment tools have led to a greater understanding of reservoir geology and the physical and chemical processes governing flows in porous media. Today, unconventional approaches such as fieldwide development using strategically placed horizontal wells, or microbial injection to improve recovery may lead to new classes of EOR technology. Innovations in thermal recovery include radio frequency heating, and enhanced gravity drainage with steam in vertically parallel horizontal wells.

Thermal recovery

Thermal recovery techniques account for some 59 percent of daily U.S. EOR production. Used in individual wells or fieldwide, *steam injection and flooding* provide effective recovery of heavy, viscous crudes, which must be "thinned" to enable oil to flow freely to the wellbore. The most common domestic EOR

ECONOMIC BENEFITS

- Worldwide production of approximately 2.3 million barrels per day (760,000 barrels per day in the United States) that would otherwise remain untapped
- Potential recovery of up to half of the 350 billion barrels of discovered, currently unrecoverable, domestic oil
- Increased production from marginal resources

ENVIRONMENTAL BENEFITS

- Fewer new wells drilled due to increased reserves from existing fields
- Less environmental impact due to reduced abandonment of marginal wells and offshore platforms

practice, this process has contributed directly to improved burning efficiencies of both gas and oil, and spawned the cogeneration industry, which uses clean-burning natural gas to create both steam and electricity at attractive prices for oil field operators and utilities. In California alone, for example, existing cogeneration plants generate enough electricity to supply 4.1 million homes.

A second type of thermal recovery, *in-situ combustion*, injects air or oxygen into the formation and uses a controlled underground fire to burn a portion of the in-place crude. Heat and gases move oil toward production wells. This process is highly complex, involving multi-phase flow of flue gases, volatile hydrocarbons, steam, hot water, and oil, and its performance in general has been insufficient to make it economically attractive to producers.

Gas-immiscible and -miscible recovery

Accounting for 40 percent of daily EOR production, gas injection is the second most prevalent technology currently in domestic use. Two basic forms exist: immiscible, in which gas does not mix with oil; and miscible, in which injection pressures cause gas to dissolve in oil. *Immiscible injection*, which can use natural gas, flue gas, or nitrogen, creates an expanding force in the reservoir, pushing additional oil to the wellbore. *Miscible gas injection* dissolves propane, methane or other gases in the oil to lower its viscosity and increase its flow rate. In place of the costly hydrocarbon gases used in some EOR projects, miscible gas drives also frequently use carbon dioxide (CO_2) and nitrogen. CO_2 flooding has proven to be one of the most efficient EOR methods, as it takes advantage of a plentiful, naturally occurring gas and can be implemented at lower pressures.

Chemical recovery

Chemical recovery techniques account for less than one percent of daily U.S. EOR production. In an enhanced waterflooding method known as *polymer flooding*, high molecular weight, water-soluble polymers are added to the injection water to increase its viscosity relative to that of the oil it is displacing, raising yields since oil is no longer bypassed. In another chemical recovery technique, *surfactant flooding* (also known as micellar-polymer flooding), a small slug of surfactant solution is injected into the reservoir, followed by polymer-thickened water and then brine. Despite its very high displacement efficiency, this technology is hampered by the high cost of chemicals and their environmental impact.

CASE STUDIES

Success in the Field

Steamflooding increases reserves fivefold at Kern River field

Discovered in 1899 by hand digging a 40-foot well, the giant Kern River field near Bakersfield, California, had nearly 600 wells by 1904. At its peak, primary production was 47,000 barrels/day, but had declined to 9,000 by 1954. Installing bottomhole thermal heaters in the 1950s succeeded in making oil less viscous so that it flowed more easily. Surface steam injection followed in the 1960s, and ultimately fieldwide steamflooding brought production to a peak 140,000 barrels/day in 1986. Production from the field was still over 134,000 barrels/day in 1997. Overall, thermal EOR has increased recovery from 10 percent of oil-in-place to over 40 percent, with ultimate recovery of 50 percent from this 3.5 billion-barrel field. Production is nearly five times greater than possible with primary recovery technology alone. Field life has been doubled, and on its 100th birthday in 1999, Kern River field will still have 7,000 producing wells.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Leak Detection and Measurement Systems

SUMMARY

Leak detection and measurement systems play an essential part in controlling emissions of methane—a potent greenhouse gas and valuable energy product—from the Nation's massive oil and gas infrastructure. Significant amounts of methane are emitted to the atmosphere during production, transmission, processing, storage, and distribution. New technology facilitates accurate, efficient leak detection and measurement by ensuring equipment and pipeline integrity and timely maintenance and repair. These controls capture saleable natural gas, create safer work places, and protect our environment.

BLUEPRINT ON TECHNOLOGY

New devices to detect and measure gas leaks aim to eliminate greenhouse gas emissions

Overcoming the limitations of conventional systems

MANAGING LEAKS IN the U.S. oil and gas infrastructure is a formidable task. This complex infrastructure involves nearly 885,000 producing oil and gas wells and related equipment, 265,000 miles of natural gas transmission pipeline, and about 1.5 million miles of distribution pipeline. New technologies overcome drawbacks in standard industry approaches, such as "leak concentration measurement" techniques. These use handheld instruments, such as organic vapor analyzers (OVAs) equipped with flame ionization detectors, to sample methane concentrations around leaking components. The leak flow rate can be estimated by the predicted relationship between concentration and leak rate. Such devices are easy to use, but accuracy rates are low. Distortions up to three orders of magnitude can occur due to wind conditions, leak velocity, the shape of the component, and the surface distribution of the leak.

Another conventional practice, "bagging," measures leaks by enclosing a component in a nonpermeable bag, adding air (or nitrogen), and then measuring an exhaust stream with an OVA. While highly accurate, bagging is costly, labor-intensive, time-consuming, and impractical when large numbers of components must be tested and measured.

High-flow samplers

Advanced technologies equip the industry to detect leaks with better accuracy and efficiency. The High-Flow Sampler, developed by the Gas Research Institute (GRI) and Indaco Air Quality Services, Inc., samples the air surrounding leaking components using a pneumatic air mover, thus eliminating the need for bagging. Although more expensive than conventional tools, this technology offers the accuracy of bagging and the ease and speed of leak concentration measurements. It can also measure much larger leaks than standard instruments, which typically malfunction above leak detection ranges of 10,000 parts per million.

Backscatter absorption gas imaging

Another new technology, backscatter absorption gas imaging (BAGI), is a state-of-the-art, remote video-imaging tool developed by Sandia National Laboratories, with

ECONOMIC BENEFITS

- More accurate information on leak characteristics and emissions, leading to successful, cost-effective leak reduction strategies
- Increased recovery and usage of valuable natural gas

ENVIRONMENTAL BENEFITS

- Reduced emissions of methane, a potent greenhouse gas
- Enhanced worker safety due to more effective and efficient leak detection

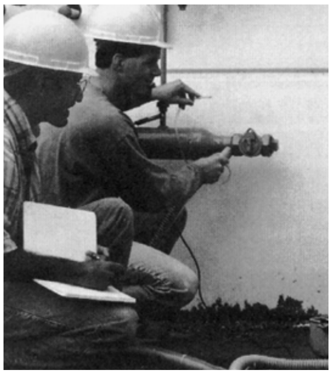

Photo: Hart Publications, Inc., and Gas Research Institute

Field trials of the new High-Flow Sampler promise more effective leak detection and measurement.

support from GRI and DOE. Whereas other surveys are performed with manually scanned point sensors, BAGI technology uses infrared laser-illuminating imaging. If a gas plume is present and resonating within the illumination wavelength, the plume attenuates a portion of the laser backscatter and appears as a dark cloud in the real-time video picture. The equipment can be tuned to the absorption resonances of a wide variety of gases. Remote video imaging, with the superior efficiency of covering an entire area at one time, could greatly simplify leak detection. The latest field trials indicate an impressive detection range, with flow rates as low as 0.1 standard cubic feet per hour at distances from up to 100 meters, and leaks as low as 0.02 standard cubic feet per hour at closer distances. Estimates are that BAGI will increase area leak search rates by a factor of 100 versus existing technology.

CASE STUDIES

Success in the Field

High-tech sampling and imaging matched by effective low-tech approach

In June 1995, a Unocal Spill Prevention Task Group used Labradors and Golden Retrievers to detect underground pipeline leaks in the 40-year-old Swanson River Field in Alaska's Kenai National Wildlife Refuge. The dogs, originally used in law enforcement, were retrained to recognize a nontoxic odorant (Tekscent) injected in the pipelines. In widely ranging temperatures, the dogs successfully detected two faulty valve box seals and leaks in pipelines down to 12 feet underground or under 3 feet of snow. The team inspected about 18 miles of pipelines in two weeks. Unocal's use of this and other innovative environmental technologies earned them an U.S. Department of the Interior "National Health of the Land" environmental excellence award in May 1997.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Low-Bleed Pneumatic Devices

SUMMARY

Throughout all sectors of the natural gas industry, pneumatic valves, regulators, and sensors use pressurized gases to control or monitor critical equipment. As part of normal operations, pneumatic devices release natural gas, primarily methane, to the atmosphere. Within the industry, pneumatic devices are the single largest source of methane emissions, venting nearly 50 billion cubic feet annually. Older designs leak, or "bleed," an average of 140 thousand cubic feet per year per device, a volume equivalent to an average household's annual use, whereas newer, low-bleed designs emit an annual average of only 8 to 12 thousand cubic feet. Replacing or retrofitting devices, or improving maintenance, can reduce gas emissions substantially, reducing greenhouse gas emissions and potentially saving the industry millions of dollars in lost methane.

BLUEPRINT ON TECHNOLOGY

Energy-efficient "low-bleed" pneumatic devices can dramatically reduce methane emissions and recover lost gas resources

Protecting the ozone layer and saving valuable gas

THE NATURAL GAS production sector uses pneumatic devices to control and monitor gas and liquid flows and levels in dehydrators and separators, temperature in dehydrator regenerators, and pressure in flash tanks. Approximately 250,000 pneumatic devices are used in the production sector alone, venting an estimated 35 billion cubic feet of methane annually, 70 percent of total methane emissions. Specific bleed rates are a function of the design, condition, and specific operating conditions of the device. By definition, a high-bleed device leaks more than six standard cubic feet per hour, although industry operators estimate that most devices typically bleed about three times that rate.

Aggressive replacement, retrofitting, inspection, and maintenance

New, technically advanced low-bleed devices and retrofit kits offer comparable performance characteristics to high-bleed models, yet reduce methane emissions considerably—on average, they vent 90 percent less methane. Although low-bleed devices typically cost more than their high-bleed equivalents, cost-benefit analyses show that replacement or retrofit project costs are typically recouped within months. While it may be impractical to replace all an operation's high-bleed devices at once, operators are finding successful alternatives, such as combining replacements and retrofits, or installing a low-bleed device when an existing device fails or is no longer efficient.

Others have implemented aggressive inspection and maintenance programs. By cleaning and repairing leaking gaskets, fittings, and seals, operators are able to reduce methane emissions substantially. Other effective practices include tuning the device to operate in the low or high end of its proportional band, minimizing regulated gas supply, and eliminating unnecessary valve position indicators.

ECONOMIC BENEFITS

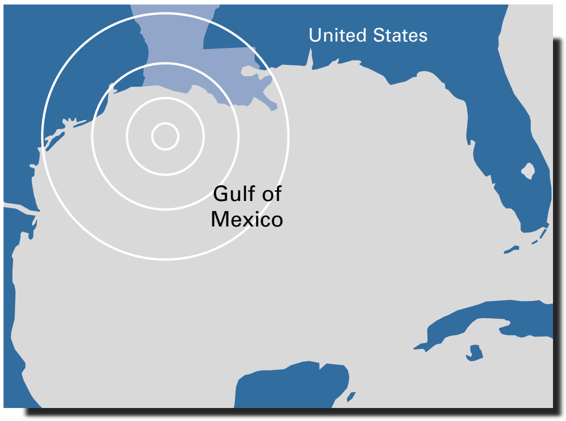
- Increased operational efficiency, as retrofit or replacement can provide better system-wide performance, reliability, and monitoring of key parameters
- Increased saleable product volume, as leaks are minimized

ENVIRONMENTAL BENEFITS

- Reduced greenhouse gas emissions
- Conservation of valuable gas resources

CASE STUDIES

Success in the Field



Chevron retrofits reduce emissions by 90 percent

Chevron installed a low-bleed retrofit valve kit on liquid level and pressure controllers on two platforms in the Vermilion field's blocks 245 and 246, roughly 60 nautical miles south of the Louisiana coast in the Gulf of Mexico. During this pilot test in January 1995, 19 devices were tested on one platform and 30 devices on another. The retrofits yielded average reductions in bleed rates of more than 90 percent. A cost-benefit analysis showed that the retrofitting costs would be recovered in less than two years, with specific payback periods based on the characteristics of the device retrofitted and an assumed natural gas wellhead price of $1.50 per thousand cubic feet.

Marathon survey drives inspection, repair, and replacement program

As an EPA Natural Gas STAR Program partner, Marathon Oil Company recently surveyed more than 155 pneumatic devices at 50 U.S. production facilities. Results indicated that Marathon devices were bleeding 5.1 million cubic feet of methane per year, on par with the annual gas consumption of 57 residential consumers. Consequently, Marathon has now implemented a comprehensive program to inspect, repair, and replace its high-bleed pneumatic devices, saving gas and reducing emissions. In fact, Marathon determined that purchasing expensive leak detection equipment was not even needed to conduct such surveys; only listening was required, because "control devices with higher emissions [could] be identified qualitatively by sound."

Gas Saved by Retrofitting Controllers at Chevron

Location	Unit	Service	Before Retrofit (scf/day)	After Retrofit (scf/day)	Savings (scf/day)
V245 "F"	Fisher 2900	Oil Dump	438	43	395
V245 "F"	Fisher 2900	Suction Scubber	211	0	211
V245 "F"	Fisher 2900	Gas Filter	397	1	396
V246 "D"	Fisher 2900	Oil Dump	328	81	245
V246 "D"	Fisher 2900	Water Dump	567	0	567
Average			**388**	**25**	**363**
V246 "D"	Fisher 2900	Water Skimmer	508	177	331
V245 "F"	Fisher 4150	Fuel Gas Reg.	145	0	145
V245 "F"	Fisher 4160	Sales Gas Reg.	108	0	108
V245 "F"	Fisher 4160	Makeup Gas Reg.	534	12	522
Average			**262**	**4**	**258**
V246 "D"	Fisher 2900	Oil Dump	950	4	946

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METRICS

Since 1991, EPA Natural Gas STAR Producer members, who account for approximately 35 percent of the Nation's natural gas production, have reduced methane emissions from pneumatic devices by nearly 11.5 billion cubic feet, worth an estimated $23 million.

Advanced technology, combined with improved maintenance practices, can reduce methane losses from pneumatic devices by approximately 90 percent.

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TECHNOLOGY

Locations: Deepwater areas of Australia, Brazil, Gulf of Mexico, North Sea, Southeast Asia, West Africa, and elsewhere

Offshore Platforms

SUMMARY

Finding economically viable methods to tap vast deepwater resources is driving innovations in offshore technology. Potential payoffs are immense. An estimated 90 percent of undiscovered global reserves are under 3,000 feet or more of water. Between 1996 and 1998, nearly 75 percent of the 66 oil discoveries greater than 100 million barrels were offshore. Effective new technology includes advanced tension leg platforms (TLPs) and mini-TLPs, which are lower-cost, small-footprint platforms suited to marginal fields. Other offshore platforms include spars, now designed to operate in depths of up to 8,000 feet, semisubmersible floating production systems (FPS), and new-generation floating production, storage, and offloading systems (FPSOs). Ongoing technology refinement continues to optimize recovery, reduce costs, and minimize environmental risks and impacts.

BLUEPRINT ON TECHNOLOGY

Advanced offshore platform technology reduces project duration, costs, and impacts on marine environments

Enhanced recovery with fewer risks

PLATFORM DESIGN is key to cost-effective deepwater field development. Variables include field remoteness, size, and characteristics, water depth and condition, and weather patterns. Today, eight floating TLPs, moored to the ocean floor with high-strength tendons that provide vertical and lateral stability, operate in large, multi-well fields worldwide. TLPs offer the advantages of fixed platforms—space for crew quarters, drilling rigs, and production facilities—with lower investment costs. Maturation of TLP technology has enabled more aggressive production schedules and less exposure to economic risks. Platform construction time has been cut in half. Today's TLP can withstand hurricane-force winds and waves, and its deepwater limits are being extended, perhaps to 6,000 feet. High-performance composites, stepped tendons, cables, and other options can increase tendon stiffness and reduce vertical motion in harsh ocean settings. The conceptual raft TLP, a submerged hull tensioned to the sea floor, would also minimize motion at reduced cost.

TLP innovations have spawned mini-TLPs with small footprints and permanent tension leg moorings that allow installation close to other platforms. The required investment in conventional TLPs can make their use for smaller discoveries unprofitable. Less costly mini-TLPs can be constructed and deployed swiftly in marginal deepwater fields.

Spar drilling and production platforms—large, cylindrical platforms supported by buoyancy chambers and fastened with catenary mooring systems—have been used for research, communication, storage, and offloading for more than 30 years. The first spar production platform, installed in 2,000 feet at the Gulf's Neptune Field in 1996, was designed for maximum production of 25,000 barrels of oil per day and features a 707-by-72-foot hull enclosing buoyant risers and surface wellheads. Advances have led to units designed to operate in more than 8,000 feet of water. Inherent design versatility and optional hulls

ECONOMIC BENEFITS

- Recovery of significant deepwater oil and gas reserves that may otherwise remain undeveloped; enhanced recovery of marginal resources
- Combined with advanced subsea completion technology, shorter construction and development schedules, leading to reduced costs
- FPSO and FPS deployment facilitates low-cost field abandonment

ENVIRONMENTAL BENEFITS

- Optimized recovery of valuable deepwater oil and gas resources
- Shorter construction and production schedules ultimately reducing operational footprints, and protecting marine habitats and ocean resources

("classic" and "truss") allow flexibility of use, from storage to any combination of drilling, production, and workover, decreasing financial risk. Spars, easily relocated and reused, are also attractive for marginal fields.

Marginal fields, mild climates, and shallow depths were the criteria for using the first FPSO and FPS 20 years ago, but today an estimated 80 units operate worldwide in varied climates and depths. Enhanced FPSOs have a compression system for gas lift, injection, and export, desalters, water injection and natural gas liquids recovery systems, as well as a conventional production system.

FPSOs are selected in remote locations lacking pipelines and fixed infrastructure, marginal fields, and depths too great for fixed platforms, whereas FPSs are used where infrastructure connections are available. Combined with subsea completion technologies, FPSO and FPS platforms are considered critical to industry's move toward 10,000-foot water depths, and many believe that this combination offers the most viable option over 5,000 feet. Compared with spars and TLPs, deepwater subsea completions offer shorter development schedules and more flexibility in location and well number.

CASE STUDIES

Success in the Field

Ram-Powell TLP

Production began in September 1997 at the $1 billion Ram-Powell Unit, a 41,000-ton, 3,570-foot high TLP in the Gulf of Mexico about 80 miles south of Mobile, Alabama. A development joint venture between Shell, Exxon, and Amoco, Ram-Powell employs a permanent crew of 110 and has peak gross production capacity of 60,000 barrels of oil and 200 million cubic feet of gas per day. Twelve 28-inch diameter tendons, each about 3,145 feet long, support the unit in more than 3,200 feet of water, a new depth record for a permanent production platform. Ram-Powell can drill down to 19,000 feet below the sea floor, and has complete oil and gas processing separation, dehydration, and treatment facilities. Estimated recovery from this project is approximately 250 million barrels of oil equivalent.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Downhole Oil/Water Separation

SUMMARY

New downhole separation technologies promise to cut produced water volumes by as much as 97 percent in applicable wells. Usually, both water and oil are pumped to the surface for separation, but novel mechanisms installed below the surface can now separate the formation's oil and water in the wellbore. Oil is then produced, but water is directly pumped into a subsurface injection zone. This minimizes environmental risks and reduces fluid lifting and disposal costs. Downhole separation can also increase oil production significantly, and this, combined with reduced operating costs, could potentially extend the life of marginal wells or reactivate shut-in wells. Field testing and demonstration projects are currently under way in numerous projects throughout the United States and the world.

BLUEPRINT ON TECHNOLOGY

Emerging technologies for downhole fluids separation can reduce the volume of produced water brought to the surface, while increasing oil recovery

Conventional surface separation

IN TODAY'S TYPICAL oil well, produced water and oil are pumped to the surface for separation, after which the oil is pumped off and the water treated, then reinjected into the ground. This approach brings contaminants up through the well piping, and incurs significant water lifting and handling costs. Emerging downhole separation technologies can minimize the environmental risks associated with produced water handling, treatment, and disposal, and greatly reduce the costs of lifting and disposing of the produced water.

Three promising mechanisms for downhole separation

Downhole oil/water separation involves the use of mechanical or natural separation mechanisms in the wellbore to separate the formation's oil and water. Although not applicable to heavier, low-API gravity crudes, three basic downhole separation techniques are currently under development.

Gravity separation in the reservoir enhances and maintains the gravitational oil/water separation that occurs naturally in reservoirs. The normally level oil/water contact is skewed by the production process, which causes the water/oil interface to rise in a phenomenon called "coning." When the tip of the water cone reaches the perforations in the well casing, the well begins to produce large amounts of water. This technique for downhole separation maintains a flat oil/water zone by using dual perforations in the well casing to produce water from below the zone (for downhole injection into another formation) simultaneously with oil from above the zone. This helps to maintain the natural oil/water gravity segregation and avoids coning.

ECONOMIC BENEFITS
Significant reductions in water lifting and disposal costs
Enhanced oil production
Increased access to marginal or otherwise uneconomic wells

ENVIRONMENTAL BENEFITS
Volume of produced water brought to surface reduced significantly, greatly minimizing risk from contaminants on the surface and to drinking water aquifers
Less drilling of new wells, due to greater recovery from existing wells
Reduced production footprints, as surface facilities may be smaller

Gravity separation in the well casing allows the produced fluids to separate naturally in the well casing, then uses a dual-action pump system (DAPS) to pump the oil up and inject the water downhole. The DAPS has two pump intakes that are positioned above and below the oil/water interface.

Hydrocyclone separation is a promising technique that uses centrifugal force to separate oil and water. Most such systems rely on electrical submersible pumps (ESPs) to push or pull water through the hydrocyclone. While this approach can handle larger volumes of fluids, the higher cost of the hydrocyclone and pump equipment has limited its use to date.

Although developed initially for onshore application, rapid advances in downhole separation technologies are heightening interest in offshore use. For example, a new generation of "intelligent," computer-driven subsea downhole separation systems, currently under development, will remotely monitor and control fluid flow and downhole injection. These systems promise to be particularly useful in multilateral environments, by controlling downhole water injection into a dedicated lateral strategically placed to enhance waterflooding and pressure maintenance.

CASE STUDIES

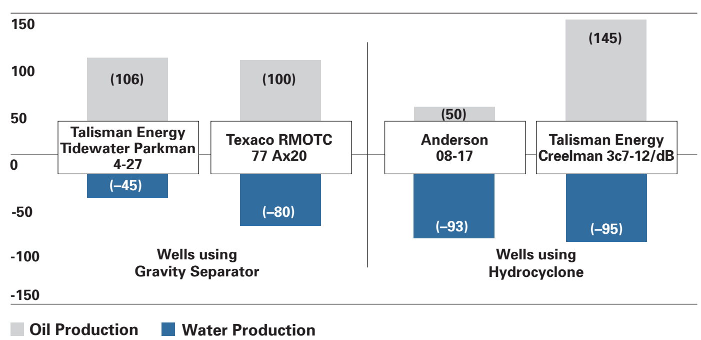
Success in the Field

Significant pilot results

A collaborative Mobil, BP Amoco, Texaco, and Chevron consortium (MoBPTeCh) was chartered to develop innovative solutions to common environmental problems in the oil and gas industry. MoBPTeCh has recently conducted extensive research on produced water downhole separation technologies, with 15 test wells in operation using gravity separation in the well casing. At this time, the project uses rod pumps only, but future tests with ESPs are expected to greatly increase the handling capacity of liquid volumes. Initial results indicate great potential for downhole separation technologies to reduce produced water volumes and increase production.

METRICS

Field trials in Canada and the United States show increased oil production and decreased water production



Source: Argonne National Laboratory, 1999

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TECHNOLOGY U.S. Offshore (Gulf of Mexico, California, and Alaska)

Safety and Environmental Management Programs

SUMMARY

Offshore operations represent over one quarter of the Nation's oil and natural gas production. Since the early 1990s, Federal regulators and industry have successfully cooperated in the development and implementation of recommended practices for voluntary safety and environmental management programs (SEMP) for Outer Continental Shelf (OCS) operations. Using the SEMP approach, industry is responsible for voluntarily identifying potential hazards in the design, construction, and operation of offshore platforms and for implementing specific processes to improve safety and environmental protection. These measures are designed to reduce the risk and occurrence of accidents, injuries, and oil spills. By 1997, almost all OCS production operators were in the process of voluntary SEMP implementation.

BLUEPRINT ON TECHNOLOGY

Implementation helps offshore operators avoid costly injuries, platform damage, and environmental incidents

Standards and training reduce human error

RESEARCH INDICATES that nearly 80 percent of offshore accidents are caused by human error, even when operations are fully compliant with regulations. In response to these risks, Minerals Management Service, in partnership with the American Petroleum Institute (API) and the Offshore Operator's Committee, has delineated voluntary standards that address human and organizational errors and help ensure worker safety and environmental protection as primary operating goals among offshore producers. *Recommended Practice for Development of a Safety and Environmental Management Plan for Outer Continental Shelf Operations and Facilities* (RP 75), first issued by API in 1993, provides safety and operating guidelines for offshore operators of all sizes. These guidelines are especially valuable to small- and mid-sized producers, who may lack the resources and experience of larger companies in developing and implementing such policies. This cooperative relationship between industry and government represents a successful alternative to prescriptive regulations, with MMS' collaboration encouraging industry to focus on risk identification and mitigation instead of mere compliance. Because of widespread RP 75 implementation, MMS has recently announced the continuation of its voluntary partnership with industry and sponsorship of joint industry workshops to share best management practices.

> "We have seen strong evidence that adoption of SEMP can not only accomplish public objectives in the areas of promoting safety and environmental protection... it can also make good business sense by avoiding or containing accident and pollution costs. The vast majority of OCS operators have undertaken, in earnest, to develop and implement SEMP plans."
>
> *Minerals Management Service, 62 Federal Register 43346, 8/13/97*

ECONOMIC BENEFITS

- Fewer accidents and equipment failures, thereby reducing operating and remediation costs
- Potential avoidance of fines and litigation due to reduced risk of accidents and pollution

ENVIRONMENTAL BENEFITS

- Reduced risk of spills, fugitive air emissions, blowouts, and accidents
- Better protection of sensitive marine ecosystems and habitats
- Enhanced worker safety, leading to fewer job-related injuries and illnesses

CASE STUDIES

Success in the Field

DOE and its partners blaze a trail to safety

To allay small- and mid-sized producers' concerns over the perceived costs and burdens of RP 75, DOE recently supported a real-world pilot implementation project with Louisiana-based Taylor Energy Company. The goal was to develop a single-model SEMP that could be shared throughout the industry, streamlining redundancies and reducing costs, particularly for smaller, independent companies.

Taylor, assisted by subcontractor Paragon Engineering Services, Inc., developed and implemented an 11-part SEMP at seven offshore platforms in the Gulf of Mexico. First, existing site safety procedures were updated for incorporation into the new safety program. Next, Taylor developed company-wide documentation of its safety and environmental program management, safety procedures, and safe drilling and workover practices, as well as a pocket-sized safety handbook summarizing these practices. In addition, Taylor performed risk-based hazard analyses at each site and issued site-specific operating procedures for startup, normal, and emergency response. Employee training on these general safety guidelines and all site-specific safety practice followed. Finally, Taylor audited the program to verify its successful implementation, using an OSHA-based audit protocol that included document review, visual inspection, interviews, and written testing.

While long-term outcomes are pending, Taylor's lost-time accident rate declined significantly at the pilot sites over the 30-month project period. DOE and MMS expect similar experiences at other companies, including eventual operating cost reductions due to SEMP and the resulting downward trend in accidents.

Taylor is sharing its experience and offering recommendations to others in DOE- and MMS-sponsored workshops and publications, including technical conferences, trade shows, and leading trade journals. These presentations have enabled many small- and mid-sized producers to learn firsthand about the program, leading to more effective SEMP implementation at their own facilities.

An effective plan addresses how to:

- Operate and maintain facility equipment
- Identify and mitigate safety and environmental hazards
- Change operating equipment, processes, and personnel
- Respond to and investigate accidents
- Purchase equipment and supplies
- Work with contractors
- Train personnel

A fully implemented SEMP covers all phases of offshore operations, including design, construction, startup, operation, inspection, and maintenance of new, existing, or modified drilling and production facilities. (API RP 75)

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TECHNOLOGY Worldwide, onshore and offshore

Vapor Recovery Units

SUMMARY

Vapor recovery units can significantly reduce the fugitive hydrocarbon emissions vaporizing from crude oil storage tanks, particularly tanks associated with high-pressure reservoirs, high vapor releases, and larger operations. These emissions are typically made up of 40 to 60 percent methane, a potent greenhouse gas, along with other volatile organic compounds (VOCs), and hazardous air pollutants (HAPs). U.S. crude oil storage tanks emit an estimated 26.6 billion cubic feet of methane per year, representing a significant portion of the oil and gas industry's total annual methane emissions. While vapor recovery units are only feasible for a minority of existing tanks, this technology can capture over 95 percent of these emissions and compress them for use on-site or for sale. These units help protect our environment from harmful air pollutants and greenhouse gases.

BLUEPRINT ON TECHNOLOGY

Vapor recovery units cut up to 95 percent of light hydrocarbon vapors vented from crude oil storage tanks, while recovering valuable gas

Resources that vanish into thin air

CRUDE OIL STORAGE tanks hold oil for brief periods of time to stabilize flow between production wells and pipeline or truck transport. During storage, light hydrocarbons dissolved in the oil vaporize and collect below the tank roof. The chief component of this gas is typically methane, although other gases such as propane, butane, ethane, nitrogen, and carbon dioxide may be present. These vapors also contain HAPs such as the BTEX compounds (benzene, toluene, ethylbenzene, and xylene). As the oil level in the tank fluctuates, these vapors often escape into the air, either through *flash losses* (due to pressure changes during transfer of crude oil), *working losses* (due to the changing fluid levels and agitation of tank contents associated with the circulation of new crude through the tank), or *breathing losses* (due to daily and seasonal temperature and pressure variations). The amount of gas lost depends on the stored oil's gravity, the tank's throughput rate, and the operating temperature and pressure of the oil being added.

The advantages of vapor recovery

Vapor recovery systems can capture more than 95 percent of these fugitive emissions and recover substantial amounts of gas for use or sale. In addition to onshore use, they are also employed in offshore settings such as marine crude oil loading terminals. Producers may opt to pipe the recovered vapors to natural gas gathering pipelines for sale as a high Btu-content natural gas, or to use the gas to fuel on-site operations. Alternatively, they may strip the vapors to separate natural gas liquids (NGLs) and methane. In some cases, vapor recovery units will reduce emissions to below the actionable levels set out in Title V of the 1990 Clean Air Act Amendments. By installing vapor recovery systems, producers may be able to avoid permitting charges, emissions fees, and other regulatory costs.

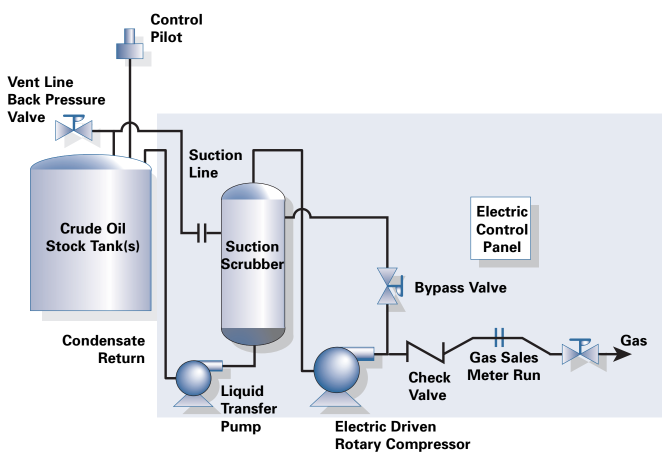
ECONOMIC BENEFITS	ENVIRONMENTAL BENEFITS
Lower operating costs if captured gas is used to fuel on-site equipment	Significantly reduced greenhouse gas emissions
Gas recovered for sale as a high-Btu natural gas	Improved local air quality, due to reduced emissions of VOCs and HAPs
Gas recovered and stripped to separate NGLs and methane, if volume and NGL prices are sufficient	Optimized recovery of a valuable natural resource
Potential avoidance of regulatory permitting and compliance costs	

How the Technology Works

In a typical recovery system, hydrocarbon vapors are drawn from the storage tank under low pressure, usually between 0.25 and 2 psi, then piped to a separator "suction scrubber," which collects any condensed liquids. Any recovered liquids are usually recycled back to the storage tank. The vapors then are compressed, metered, reused, or resold.

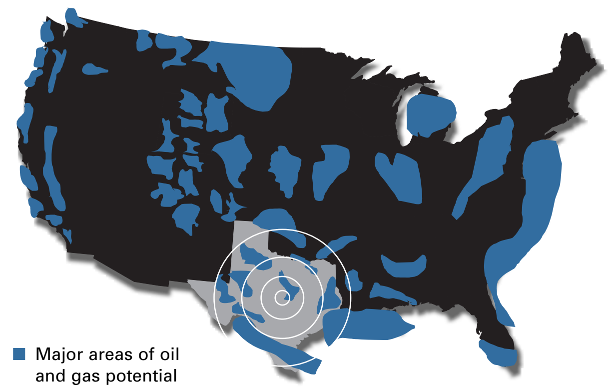
To prevent the creation of a vacuum in the top of the storage tank as vapors are removed, the unit is equipped with controls that shut down the compressor, permitting reflow of vapors into the tank as necessary. These systems can recover practically all the hydrocarbon vapors that would otherwise be lost to the atmosphere with negative environmental impacts.

Vapor Recovery Unit



Case Studies

Success in the Field



Vapor recovery units succeed in the Austin Chalk field

In 1992–93, Union Pacific Resources (UPR) installed 27 vapor recovery units on its crude stock tanks in the Austin Chalk. UPR's horizontal wells in the area are high-rate producers with high gas-to-oil ratios. Under these conditions, gas-oil separation is difficult, leading to high volumes of gas in the tanks. The vapor recovery systems proved very effective in reducing high emissions levels and generating profits. UPR recovered an average of 2,015 thousand cubic feet of gas per day, equivalent to the annual gas consumption of 23 residential consumers. The recovered natural gas netted UPR an additional $700,000 in revenue over a one-year period.

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TECHNOLOGY Locations: Worldwide, onshore and offshore

Advanced Approaches to Site Restoration

SUMMARY

At the end of an oil or gas well's economic life, typically spanning 15 to 30 years, the well must be plugged and abandoned, all production equipment removed, and the surrounding area restored as closely as possible to its original state to prevent potential environmental or public health risks. To ensure the future ecological and economic viability of closed site lands, the industry is continually developing and applying innovative site restoration practices and technologies, including Risk-Based Corrective Action, soil bioremediation, and wetlands restoration. In addition, operators are actively supporting industry-led clean-up efforts such as those being carried out by the Oklahoma Energy Resources Board, a privatized state agency funded solely by industry's voluntary contributions.

BLUEPRINT ON TECHNOLOGY

Advanced technology and practices underscore a widespread commitment to environmental excellence

Closing sites

Of approximately 3.4 million oil and gas wells drilled in the United States since 1859, more than 2.5 million have been plugged and abandoned—a complex effort involving significant planning and expense. Onshore, wellbores are permanently plugged with cement to prevent any flow of subterranean fluids into the wellbore, thereby protecting groundwater. Waste-handling pits are closed, and storage tanks, wellheads, processing equipment, and pumpjacks removed. Offshore, wellbores are sealed below the sea floor and platforms are fully or partially removed, or toppled in place as part of artificial reef programs. About 17,000 onshore wells are plugged and abandoned annually, and 100 offshore platforms decommissioned each year.

Unplugged or orphaned wells with no existing owner or operator are largely a legacy of historic operations, when site restoration was not considered necessary. Today, a new approach to restoration integrates advanced technology, increased research and development, and a spirit of voluntarism and responsibility.

An exemplary model

A highly effective industry-led site restoration program is run by the Oklahoma Energy Resources Board (OERB), with near-unanimous support from Oklahoma producers and royalty owners, whose annual voluntary contributions solely fund this unique initiative. Since 1995, this privatized state agency has restored more than 1,000 orphaned and abandoned well sites across Oklahoma—with 500 more sites under way—mitigating potential health and environmental risks and restoring blighted lands to the benefit of landowners, the community, and the environment, at no cost to the landowner. OERB's success demonstrates industry's commitment to preserving the lands on which it operates.

Diverse approaches

Rather than employing a "one-size-fits-all" approach to site restoration, industry is turning to flexible Risk-Based Corrective Action (RBCA) processes to ensure swift, efficient clean-ups. A joint American Petroleum Institute-Gas Research Institute (GRI) project has resulted in development of an E&P-specific set of RBCA tools to help operators undertake risk-based remedial planning. In this approach,

ECONOMIC BENEFITS

- Reduced long-term environmental clean-up costs and lowered risk of future liability
- Increased economic value of land returned to productive agricultural, residential, or commercial uses

ENVIRONMENTAL BENEFITS

- Mitigation of potential public health and environmental risks
- Restoration of sensitive habitats and ecosystems
- Organic cleaning of petroleum-stained soil through bioremediation, maintaining and sometimes even improving soil health

human-health and ecological-risk analyses and decisions are integrated with the corrective action process, ensuring that remedial measures are appropriate given a specific site's characteristics and risk levels, and that resources are focused first on sites presenting the greatest potential risk.

Emerging bioremediation technology is a cost-effective tool with powerful environmental advantages. During E&P operations, soil layers can become stained with hydrocarbon molecules ranging from heavy crudes to volatile organic compounds. Bioremediation involves stimulating existing or placing carbon-eating microorganisms in stained soils to digest excess hydrocarbons or break them down into simpler, non-toxic compounds such as carbon dioxide and water. Bioremediation maintains the microbial populations needed to keep soil healthy, and can also enhance soil health.

Within the natural gas industry, R&D efforts focus on remediating mercury-contaminated sites, which can entail potentially significant environmental and public health risks. In conjunction with DOE, GRI is examining the extent of the contamination, developing risk-based prioritization models, and testing advanced remediation technologies, including physical separation, chemical, and thermal techniques.

New techniques for restoring wetlands lost to saltwater encroachment are under development. For example, with assistance from DOE-funded research at Southeastern Louisiana University (SLU) is demonstrating that drill cuttings can be safely used to restore and create wetlands. Using SLU's unique temperature-controlled mesocosm greenhouse facilities to simulate wetlands' full range of tidal fluctuations, researchers have found that certain processed drill cuttings appear capable of supporting healthy wetlands vegetation.

CASE STUDIES

Success in the Field

Proactive, global, site restoration

Together with other companies and the State of California, Phillips Petroleum is leading the restoration of the abandoned 880-acre Bolsa Chica oil field near Huntington Beach, California. The project includes cleaning up old well sites and building a tidal inlet where waterfowl can rest and feed before migrating 3,000 miles across the Pacific Flyway.

In Phu Khieo, Thailand, Texaco restored a nonproductive exploratory drill site, although not legally obligated under Thai law, by treating drilling wastes, capping the site with clean topsoil, and building dikes to support rice paddies and sugar cane fields. The Thai government has since proposed Texaco's approach as a regulatory environmental management model.

Working with Kansas State agencies, Mobil E&P U.S., Inc. bioremediated hydrocarbon-stained soils at its Hugoton Gas Field. Using cow manure as a soil nutrient and microbial base catalyst, total petroleum hydrocarbon levels were reduced by more than 99 percent. At the project's conclusion, native grasses were planted to re-vegetate the area.

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TECHNOLOGY Locations: Gulf of Mexico

Rigs to Reefs

SUMMARY

Industry, regulators, and environmentalists now recognize the advantages of toppling decommissioned offshore platforms and anchoring them on the sea floor as permanent artificial reefs. Under existing State programs, oil and gas companies can donate platforms to States for use as artificial reefs, along with a percentage of their cost savings to be used for reef maintenance and development. Designed for marine environments and impervious to displacement or breakup, these steel platforms make ideal reefs. Thriving habitats are typically well established on working rigs, and dismantling and moving them threatens these habitats. To date, more than 100 donated offshore platforms have been placed off the coasts of Texas, Louisiana, and other Gulf States, where they host complex ecosystems that attract fish and enhance commercial fishing and recreational activities.

BLUEPRINT ON TECHNOLOGY

Converting obsolete platforms into artificial reefs benefits marine habitats, commercial fishers, divers, vacationers, and the oil and gas industry

Removing rigs

THE U.S. MINERALS Management Service (MMS) requires removal of all platforms in Outer Continental Shelf (OCS) waters within one year from production shutdown. Currently, platform removals from the Gulf of Mexico OCS are averaging 100 platforms per year. MMS estimates that over half of about 3,900 remaining structures will require removal by 2000. For smaller structures in shallow waters, companies typically dismantle the platform using explosives, or sometimes torches or cutters, and then tow the deck and jacket to shore for refurbishment or scrapping. This option is often elected when the platform is not located near a "rigs to reefs" zone.

Creating artificial reefs

When decommissioning in deeper waters (generally beyond 100 feet) at more remote locations, operators can reduce removal costs significantly by toppling structures (fully or partially) in place as artificial reefs, or towing them to a designated site for toppling. To date, about 10 percent of the Gulf's platform removals have been converted to artificial reefs; this percentage is expected to increase as more decommissioned deepwater platforms require removal.

The typical 20-story steel jackets that support offshore platforms provide acres of habitat for various underwater flora and fish species—within six months to one year of initial placement, platforms are covered with marine life. The submerged hard surfaces invite invertebrates such as barnacles, corals, sponges, clams, bryo-zoans and hybroids, which in turn attract resident reef fish such as snapper and grouper and transients like mackerel and billfish. Fish are also drawn by

ECONOMIC BENEFITS
Potential for significant reductions in platform removal and disposal costs, particularly in locations where partial removal is viable
Industry cost savings fund State reef maintenance and development programs
Enhancement of commercial fishing opportunities
Promotion of local tourism through enhanced recreational fishing and diving opportunities

ENVIRONMENTAL BENEFITS
Enhanced protection and nurture of complex marine ecosystems and habitats
Creation of new marine habitats
Reduced impacts of platform demolition and relocation
Increased recreational use of water resources

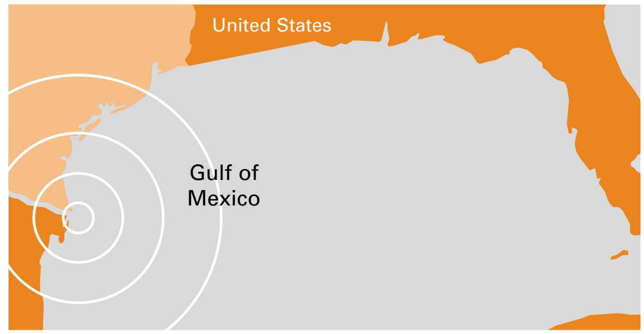
the shape, size, and openness of these structures, which attract an estimated 20 to 50 times more fish than the Gulf's naturally flat, soft bottom.

Removing platforms after shutdown threatens these complex fish populations as well as the commercial and recreational industries that rely on them. Through "rigs to reefs," industry and State governments are collaborating to ensure the greatest possible number of platform conversions, thereby protecting rich marine ecosystems and enriching the Gulf's commercial fishing and recreational opportunities.

The first planned rigs-to-reefs conversion took place in 1979, when an Exxon-owned subsea template located offshore Louisiana was moved to offshore Florida. The National Fishing Enhancement Act, passed in 1984, led to the development of the National Artificial Reef Program and formal support from MMS. State programs followed in Louisiana (1986) and Texas (1990); Mississippi, Alabama, and Florida have since formed their own programs. Today, artificial reefs exist around the world, with the Gulf of Mexico boasting the most extensive and successful conversions.

CASE STUDIES

Success in the Field



Rig reefs boost tourism in South Texas

Mobil Exploration and Production U.S., Inc., performed an environmentally outstanding conversion in 1994. Over a 75-day period, Mobil dismantled six platforms located in several South Padre Island blocks, moving four jackets 10 miles to Port Mansfield Liberty Ship Reef and two jackets 27 miles to Port Isabel. Mobil elected to cut away the platform legs rather than blast them, despite explosives being cheaper, faster, and more reliable. Mechanical cutting avoided undue harm and disruption to the rich marine life inhabiting the rigs offshore environmentally sensitive South Padre Island.

The added time and expense of cutting and transport negated any cost savings, but Mobil still earned tremendous payback. Jeffrey Passmore of Mobil noted: "We were able. . .to give. . .structures with 15 to 20 years of [marine habitat] buildup on them." Jan Culbertson, Texas Parks and Wildlife Department, commented, "We almost begged Mobil to take the structures to Port Isabel. That's where our tourism dollars are. Mobil bent over backward to give us their structures in a natural state with no animals hurt or removed. We even had turtles living on the structures that we had to move out of the way. All the animals, the little blennies [fish] that were inside the barnacles, all made it to their new reef-site home."

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TECHNOLOGY Locations: United States

Road Mix and Roadspreading

SUMMARY

Tank cleaning and other common exploration and production operations routinely generate large amounts of non-hazardous crude oil wastes sometimes suitable for use as road paving (road mix) materials. These hydrocarbon residuals act as binders, and can be mixed on-site with native soils or imported aggregate, then safely paved into roads. Similarly, another routine oilfield waste, produced water—the brine or brackish water extracted with oil or gas during the production process—can be used for road de-icing or dust control. Road mixing and spreading technology provides useful products, significant disposal cost-savings for producers, and conservation of limited landfill capacity. Minimizing landfill use also significantly reduces the potential for reactive hydrocarbon emissions and soil and water contamination. While this practice promises environmental benefits under certain conditions, application is limited and discrimination necessary.

BLUEPRINT ON TECHNOLOGY

Crude oil residuals and produced water can be safely and creatively recycled for road building, stabilization, de-icing, and dust suppression

Creative use of oilfield waste

As landfill and other traditional disposal methods become more limited and costly, in some areas the petroleum industry is increasingly recycling various oilfield wastes as road mix material.

Paralleling the commercial road mixing process, the petroleum industry mixes crude oil residuals from tank cleaning, sump abandonments, and production flowline leaks with imported aggregate (coarse binding materials) or native soils for light duty road paving or dust suppression.

Tank residuals are the largest source of recycled binding agents. These residuals, made up of fine sediments or sands and heavy, low-volatility hydrocarbons that settle during storage, are periodically cleaned out of tanks by high-pressure water jets, creating a slurry that is dewatered to make sludge. The sludge—with cohesive and adhesive properties similar to commercial road mix materials—is mixed with aggregate, graded, and cured.

The resulting road mix can either be stockpiled or applied immediately with standard paver/spreader equipment, and compacted if necessary. Depending on final use, the hydrocarbon content of the raw materials, and the type of road mix needed, petroleum facilities may add commercial asphalt cements to their road mix.

Other oilfield wastes, such as completion and workover fluids and produced brine, are also suitable for roadspreading to suppress dust or de-ice unpaved roads. In northern

ECONOMIC BENEFITS

- Significant reduction in costs and potential liability associated with management and disposal of nonhazardous oilfield wastes
- More expensive alternatives such as paving would be necessary without recycled road mix
- Landfill space conserved
- Conservation of natural resources through product substitution

ENVIRONMENTAL BENEFITS

- Reduced waste volumes to landfill or reinject into the earth's subsurface, thus reducing potential environmental risks and future liability
- Reduced dust and particulate matter emissions from unpaved roads
- Greatly reduced reactive organic hydrocarbon compound emissions, compared with landfill disposal
- Demonstrated low hydrocarbon and metal leachability
- Demonstrated nonhazardous by acute aquatic testing

States, using these wastes to de-ice roads instead of salt can conserve this limited natural resource.

Today, the petroleum industry uses most of its recycled road mix to develop access roads to remote exploration and production sites and to control dust in production areas. California operators have been using crude oil-impacted waste materials as road mix for nearly a century with no adverse environmental impacts. Similarly, brine spreading to stabilize roadways and control dust has been used effectively in certain areas for years. The primary alternatives to road mixing and roadspreading are landfilling the solid wastes at an average cost of $75 per ton, and subsurface reinjection of produced water for disposal or enhanced oil recovery, also very costly.

CASE STUDIES

Success in the Field

Roadspreading in Pennsylvania

A portion of the 1.7 million barrels of brine produced annually by Pennsylvania's oil and gas wells is spread on its unpaved secondary roads for dust suppression and road stabilization. To minimize environmental impacts from this practice, including the risk of contaminants leaching into surface or ground waters, the Pennsylvania Department of Environmental Protection (DEP) has developed mandatory roadspreading guidelines for brine generators, transporters, applicators, and roadway administrators.

Funded by a Federal Clean Water Act grant, the DEP tested water quality impacts along seven unpaved roadways in western Pennsylvania on which brine had been spread. Between 1992 and 1995, surface water samples were taken from culverts, roadside ditches, streams, and ponds at the selected road sites, while groundwater was sampled from monitoring wells installed to measure the impact of brine-spreading on water quality. Over the sampling period, lysimeters were used to determine whether brine had migrated from the roadbed. Soil and roadbed samples were also taken to identify any leaching or accumulation of heavy metals or other harmful pollutants. Through monitoring and subsequent analyses, the DEP concluded that although potential exists for harm to surface water and groundwater from brine migration or run-off, risks could be significantly minimized by controlling the frequency and application rate of brine and by following the roadspreading guidelines. Roadspreading offers a cost-effective means to recycle and dispose of a portion of Pennsylvania's produced water waste stream, with minimal environmental impact.

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TECHNOLOGY Locations: United States, onshore

DOE-BLM Partnership

SUMMARY

The Bureau of Land Management (BLM) and the Department of Energy (DOE) have joined forces to enhance protection of environmental and cultural resources on sensitive public lands. In these joint projects, advanced technologies and practices are shared across BLM, DOE, and the oil and gas industry to improve resource management and access to Federal lands. Currently, teams are studying issues such as the reversal of subsurface damage to freshwater aquifers at abandoned well sites in Oklahoma, the protection of archaeological remains in Nevada, and the improvement of air quality monitoring in remote Wyoming locations. In concert with Federal agencies striving to balance competing demands for the use of public lands, the DOE/BLM partnership seeks to ensure maximum resource recovery consistent with high levels of environmental protection and cultural sensitivity.

BLUEPRINT ON TECHNOLOGY

Strategic alliances leverage DOE and BLM resources and expertise to protect cultural resources and sensitive environments

The role of BLM

BLM oversees 264 million acres of Federal land and 300 million acres of subsurface mineral resources, primarily in the western United States and Alaska, about an eighth of the land in the United States. Federal lands under BLM oversight include extensive grasslands, forests, high mountains, arctic tundra, and deserts, as well as many fish and wildlife habitats and archaeological and historical sites. These lands contain subsurface resources amounting to eight percent of the natural gas and five percent of the crude oil produced annually, in addition to resources like coal, forest products, grazing forage, and rights-of-way for pipelines and transmission lines. Of the total $1.4 billion in annual revenues these lands bring, nearly $835 million, or 60 percent, is generated by royalties, rents, bonuses, sales, and fees from oil and gas operations. The total direct and indirect economic output of oil and gas production is estimated at nearly $12 billion annually.

The role of DOE

DOE and BLM have entered into a memorandum of understanding (MOU) to help improve access to Federal land for oil and gas development, consistent with effective environmental protection. This includes technology transfer, data sharing, technical support, and sharing of expertise. Cooperative efforts under this agreement have included DOE participation on BLM streamlining and environmental incentives teams and BLM contributions to DOE's oil and gas databases. In addition, as part of the MOU activities, DOE and BLM have formed a Federal Lands Technology Partnership to address access issues and provide technical support to Federal land managers. Fiscal year 1998 was the first year of DOE funding under this partnership. The two agencies solicited projects from BLM field offices and worked together to prioritize the proposals. Three resulting projects initiated this year are discussed here.

ECONOMIC BENEFITS

Enhanced Federal revenues from increased oil and gas production on public lands

Accelerated planning and permitting schedules, reducing development costs and time

ENVIRONMENTAL BENEFITS

Greater protection of environmentally and culturally sensitive areas

Increased, more efficient recovery of oil and gas on Federal lands

CASE STUDIES

Success in the Field

Well decontamination in Oklahoma

BLM recently discovered brine and salt water contamination of both soil and freshwater sources on land held in trust to the Pawnee Indians in Payne County, Oklahoma. Today, BLM and DOE are working together with the Oklahoma Energy Resources Board, an industry-funded, publicly chartered site restoration agency, to reverse subsurface damage to a freshwater aquifer and to restore the area's damaged grasses, shrubs, and trees. Knowledge gained in this project will apply to a wide range of water-injection and water-disposal well problems, and technology developed for salvaging the contaminated aquifer will benefit other damaged sites on public lands.

Archaeological and resource development in Nevada

BLM, DOE, and state agencies in Nevada are developing a predictive geographical information system (GIS) model that will help protect the rich archaeological remains of the northern Railroad Valley in Nye County, Nevada. This will enhance access to the area's rich oil and gas resources, often restricted by concerns about archaeological remains. A potentially powerful management tool, the model provides critical information on both subsurface resources and cultural sites, making it easier to determine lease boundaries, isolate sensitive areas, and accelerate resource development. For example, by identifying the likelihood of precious cultural resources in a specific area within the Nye Valley, the model will improve the routing of access roads and pad orientation, and help manage resource, range, wildlife, and recreation programs.

Air quality monitoring in Wyoming

Since ongoing air quality data is often unavailable in many remote areas, it is becoming increasingly difficult for land management

agencies to complete air quality impact assessments required as part of Environmental Impact Statements (EIS). Because new oil and gas development projects are permitted only on condition that air quality will not significantly deteriorate, future access to some resources may be denied where air monitoring data are insufficient, even in areas where actual air quality impacts would be minimal.

To address this concern, BLM and DOE, in collaboration with other agencies, are establishing a network of low-cost, portable, solar-powered monitoring stations in southwestern Wyoming, which has seen a marked increase in oil and gas development over the last five years. These stations will measure ambient air concentrations and calculate dry deposition of nitrogen oxides and sulfur oxides in remote areas where environmental concerns are high and development is likely to increase. This will greatly enhance permitting decisions and EIS preparation. Five aerometric stations currently used to measure climate and air quality parameters will be converted for operational air quality monitoring. Three will be mobile; the other two will remain fixed to provide long-term air quality data.

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Technology | Locations: Worldwide

Coastal and Nearshore Operations

Summary

From Alabama's Mobile Bay to the North Irish Sea, operators are employing advanced exploration, drilling, production, and site restoration techniques to protect sensitive coastal wetlands and nearshore environments. For example, through collaborative planning with several Federal and State agencies and state-of-the-art drilling and site restoration technologies, Bright & Co. drilled an environmentally unobtrusive exploratory well on the Padre Island National Seashore. In conformance with extensive regulatory requirements, every phase of Bright's operation was designed to minimize environmental impacts, leaving virtually no footprint on the area. Although no hydrocarbon resources were found, the undertaking demonstrated that exploratory drilling can be done without disturbing coastal environments. The use of advanced technology helps preserve delicate ecosystems.

Blueprint on Technology

Cooperative planning, advanced technology, and detailed habitat enhancement render operations virtually invisible

Gulf coast breakthrough

A federally managed recreational area and wildlife and nature preserve, Padre Island National Seashore has 133,000 acres of beaches, grasslands, tidal flats, dunes, and ponds that are home to a huge variety of plant life as well as marine life, reptiles, sea turtles, coyotes, waterfowl, and more than 350 species of birds, including some threatened or endangered species. Hiking, camping, fishing, nature studies, and water sports attract some 800,000 visitors annually. This 80-mile long barrier island sits four feet above an underground freshwater aquifer, which is the primary source of drinking water for area wildlife and thus critical to the island's ecosystem. The island is also situated in a high-potential oil and gas resource zone, challenging private parties who own subsurface oil and gas rights to develop these resources under the strict environmental regulatory oversight of several Federal and State agencies, including the U.S. Army Corps of Engineers, the National Park Service, and the Texas Railroad Commission.

Planning for all contingencies

Before Bright & Co. could begin drilling, the National Park Service required a comprehensive plan of operations, including a timetable and description of all proposed construction, drilling, completion, and production activities; spill control and site reclamation plans; environmental impact statements; and documentation of the archaeological and cultural resources potentially affected by the operations. Bright & Co.'s plan included site management equipment to minimize the operation's footprint and safely manage wastes as well as a directional drilling strategy that would minimize contact with sensitive wetlands and environmental impacts. Upon plan approval, Bright & Co. also posted a $200,000 performance bond, the estimated maximum cost of site reclamation and clean-up should an oil spill occur. Finally, a U.S. Army Corps of Engineers permit to build an access road across reclaimed wetlands was obtained, requiring Bright & Co. to compensate the 0.4 acres of nontidal wetlands lost to road construction with 0.8 acres of new wetlands.

Economic Benefits

- Sensitive project execution averted potential negative impacts on a popular tourist area
- Cost-effective, low-impact operations proven successful

Environmental Benefits

- Virtually no footprint following operation
- Habitats, wildlife, and cultural resources intact and unmolested
- Fresh and marine water resources meticulously safeguarded
- Reduced air emissions and lower risk of fuel spills through use of electric equipment

A "no footprint" drilling site
Using 7,600 tons of imported, compacted caliche, Bright & Co. built a 1.6-mile, 14-foot wide access road to the drill site. They constructed a 300-foot square caliche pad, covered by a polyethylene liner, on which they mounted the drill rig, mud tanks, and pipe racks. The company then built a berm around the liner and sloped the pad to capture any discharges in a subsurface "cellar," draining it with a centrifugal pump. A three-foot high levee ringed the pad perimeter, ensuring no groundwater contamination.

Advanced technology at work
Mesa Drilling Inc. drilled the well with a diesel-electric, silicon controlled rectifier unit, significantly reducing noise impact on visitors and wildlife. Most of the rig's components were wheel-mounted, thus minimizing equipment mobilization across the beach. Electric mud pumps and draw works reduced air emissions and potential oil leaks. An advanced closed-loop mud system collected drill cuttings in 85-barrel boxes mounted on tracks for immediate transport and disposal off site.

Bright & Co. employed directional drilling to hit the targeted pay zone—the Frio Marg A sand at approximately 7,500-foot true vertical depth—located beneath a large wetlands area. Directional drilling allowed Bright & Co. to avoid reclaiming additional wetlands for the drilling pad. An 8 3/4-inch polycrystalline diamond compact drill bit was selected to maintain direction and angle, prevent formation damage, and minimize drilling time and air emissions. At an average rate of 58 feet per hour over 14 days, the well was first drilled vertically to 1,830 feet, then angled 2 degrees per 100 feet, reaching an ultimate angle of 29 degrees and a measured depth of 8,900 feet. When no productive zones were found, Bright & Co. plugged the well, removed the pad and access road, restored the ground surface to its original contours, and reseeded with native grasses.

CASE STUDIES

Beyond South Padre Island

Advanced technology is enhancing access to oil and gas resources while protecting sensitive coastal and wetlands ecosystems throughout the United States:

In Mobile Bay, Alabama—a complex marine environment with important commercial fisheries and recreational facilities—ARCO's Dauphin Island production facility has successfully minimized visual and environmental impacts while developing the area's rich natural gas resources. Less than three miles from Dauphin Island residents, the ARCO platform's unique structural design minimizes aesthetic drawbacks. The facility also used advanced horizontal drilling techniques to reduce the production footprint.

Covering 125,000 acres in southwest Louisiana, the Sabine National Wildlife Refuge sustains more than 250 species of birds, alligators, and marsh mammals, and is a major wintering ground for migratory waterfowl. In 1993, Vastar Resources selected the refuge's Black Bayou as an exploratory prospect. In close cooperation with the U.S. Fish & Wildlife Service and other Federal and State agencies, Vastar used innovative drilling, waste minimization, and site restoration techniques to drill two exploratory wells in this fragile coastal wetlands area, with minimal impacts.

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TECHNOLOGY Locations: Alaska's North Slope

Insulated Ice Pads

SUMMARY

New, prefabricated insulation panels can be used to preserve ice drilling pads from arctic summer thaw, thereby extending the exploratory drilling season as much as 50 percent. Insulated pads permit ice pad construction prior to the winter drilling season, enabling drilling operations to begin some two months earlier than if the pad had been built in December for a mid-January drilling start—the typical exploratory drilling schedule. The extended season allows single-season well completions, which reduce seasonal equipment mobilization and environmental impacts, as well as associated costs.

BLUEPRINT ON TECHNOLOGY

Extending the drilling season with insulated ice pads can minimize environmental disruption and exploratory drilling footprints, while reducing costs

Drilling in the Arctic

CLIMATIC CONDITIONS on Alaska's North Slope have restricted the exploratory drilling season in remote Arctic environments to 135 to 170 days. The tundra has to be frozen solid enough to allow equipment transport to the drilling site as well as sustainable ice road and ice pad construction and maintenance. At its longest, the tundra travel season extends from November through May, although specific conditions dictate load weight on any given date. At the drilling site, ice pad construction, often as large as an acre, is usually begun in early December, although November is possible under optimal conditions. By mid-May, equipment must be removed to a non-tundra area. While conventional ice pads are far less environmentally intrusive and less costly than gravel drilling pads, their impermanence means an additional round of equipment demobilization and storage at an off-site gravel pad. If, as is common, the exploratory well is not completed, remobilization the following season is necessary. Such operations entail environmental disturbance and additional costs.

Innovative insulated ice pads, however, can extend the available drilling season to a total of 205 days and effective well operations up to 160 days, potentially enabling completion of one or perhaps two exploratory wells in a single season. Single-season completions substantially reduce mobilization costs and related environmental effects, and also cut time between initial investment and returns.

ECONOMIC BENEFITS

- Single-season exploratory well completions, greatly reducing mobilization costs
- Valuable subsurface data one year earlier than would otherwise be possible, enhancing operational planning

ENVIRONMENTAL BENEFITS

- Smaller footprints and less time on-site
- Elimination of seasonal equipment mobilization, minimizing environmental impacts on land and air

CASE STUDIES

Success in the Field

Drilling two months earlier, saving more than $2.3 million

When a BP Exploration (Alaska) Inc. (BPXA) engineering feasibility study indicated that constructing an insulated ice pad in March 1993 at Yukon Gold #1 on the North Slope would significantly extend the winter drilling season, BPXA built a 390-by-280-foot ice pad covered with nearly 600 wind-resistant insulating panels. Summer visits confirmed that the ice beneath the panels remained sufficiently frozen. When the panels were disassembled in October 1993, they had not bonded to the resting surface, or scattered, and nearly 90 percent were in excellent condition and reusable.

BPXA began drilling in mid-November, two months ahead of conventional Arctic practice. With such an early start, Yukon Gold #1 was completed in time to begin drilling immediately at nearby Sourdough #2, where the insulated panels were placed under the rig to give BPXA the option of leaving the rig on location over the summer and avoiding remobilization should the well not be completed before season's end. This was not necessary, however, as the Sourdough well was also successfully completed during the same season.

Overall, BPXA netted a cost savings of more than $2.3 million from the two single-season completions. In addition, the tundra endured significantly less impact than would have been the case had seasonal equipment mobilization been required. Subsequent site monitoring showed no long-term environmental impacts.

METRICS

Results of a BPXA study, comparing drilling season length using conventional practices versus insulated ice pads

Time Period	Conventional	Insulated Ice Pad
Construction start date	December 1–15	Previous Winter
Start of rig mobility	December 15–31	October 7–21
Spud date for first well	January 15–31	November 7–21
Tundra-travel end of season	April 29–May 22	April 29–May 22
End of well operations	April 15–May 8	April 15–May 8
Total Season Available	**135–170 days**	**175–205 days**
Effective Well Operations Season	**75–110 days**	**145–160 days**

©SPE 35686, 1996

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TECHNOLOGY Locations: Alaska's North Slope

North Slope Operations

SUMMARY

North Slope oil and gas operations showcase a number of technological triumphs over powerful natural forces, enabling successful operations in this extreme, sensitive environment. Since these resources represent nearly a quarter of U.S. oil reserves, the need to access them has accelerated development of environmentally responsible, cost-effective practices and technologies. For instance, the difficulties of winter exploration have been mitigated by innovations such as ice roads and ice pads that have no lasting effects on delicate tundra. Drilling advances—extended reach drilling, coiled tubing drilling, multilateral completions and "designer" wells—are increasing resource recovery and reducing drilling costs, footprints, and waste volumes. Today's exploration and production facilities are radically streamlined, occupying far less surface area than operations did 25 years ago.

BLUEPRINT ON TECHNOLOGY

Technology advances protect the environment and improve recovery under hostile arctic conditions

Low-impact operations increase resource recovery, reduce costs, and protect sensitive habitats

THE LARGEST OIL field in North America, the North Slope's Prudhoe Bay has estimated total recoverable reserves of 13 billion barrels of oil and 46 trillion cubic feet of natural gas. Alaska is also home to diverse, unique, and fragile ecosystems, inspiring extensive Federal, State, and local regulatory protection. Since the onset of the North Slope oil boom in the late 1960s, operators have been forced to develop more cost-effective, less environmentally intrusive ways to develop these resources. For example, the exploration sector has developed innovative ice-based transportation infrastructure serving remote locations, even during winters characterized by -70°F temperatures, 20-foot snowdrifts, and limited daylight. In the 1920s, road construction by bulldozing tundra proved disastrous. After only one season, the route was impassable when the permafrost thawed. Operators turned to gravel to insulate the permafrost and stabilize roadbeds, airstrips, and drilling pads, but gravel mining and construction are expensive and environmentally harmful. In the last decade, ice-based technology has become the new standard for exploration. Its low-cost, low-impact performance continues to be refined by techniques like ice pad insulation, which can extend drilling seasons and reduce equipment mobilization. Where ice roads are impractical, low-pressure balloon-tire vehicles haul loads, leaving practically no footprint.

Recent advances in drilling technology are increasing North Slope E&P productivity and protecting the environment. Through-tubing rotary drilling, for example, allows new wells to be drilled through the production tubing of older wells, saving time

ECONOMIC BENEFITS

- Enhanced resource recovery and more efficient operations
- Lower operating costs

ENVIRONMENTAL BENEFITS

- Reduced surface footprints and disturbance
- Protection of sensitive habitats, wildlife, and cultural resources
- Greater access to resources with fewer wells drilled, through advanced drilling technology
- Reduced waste volumes requiring disposal, through innovative waste management and recycling techniques

and, potentially, up to $1 million in operating costs per well. New directional drilling tools and an advanced form of horizontal drilling (“designer wells”) permit drillers to curve around geological barriers to tap small, difficult-to-reach pay zones. Another advanced technology is coiled tubing, which allows extended-reach, directional drilling, and multilateral completions—all major contributors to increased resource recovery, reduced costs, smaller footprints, and less waste.

METRICS

Advanced technologies have significantly reduced the footprint of North Slope operations

- If Prudhoe Bay were developed with today’s technology, its footprint would be 64 percent smaller: the drilling impact area would be 74 percent smaller, roads would cover 58 percent less surface area, and oil and gas separating facilities would take 50 percent less space.
- A new 55-acre contractor base supports ARCO Alaska’s Kuparuk field; similar facilities built over 20 years ago occupy more than 1,000 acres.
- Surface wellhead spacing has been reduced from 145 feet to 35 feet onshore and 10 feet offshore.
- Production pads are dramatically streamlined: the 1971 Prudhoe Bay “A” Pad was built with 35 wells on 44 acres; the 1989 “P” Pad was built with 21 wells on less than 11 acres.

Source: Alaska Department of Natural Resources and BP Exploration (Alaska) Inc.

CASE STUDIES

Success in the Field

Improving waste management

North Slope operators are using advanced technology to manage drilling wastes more effectively. A 1988 ARCO pilot project demonstrated that processed drill cuttings could be safely used as road construction materials, since the cuttings’ composition was essentially identical to that of native gravel and surface soils. Based on these findings, in 1990 BPXA built a prototype grinding and injection facility that recycled recovered cuttings into construction gravel, and ground remaining waste for subsurface reinjection. By 1994, refined grind-and-inject technology enabled BPXA and other Prudhoe Bay operators to achieve “zero discharge” of drilling wastes, eliminating the need for reserve pits. These innovative strategies yield significant environmental benefits—decreased waste volumes, less mining of surface gravel, smaller pad sizes, and less surface disturbance.

Restoring affected areas

The fragile North Slope ecosystem makes site restoration and habitat enhancement a vital post-production process. In recent years, BPXA and ARCO Alaska have created artificial lakes by flooding abandoned gravel mining sites. This practice, encouraged by the Alaska Department of Fish and Game, creates over-wintering habitats for fish and predator-free nesting areas for waterfowl. BPXA and the U.S. Department of Fish and Wildlife collaborated to restore 10 miles of habitat along Endicott Road, demonstrating that transplanting Arctic pendant grass effectively revegetated disturbed aquatic sites. This technique was also applied at BPXA’s BP Pad, where restoration began in 1988. Within three years, native vegetation was restored.

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Appendices

THE FOLLOWING PAGES LIST SOURCES OF ADDITIONAL INFORMATION, DEPARTMENT OF ENERGY OIL AND GAS PROGRAMS AND CONTACTS, AND REFERENCES THAT PROVIDE DOCUMENTATION FOR THIS REPORT.

Sources of Additional Information

The following list, while not inclusive, illustrates the broad array of organizations concerned about oil and gas E&P technology and protection of the environment. Also, see Appendix 2, DOE Oil and Gas Programs.

Industry Associations and Professional Societies

American Association of Petroleum Geologists

More than 31,000 members in 115 countries. Established in 1917, its purpose is to foster the spirit of scientific research among its members and to advance the science of geology—particularly as it relates to petroleum, natural gas, other subsurface fluids, and mineral resources. The Division of Environmental Geosciences, formed in 1992, provides members with opportunities to increase their knowledge about the environment and the petroleum industry, including concepts for using geological, geochemical, geophysical, and hydrogeological principles and methodologies to resolve environmental problems. Tulsa, Oklahoma (918) 584-2555. Internet: www.geobyte.com

Association of American State Geologists

Organization of the chief executives of the State geological surveys in 50 States and Puerto Rico. The responsibilities of the various State surveys differ from State to State, depending on the enabling legislation and the traditions under which the survey evolved. Almost all function as a basic information source for their State governments' executive, legislative, and judicial branches. Some have regulatory responsibilities for water, oil and gas, and land reclamation. Web site includes an Earth Science Education Source Book for Teachers and Students, a compendium of earth science education materials and services available from the 50 State Geological Surveys in the United States, Puerto Rico, and the Association of American State Geologists. Internet: http://www.kgs.ukans.edu/AASG/AASG.html

American Gas Association

Represents natural gas utilities and pipeline companies. Interests include all technical and operational aspects of the gas industry. Publishes a comprehensive statistical record of gas industry; conducts national standards testing for gas appliances; monitors legislation and regulations. Web site includes extensive information on natural gas. Washington, DC (202) 824-7000. Internet: www.aga.org

American Geologic Institute

Nonprofit federation of 32 geoscientific and professional associations that represent more than 100,000 geologists, geophysicists, and other earth scientists. Founded in 1948, the Institute provides information services to geoscientists, serves as a voice of shared interests in the profession, plays a major role in strengthening geoscience education, and strives to increase public awareness of the vital role the geosciences play in mankind's use of resources and interaction with the environment. Maintains a Clearinghouse for Earth Science Education with an electronic database for elementary school teachers and secondary school science teachers. Produces directories of geoscience organizations and academic institutions. Its GeoRef database provides access to the geoscience literature of the world. Alexandria, Virginia (703) 379-2480. Internet: www.agiweb.org

American Geophysical Union

International scientific society of more than 35,000 researchers, teachers, and science administrators in more than 115 countries, over 30 percent of whom are outside the U.S. Dedicated to advancing the understanding of the earth and its environment in space and making results available to the public. Washington, DC (202) 462-6900. Internet: www.agu.org

American Petroleum Institute

Represents producers, refiners, marketers, and transporters of oil, natural gas, and products. Provides data and information on industry performance, including an annual report on E&P Environmental Performance. Develops guidelines for E&P environmental operations. STEP program encourages responsible environmental operations. Web site includes extensive education information on topics such as the history of oil, materials for teachers, petroleum products at home, and petroleum museums. Washington, DC (202) 682-8000. Internet: www.api.org

Independent Petroleum Association of America

Represents independent oil and gas producers, land and royalty owners, and others with interests in domestic exploration, development, and production of oil and natural gas. Advocates environmental policy being guided by good science, economics, and reasonable goals. Washington, DC (202) 857-4722. Internet: www.ipaa.org

International Association of Drilling Contractors

Promotes safety, preservation of the environment, and advances in drilling technology. Member companies are involved in oil and gas exploration and production, well servicing, oil field manufacturing, and other rig site services. Houston, Texas (281) 578-7171. Internet: www.iadc.org

Sources of Additional Information

Interstate Natural Gas Association of America

Represents U.S. interstate and Canadian interprovincial natural gas pipeline companies. Promotes technologies to reduce methane emissions through EPA Natural Gas STAR Program. Washington, DC (202) 216-5900. Internet: www.ingaa.org

Natural Gas Supply Association

Organization of major and independent producers of domestic natural gas. Interests include the production, consumption, marketing, and regulation of natural gas. Monitors legislation and regulations. Encourages producers to apply cost-effective methane emission reduction strategies. Maintains a natural gas education site on the Internet. Washington, DC (202) 326-9300. Internet: www.ngsa.org

National Ocean Industries Association

Sole national trade association representing all facets of the domestic offshore petroleum and related industries —producers of crude oil and natural gas, contractors, oil field service companies, and others with an interest in the process of exploring for and producing hydrocarbon energy resources from the Nation's Outer Continental Shelf in an environmentally responsible manner. Washington, DC (202) 347-6900. Internet: www.noia.org

Society of Exploration Geophysicists

Promotes the science and education of exploration geophysicists. Fosters the expert and ethical practice of geophysics in the exploration and development of natural resources, in characterizing the near-surface, and in mitigating earth hazards. More than 15,000 members working in 110 countries. Tulsa, Oklahoma (918) 497-5500. Internet: www.seg.org

Society of Petroleum Engineers

Largest individual-membership organization serving professional engineers, scientists, and managers in E&P segments of the worldwide oil and gas industry. Members include more than 50,000 professionals from oil- and gas-producing regions around the world. Facilitates the collection, dissemination, and exchange of technical information concerning the development of oil and gas resources, subsurface fluid flow, and production of other materials through wellbores for the public benefit. Provides opportunities for interested (and qualified) individuals to maintain and upgrade their individual technical competence in these areas. Web site includes a Virtual Suitcase to explore career opportunities in petroleum engineering. Richardson, Texas (972) 952-9393. Internet: www.spe.org

Colleges and Universities

Numerous colleges and universities, including historic black colleges and universities, offer educational courses and degrees in geology, petroleum engineering, and other fields related to oil and gas and the environment. Listings are relatively easy to find via professional organization Web sites or various Internet search engines. Representative of such institutions are:

Louisiana State University

Learn about petroleum engineering, the jobs of drilling, production, and reservoir engineers, and well log analysts on the Craft and Hawkins Department of Petroleum Engineering Web site: www.pete.lsu.edu

New Mexico Institute of Mining and Technology (New Mexico Tech)

Founded in 1889 to advance the geological sciences and mineral industries in New Mexico. Throughout its century-long history, Tech has maintained a tradition of excellence in geoscience. Earth and Environmental Science Department, Socorro, New Mexico (505) 835-5635. Internet: www.ees.nmt.edu

University of Oklahoma

The School of Petroleum and Geological Engineering, rated among the top three petroleum engineering programs in the world, has almost 4,000 alumni, including top executives in Fortune 500 companies. Norman, Oklahoma (405) 325-2921 or (800) 522-0772, ext. 2921. Internet: www.ou.edu/engineering/peteng

The Sarkeys Energy Center includes seven interdisciplinary institutes and a research program encompassing oil and gas exploration, production, utilization, and policy and environmental concerns, involving faculty from the colleges of Geosciences, Arts and Sciences, Law, Business, and Engineering. Norman, Oklahoma (405) 325-3821 Internet: www.ou.edu/sec

Research and Technology Organizations

Gas Research Institute

Research arm of the Nation's gas supply and transportation industry. Its mission is to discover, develop, and deploy technologies and information that measurably benefit gas customers and the industry. Evaluates and transfers information about gas resources and technologies, including E&P environmental technology. Chicago, Illinois (773) 399-8100. Internet: www.gri.org

Sources of Additional Information

International Centre for Gas Technology Information
International forum on gas technology serving senior executives and technical and marketing professionals' information needs. Transfers information on gas technologies to ensure that global gas market needs are met efficiently. Arlington, Virginia (703) 526-7810. Internet: http://www.gtion.org/

Institute of Gas Technology
Independent, not-for-profit center for energy and environmental research, development, education, and information. Performs sponsored and in-house research, development, and demonstration. Provides educational programs and services. Disseminates scientific and technical information in four areas: energy utilization; energy supply; environmental protection and remediation; and natural gas transmission, distribution, and operations. Des Plaines, Illinois (847) 768-0500. Internet: www.igt.org

Petroleum Technology Transfer Council
National clearinghouse, with 10 regional centers, to identify and transfer E&P technologies to enable domestic oil and gas producers, principally smaller independent oil and gas producers, to reduce costs, improve operating efficiency, increase ultimate recovery, enhance environmental compliance, and add new oil and gas reserves. Funded primarily by DOE oil and natural gas programs with additional funding provided by State governments, industry, universities, State geological surveys, and other sources. Washington, DC (202) 785-2225. Internet: www.pttc.org

Education and Environmental Organizations

Ground Water Protection Council
A nonprofit organization dedicated to the protection of the Nation's groundwater supplies. Its mission is to promote the safest methods and most effective regulations regarding comprehensive groundwater protection and underground injection techniques. Meetings, workshops, seminars, and symposia provide forums, educational resources, open communication, and active participation by members who include local, State, and Federal governments, citizen groups, industry, academia, and other parties interested in responsible protection and management of groundwater resources. Oklahoma City, Oklahoma (405) 516-GWPC. Internet: http://gwpc.site.net

Environmental Defense Fund
Nonprofit organization with more than 300,000 members and five regional offices, addressing a broad range of regional, national and international environmental issues. A leading advocate of economic incentives as a new approach to solving environmental problems. Provides environmental information by mail and electronically; participates in environmental education projects; maintains a Member Action Network to influence national environmental policy; works with grassroots groups at the local and regional level in the U.S. and abroad. Efforts include the Alliance for Environmental Innovation, a joint initiative with the Pew Charitable Trust to work with private companies to create environmental change. New York, New York (800) 684-3322. Internet: www.edf.org

National Academy of Sciences
A private, nonprofit society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Under the charter granted to it by Congress in 1863, the Academy has a mandate that requires it to advise the Federal government on scientific and technical matters. The National Research Council, organized in 1916, is the working arm of the National Academy of Sciences and the National Academy of Engineering, carrying out most of the studies done in their names. Most requests for such studies come from government agencies or Congress. Washington, DC (202) 334-2000. Internet: www.nas.edu

National Energy Education Development (NEED) Project
Established by a Congressional Resolution in 1980, and founded on the conviction that an energy-literate public is essential to a coherent and viable energy future. NEED is "Educating for America's Energy Future." Promotes an energy conscious and educated society by creating effective networks of students, educators, business, government, and community leaders to design and deliver objective, multi-sided energy education programs. Herndon, Virginia (703) 471-6263. Internet: www.tipro.com/need or www.energyconnect.com/need

National Fish and Wildlife Foundation
Nonprofit organization, with five regional offices, established by Congress in 1984. Dedicated to promoting conservation and sustainable use of our natural resources through environmental education, natural resource management, habitat protection, ecosystem restoration, and public policy development. Since 1986, has awarded more than 2,550 "challenge" grants using over $100 million in Federal funds, which have been matched with nonfederal dollars to bring more than $300 million to conservation projects. Privately funded partnerships include the Shell Marine Habitat Program to support projects to protect and enhance the Gulf of Mexico ecosystem and the Save the Tiger Fund, an international effort with Exxon to assist in the long-term survival of Asia's remaining populations of wild tigers. Washington, DC (202) 857-0166. Internet: www.nfwf.org

Nature Conservancy
Responsible for the protection of more than eight million acres in 50 States and Canada. Preserves habitats, species, and natural communities by buying the lands and waters they need to survive. Manages the resulting preserves with the most sophisticated ecological techniques available. With partner organizations, has preserved millions of acres in Latin America, the Caribbean, the Pacific, and Asia. Owns more than 1,400 preserves—the largest private system of nature sanctuaries in the world. Arlington, Virginia (703) 841-5300. Internet: www.tnc.org

Sources of Additional Information

National Energy Foundation
Nonprofit provider of educational materials and programs related to energy, natural resources, and the environment. Supported by businesses, government agencies, professional associations, and the education community. Salt Lake City, Utah (801) 539-1406. Internet: www.xmission.com/~nef

Oklahoma Energy Resources Board
Nonprofit organization funded by voluntary industry contributions. Restores abandoned oilfield sites and educates public about the Oklahoma oil and gas E&P industry. Encourages efficient use of energy; promotes environmentally sound production methods and technologies; supports research and educational activities. Oklahoma City, Oklahoma (405) 942-5323 or (800) 664-1301. Internet: www.oerb.com

Oil and Gas Museums

From the grassroots perspective, local oil and gas museums offer excellent opportunities to learn about the evolution of oil and gas E&P technology in the United States. For information, explore local Chamber of Commerce, oil and gas industry, and professional organization Web sites such as www.api.org/edu/museums.htm These museums include:

East Texas Oil Museum at Kilgore College
A tribute to the independent oil producers and wildcatters, the men and women who dared to dream as they pursued the fruits of free enterprise. Kilgore, Texas (903) 983-8295. Internet: http://kilgore.cc.tx.us/attr/etom/etom.html

Healdton Oil Museum
The opening of the Healdton oil field in 1913 set into motion one of Oklahoma's greatest oil booms, establishing southern Oklahoma as a major petroleum-producing area. By 1937, this field, the largest of nine such fields located in Carter County, had produced over 200 million barrels of oil, making it one of the most productive pools in the State. Healdton, Oklahoma (580) 229-0317. Internet: http://www.brightok.net/chickasaw/ardmore/county/healdoil.html

International Petroleum Museum and Exposition
Maintains "Mr. Charlie," an authentic offshore drilling rig, for public viewing. A tribute to the pioneering men and women of an industry that developed a culture based on initiative, perseverance, creativity, and hard work. Efforts under way include a Web site "virtual tour." Morgan City, Louisiana (504) 384-3744. Internet: www.rigmuseum.com

Kansas Oil Museum and Hall of Fame
Founded in 1990 to preserve the history of the oil and gas industry. El Dorado, Kansas (316) 321-9333. For more information see: http://www.greatbend.net/gbcc/tourism/oilmus/

Offshore Energy Center
Operates a state-of-the-art refurbished jackup facility, the Ocean Star, which is a museum, educational attraction, and working drilling rig all rolled into one. Visitors absorb the day-to-day excitement of offshore drilling and production, marine transportation, environmental protection, construction, pipelining—all experienced through three decks of videos, equipment exhibits, and interactive displays. Galveston, Texas (409) 766-STAR. Internet: www.oceanstaroec.com

Penn-Brad Oil Museum
Preserves the philosophy, the spirit, and the accomplishments of an oil country community; takes visitors back to the early oil boom times of The First Billion Dollar Oil Field. Guided tours are conducted by over 100 oil country veterans who volunteer their time to relate first-hand experiences. Talks are illustrated with colorful display items such as yellow dogs and barkers, headache posts and Samson posts, hurry-up sticks and sucker rods, all used to produce Pennsylvania oil. Bradford, Pennsylvania. Internet: http://bradford-online.com

Pennsylvania Historical and Museum Commission Drake Well Museum
Located on the site where Edwin L. Drake drilled the first commercially successful oil well in 1859. Documents the birthplace of the petroleum industry with exhibits, operating field equipment, an extensive photographic collection, and a research library. Titusville, Pennsylvania (814) 827-2797. Internet: www.usachoice.net/drakewell

Texas Energy Museum
Offers a learning experience for both children and adults through multimedia techniques that include rig sounds, motion, light, cinema projection, voice, and photo-mural backgrounds. Exhibits deal with the geology of hydrocarbons and the history of the petroleum industry within a total energy picture. Beaumont, Texas (409) 833-5100.

Spindletop Gladys City Boomtown Museum
A reconstruction of an oil boomtown that appeared almost overnight following the discovery of the Spindletop oil fields in 1901. The site includes a 58-foot granite monument to the Lucas Gusher and is a national historic landmark located on the Lamar University Campus. Beaumont, Texas (409) 835-0823.

Oil and Gas Companies

Corporations are too numerous for a complete listing. Following are three with interesting Web sites:

Chevron
Check out the Exploration Zone for an educational primer about oil production and refining. With simple graphics and nontechnical text, it's great for students and teachers. Internet: www.capitalchevron.com

BP Amoco
Takes a leadership position in addressing climate change and other environmental issues; offers energy educational materials in six languages for teachers and students worldwide as part of its Science Across the World Web site. Internet: www.bpamoco.com and http://www.bp.com/saw/

Conoco, Inc.
Conoco's Web site features short on-line movies about some of the industry's newest and most innovative technologies. These videos provide an excellent tool for understanding how advanced oil and gas exploration and production technology is impacting the world and protecting the environment in which we live, both in the United States and around the world. Internet: www.conoco.com/about/glance/index.html

Sources of Additional Information

Other Government Agencies and Offices

Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and to honor our trust responsibilities to tribes. This mission as related to oil and gas is implemented by several agencies:

Bureau of Land Management, which manages fluid and solid mineral leasing on Federal lands as part of its mission to sustain the health, diversity, and productivity of public lands for the use and enjoyment of present and future generations. Washington, DC (202) 452-5125. Internet: www.blm.gov

Minerals Management Service (MMS), which manages the Federal offshore oil and gas leasing program, including Rigs to Reefs and Safety and Environmental Management Plan activities in cooperation with industry. These activities are part of MMS' mission to manage the mineral resources on the Outer Continental Shelf in an environmentally sound and safe manner and to timely collect, verify, and distribute mineral revenues from Federal and Indian lands. Washington, DC (202) 208-3985. Internet: www.mms.gov, MMS Internet KidsPage: www.mms.gov/mmskids

United States Geological Service, which evaluates and classifies onshore oil, natural gas, geothermal resources, and all solid energy and mineral resources, including coal and uranium on Federal lands, as part of its mission to provide the Nation with reliable, impartial information to describe and understand the earth.
Reston, Virginia (888) 275-8747
Internet: http://energy.usgs.gov

Department of Labor Occupational Safety and Health Administration

Dedicated to saving lives, preventing injuries, and protecting the health of America's workers through regulatory and voluntary programs and partnering with Federal and State agencies to protect more than 100 million working men and women and their 6.5 million employers who are covered by the Occupational Safety and Health Act of 1970. Voluntary Protection Programs recognize outstanding achievements by companies that successfully integrate a comprehensive safety and health program into their total management system. Washington, DC (202) 693-2000 and (202) 693-1999. Internet: www.osha.gov

Department of Transportation Coast Guard

Carries out search-and-rescue missions in and around navigable waters and on the high seas. Enforces Federal laws on the high seas and navigable waters of the United States and its possessions. Conducts marine environmental protection programs; administers boating safety programs; inspects and regulates construction, safety, and equipment of marine vessels, including those for oil and gas E&P. Establishes and maintains a system of navigation aids; carries out domestic icebreaking activities. Washington, DC (202) 267-2229. Internet: http://www.uscg.mil

Department of Transportation Office of Pipeline Safety

Issues and enforces Federal regulations for oil, natural gas, petroleum products, and hazardous liquids pipeline safety. Conducts a voluntary program to advance pipeline safety. Washington DC (202) 366-4595.
Internet: http://ops.dot.gov/

Energy Information Administration

Clearinghouse for statistical information on energy data, including information on natural gas and oil production. Established in 1977, its mission is to develop energy data and analyses that enhance the understanding of energy issues on the part of business, government, and the general public. A KidsPage is under development in cooperation with the National Energy Education Development Project. Washington, DC (202) 586-8800. Internet: www.eia.doe.gov

Environmental Protection Agency

Implements Federal laws designed to promote public health by protecting our Nation's air, water, and soil from harmful pollution. Aims to accomplish its mission by integration of research, monitoring, standard-setting, and enforcement activities. Coordinates and supports research and antipollution activities of State and local governments, private and public groups, individuals, and educational institutions. Washington, DC (202) 260-2090. Internet: www.epa.gov

Agency programs include:

Natural Gas STAR to encourage the natural gas industry to reduce leaks through cost-effective best management practices.

Coalbed Methane Outreach to increase methane recovery at coal mines.

Project XL to allow companies to test alternative approaches that achieve cleaner and cheaper environmental results than would be realized under existing requirements.

Environmental Technology Initiative, an interagency effort supporting more than 250 partnerships and projects throughout the United States to promote improved public health and environmental protection by advancing the development and use of innovative environmental technologies.

Interstate Oil and Gas Compact Commission

An organization of States which promotes conservation and efficient recovery of domestic oil and natural gas resources while protecting health, safety and the environment. Represents the governors of 37 States—30 members and seven associate States—that produce virtually all the domestic oil and natural gas in the United States. Established in 1935, it is among the oldest and largest interstate compacts in the Nation. Oklahoma City, Oklahoma (405) 525-3556. Internet: www.iogcc.oklaosf.state.ok.us

National Governors Association

A bipartisan organization comprising the governors of the 50 States, the commonwealths of the Northern Mariana Islands and Puerto Rico, and the territories of American Samoa, Guam, and the Virgin Islands. Founded in 1908 after the Governors met with President Theodore Roosevelt to discuss conservation issues. Through three standing committees on Economic Development and Commerce, Human Resources, and Natural Resources, the Association's Center for Best Practices, and other activities, the governors identify priority issues and deal collectively with issues of public policy and governance at both the national and State levels. Washington, DC (202) 624-5300. Internet: www.nga.org

Sources of Additional Information

United States Congress

Numerous committees, such as those listed below, have jurisdiction over energy, environment, and science and technology issues and the capability to make national public policy decisions affecting the advancement of oil and gas technology. Washington. DC. More information is available on the Internet: www.senate.gov and www.house.gov

U.S. House of Representatives: Committees on Appropriations, Commerce, Resources, Science, Small Business, Transportation and Infrastructure, and Ways and Means.

U.S. Senate: Committees on Appropriations, Commerce, Science and Transportation, Energy and Natural Resources, Environment and Public Works, Foreign Relations, and Small Business.

On-Line Petroleum Business Information

Numerous Internet sites are maintained by private services. For example:

Oil-Link, a privately owned on-line directory of petroleum-related Internet sites and information, rated #1 by the Dow Jones Business Directory: www.oillink.com

Offshore Technology, a London-based Web site for the offshore oil and gas industry that includes information on current E&P projects and organizations, country-by-country, worldwide: www.offshore-technology.com

Journals and Publications

For more information about the oil and gas industry and advanced oil and gas technologies, talk to your local librarian. The following are just some of the numerous journals and publications on the oil and gas industry.

The American Oil & Gas Reporter

A monthly independent trade magazine on exploration, drilling, and production that also serves as the official publication for 23 oil and gas associations and two biennial oil and gas industry trade shows.

E&P Environment

A biweekly newsletter reporting on environmental issues, technological innovations, and State and Federal regulations affecting oil and gas E&P. Web site links from www.epeonline.com include an Amazing Environmental Organization Web Directory characterized as the Earth's Biggest Environment Search Engine.

Hart's Petroleum Engineer International

A monthly magazine for engineering, management, and operating decision makers engaged in drilling, production, and reservoir engineering worldwide.

Improved Recovery Week

A newsletter published since 1982 on news and developments in worldwide improved and enhanced oil and gas recovery.

Inside Energy/with Federal Lands

A weekly newsletter from McGraw-Hill Companies on Department of Energy programs in energy, science and technology, and nuclear-weapons cleanup, and the Department of Interior's management of energy and minerals on Federal lands.

Journal of Petroleum Technology

Official publication of the Society of Petroleum Engineers, with peer-reviewed oilfield management and engineering articles focusing on practical engineering solutions to oilfield problems.

Oil & Gas Journal

A magazine published weekly by PennWell Publishing Co. on technology, industry news, statistics, and special reports and analyses for the petroleum industry. Other publications include Offshore Magazine and Revista Latinoamericana Magazine, published quarterly in Spanish about the petroleum industry in Latin America.

Energy Alert, Natural Gas Week, Oil Daily, Petroleum Intelligence Weekly, World Gas Intelligence

Five of 12 publications from the Energy Intelligence Group that disseminate market, financial, and technology information related to the oil and gas industry.

Department of Energy Oil and Gas Programs

A primary mission of the Department of Energy's Office of Fossil Energy is to foster advanced, more efficient, and cleaner fossil energy technologies through research and development programs. Planning and implementation of our Natural Gas and Petroleum Technology Programs reflects the collaboration of DOE staff in the Office of Natural Gas and Petroleum Technology in Washington, DC; at the National Petroleum Technology Office in Tulsa, Oklahoma; and at the Federal Energy Technology Center in Morgantown, West Virginia and Pittsburgh, Pennsylvania.

Our overall goals are to (1) reduce the vulnerability of the United States economy to disruptions in oil supply by stabilizing domestic oil production; (2) increase domestic energy production in an environmentally responsible manner by increasing domestic gas production and recovering oil with less environmental impact; (3) ensure energy system reliability, flexibility, and emergency response capability of oil and gas transportation and storage systems; and (4) develop technologies that expand long-term energy options.

For further information on the *Environmental Benefits of Advanced Oil and Gas Exploration and Production Technology*, contact:

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Like any organization, DOE is made up of people — people who care about having a healthy domestic oil and gas industry and a healthy environment. DOE staff are committed to finding real solutions that allow the Nation to benefit from a strong economy and a clean environment. Advanced oil and gas technologies and innovation are part of America's heritage and its future.

We offer our gratitude to the many individuals who made this report possible. Special thanks are extended to Sandra L. Waisley for her efforts on this report.

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Department of Energy Oil and Gas Programs

DEPARTMENT OF ENERGY OUTREACH

National *Washington, DC*

U.S. Department of Energy
http://www.doe.gov
DOE programs, science education, recent DOE news. Links to related government offices and all National Laboratories.

Office of Fossil Energy (FE)
http://www.fe.doe.gov
Fossil-energy-related DOE activities, including news, technology information, publications, speeches, events, issues, international activities, and projects within FE's coal and power, oil and gas, or regulatory areas.

Office of Natural Gas and Petroleum Technology
http://www.fe.doe.gov/programs_oilgas.html
Details on oil and gas research and development projects, with links to Fossil Energy's Strategic Petroleum Reserve and the Naval Oil Shale Petroleum Reserves sites.

National Energy Information Administration (EIA)
http://www.eia.doe.gov
Extensive archive of historical data as well as current facts and figures on energy resources and trends in the energy industry.

Petroleum Technology Transfer Council (PTTC)
http://www.pttc.org
National technology clearinghouse for oil and gas producers, offering software, workshops, and resources for industry, especially small independent producers.

Regions

- West Coast
- Southwest
- South Midcontinent
- Rocky Mountains
- Texas
- Appalachia
- North Midcontinent
- Midwest
- Eastern Gulf
- Central Gulf

Field Offices

- Natural Gas and Oil Technology Partnership (NGOTP) *Albuquerque, NM*
  http://132.175.127.176/ngotp/NGOTP.htm
  Describes research activities of the National Laboratories in partnership with industry, working to transfer new technologies to the oil and gas industry.

- National Petroleum Technology Office (NPTO) *Tulsa, OK*
  http://www.npto.doe.gov
  NPTO news, calendar of workshops, and resources for companies, including valuable software to download.

- Federal Energy Technology Center (FETC) *Morgantown, WV and Pittsburgh, PA*
  http://www.fetc.doe.gov
  Project fact sheets, electronic business center for procurements and on-line publications, as well as a "cool science" educational page for students.

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WZI, Inc.—fact sheet 6 (truck / drill)

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Comprehensive National Energy Strategy

In coming decades, our quality of life will depend significantly on scientific and technological advances supported by today's energy policies:

- Improve the efficiency of the energy system. **Efficient resource use is a fundamental tenet of sustainable development, enhancing overall economic performance while protecting the environment and advancing national security.**

- Ensure against energy disruptions. **Reducing the vulnerability of the United States economy to disruptions in oil supply relies on stabilizing domestic oil production; maintaining readiness of the Strategic Petroleum Resource, our Nation's oil stockpile; diversifying import sources; and reducing consumption.**

- Promote energy production and use in ways that respect health and environmental values. **Improving our health and local, regional, and global environment quality must be integral to domestic energy production. Advanced oil and gas technologies are critical to achieving this goal.**

- Expand future energy choices. **Pursuing continued progress in science and technology will provide future generations with a robust portfolio of clean and reasonably priced energy sources.**

- Cooperate internationally on global issues. **The development of open, competitive international energy markets and facilitating the adoption of clean, safe and efficient energy systems are vital to addressing global economic, security, and environmental concerns. Advanced oil and gas technologies provide opportunities for international cooperation and demonstrating United States leadership.**

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