THE UNTOLD STORY: ENVIRONMENTAL BENEFITS OF ADVANCES IN OIL AND GAS EXPLORATION AND PRODUCTION TECHNOLOGIES

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ABSTRACT

Advances in oil and gas exploration and production (E&P) technologies have been driven by factors, including: (1) economic and market forces such as costs, prices, and competitiveness; (2) maturity of the known oil and natural gas resource base; (3) increased environmental awareness by producers, regulators, and consumers; and (4) demand for cheaper, cleaner alternatives.

Each advance and new generation of oil and gas E&P technology improve efficiency and also yield environmental benefits. These benefits include fewer wells drilled; less surface disturbance (smaller footprint); smaller volumes of waste; avoiding sensitive surface and subsurface environments; reduced air emissions; and less noise and reduced visibility. The environmental benefits are evidenced in all sectors of the E&P industry in conventional and sensitive environments. The following are few examples:

- The advances made in 3-D seismic imaging technology have been the most important developments for the oil and gas industry in the past few decades. With this technology, producers are able to evaluate prospects more effectively and drill fewer exploratory wells, creating less waste, and decreasing the impact of activities on the environment.
- New drilling technologies such as horizontal and multilateral drilling allow oil recovery from previously unreachable areas of the formation. As a result of this technology, developers now need fewer drill sites, access roads, and storage wells. Other advanced technologies, such as coiled tubing drilling and slimhole drilling, are helping operators to reduce drilling waste, minimize equipment footprints, and drill more quietly. In addition, new synthetic drilling fluids now incorporate the higher drilling performance of oil-based muds with lower toxicity and environmental impacts associated with water-based muds.
- Improved reservoir characterization and management technologies and better methods to control the flow of fluids in the reservoir are helping to reduce produced water volumes. For example, rapidly evolving downhole separation and disposal technology has the potential to reduce the volume of produced water by as much as 97 percent and increase oil production by as much as 50 percent.
- Advanced technologies are also allowing operators to explore and produce in environmentally sensitive areas. New acoustical and vibration devices have replaced explosives for generating seismic signals onshore and offshore, reducing noise and protecting marine and animal life. In the Arctic (Alaska's North Slope), use of ice pads and roads, directional drilling and multilateral completions, and annular injection of drilling wastes have reduced the footprint of operations on the fragile tundra and also reduced costs.

INTRODUCTION

In the past three decades, the petroleum industry 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 increasing demand for reliable, low cost supplies of oil and natural gas. The productivity gains and cost reductions attributable to these advances have been widely described and broadly recognized. However, public awareness of the significant and impressive environmental benefits from new exploration and production technology advances remains limited.

By using advanced technologies and efficient practices, the United States (U.S.) oil and gas industry has integrated an environmental ethic into its business culture and operations. The industry recognizes that it is good business to meet high environmental standards, and it demonstrates a commitment to these standards in its research and technology investments, its corporate policies and improved operating practices, and its participation in a host of voluntary environmental protection programs.

As the world's most mature oil and gas province – and home of the world's most rigorous environmental standards – the U.S. has been the site of much of the world industry's innovation in exploration and production technology. Technology innovations have enabled the U.S. industry to remain viable in an energy business where highly competitive global markets determine prices. Although U.S. reserves have declined from 39 billion barrels of oil in 1970 to 22.5 billion barrels of oil in 1997, the industry has developed more efficient E&P technology to enable continued exploration, development, and production despite persistently low crude oil prices. Many of these same technology advances also further our commitment to protecting the environment.

Productivity improvements and enhanced environmental protection in E&P are not mutually exclusive. Today's exploration technology, for example, is boosting industry success rates in locating new resources. The results: fewer dry holes, reduced waste volumes, reduced emissions, 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 means more reserve additions per well, which translates into fewer wells (and less impact from drilling operations) to achieve the same level of reserve.
- ***Smaller footprints.*** Smaller, lighter rigs made possible by advanced drilling technology shrink the footprint of oil and gas operations and reduce surface disturbance. Advances in directional and extended-reach drilling permit extraction of valuable resources without disturbing sensitive habitats and cultural resources.
- ***Cleaner, safer operations.*** More energy efficient drilling and production methods decrease emissions of hazardous air pollutants, nitrogen oxides, particulates, and greenhouse gases associated with electricity and fuel use. Improved vapor recovery technology and low-bleed pneumatic devices reduce emissions of methane, a potent greenhouse gas. Advanced offshore technologies and practices practically eliminate spills from offshore platforms. Better wellbore control translates into enhanced worker safety, lower risk of blowouts, and better protection of groundwater resources.

Innovations pioneered by the E&P industry are now being applied in a wide range of situations and industries. Geological and geophysical technology are used to obtain 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 technologies are predicting groundwater flow patterns. The same principles used to increase recovery of oil, such as thermal and microbial processes, are now applied to clean up spilled oil.

Industry and government both have roles to play in advancing E&P capabilities and environmental performance. Continued investment, both private and public, will be required to advance science and technology for E&P, as well as to speed the application of newly proven technology and practices. Also, the government can encourage innovation in environmental management by embracing a more flexible approach to environmental regulation. In contrast to rigidly prescriptive regulations, a flexible performance-based regulatory framework – one that sets suitable standards and gives industry and other stakeholders sufficient latitude to determine how best to meet them – will yield more effective and economical solutions.

Exploration and Production Trends: Smarter, Farther, Deeper, Cleaner: The oil and gas industry, on the threshold of the new millennium, 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. Operations incorporate high-speed computing, remote sensing and imaging, geologic interpretation, and visualization technology; and use global positioning systems, the latest geographical information systems, and three dimensional (3-D) seismic and 4-D imaging capabilities.

Because of productivity gains from advanced E&P technology, the industry has dramatically increased the ultimate recovery of resources from existing fields and become progressively more successful in locating promising new reservoirs. In turn, higher productivity means less impact on the environment and better protection of our precious resources. The U.S. has been the proving ground for developments on all these fronts, as market-based drivers and regulations 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 industry – created largely to fill gaps in technological strengths – may further accelerate the rate of future innovation.

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,[1] 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 U.S. and worldwide, commits enormous financial resources to specific measures to protect the environment. In 1996, the industry spent over $8 billion for environmental protection in the United States (see Figure 1).

International Protocols: Internationally, 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 U.S. 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 such as British Petroleum (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.

ADVANCES IN EXPLORATION

Searching for hydrocarbons 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 complicate the exploration process. It is a painstaking and very 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 U.S. 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 industry to maintain or, in many cases, improve upon, historical levels of exploration success. Today, experts can interpret geological and geophysical data more accurately, manage 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.

Fewer Dry Holes, More Production and Reserve Additions per Well: Improvements in 3-D and 4-D time-lapse visualization, remote sensing, and other exploration technology allow explorations 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)[2] in the 1970s and 1980s to over 40,000 BOE in the 1990s.

Because of 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

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[1] 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.

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

U.S. from roughly $12 to $16 per BOE of reserves added in the 1970s and 1980s to $4 to $8 today.

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 and untapped zones of hydrocarbons that were bypassed or could not be imaged in the past. Improved computer processing technology and interpretation software allow older seismic data to be reprocessed and reevaluated. 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 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.

More Advances in Exploration Technology: Beyond advanced imaging, other new exploration approaches are being applied 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 making possible 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 the complex geological basins.

ADVANCES IN DRILLING AND COMPLETION

Environmental benefits from drilling and completion advances are significant. For example, since 1985, new exploration and drilling technology has, on average, doubled the amount of oil or gas supplies developed per well. Because of this productivity increase, today's annual reserve additions are achieved with 22,000 fewer wells than would have been obtained 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, because of 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.

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 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. 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 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 (as of 1996). In the U.S., horizontal drilling now accounts for 5 to 8 percent of the land well count at any given time. Horizontal drilling may also allow a producer to contact more of the reservoir, so that more resources can be recovered from a single well.

Environmental benefits of horizontal and directional drilling include:

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

Slimhole Drilling and Coiled Tubing: Slimhole drilling, a technique gaining widespread use for tapping into mature field reserves, significantly decreases waste volumes. For example, a slimhole drilled to 14,760 feet and ending with a 4-1/8-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. Area cleared for drilling locations and site access can be as little as 9,000 square feet, including mud holding pits, up to 75 percent less than that required for conventional operations. In contrast, if technology development had stopped in 1985, drill pads today would cover an additional 17,000 acres of land in the United States.

Coiled tubing technology, a cost effective solution for drilling in reentry, underbalanced, and highly deviated wells, has similarly impressive benefits, such as reduced drilling wastes and minimized 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 results in less disruptive, quieter drilling operations, minimizing the noise impact on wildlife and humans near the well site. Because 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
- Reduce noise and visual impacts
- Reduced fuel use and emissions
- Protection of sensitive environments

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 dissembled 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 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 rig site time, advanced drill bits reduced potential impacts on soils, groundwater, wildlife, and air quality. Figure 2 shows the trend for decreasing drilling time since 1970.

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

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

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

ADVANCES IN PRODUCTION

Rapidly evolving oil recovery technology allows 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. Early producers, relying on natural pressure and primitive pumps, recovered only about 10 percent of the oil in a given field. In contrast, today's producers use an arsenal of advanced recovery techniques to keep oil and gas resources flowing, allowing 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.

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 approximately 6 barrels of water for every barrel of oil. Because 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.

Better Reservoir Management to Reduce Water Production: Improved understanding of reservoir flow mechanics, 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 the Appalachia region), a variety of methods are being pursued to treat and reuse the water or discharge it to the surface without environmental impact. Approaches include hydrocyclones, 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 the management and disposal of produced water—a significant environmental and cost issue for oil and gas operators. In today's operations, water is generally pumped to the surface along with oil, then separated from the oil. Because volumes of produced water can exceed oil production by 10 times or more, companies incur sizeable costs to lift the unwanted water, treat it on the surface, and dispose of it (usually by reinjection into the earth's subsurface). The approach also has the disadvantage of bringing 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 development, 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 produced waters brought to the surface in applicable wells, directly reducing fluid lifting and disposal costs, as well as any associated environmental concerns. New downhole separation technologies promise to cut produced water volumes by as much as 97 percent in applicable wells. Downhole separation can also increase oil production in proportion to the decrease in water production. In many parts of the U.S., 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 increase 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 in 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 significantly. 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 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 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.

SITE RESTORATION

Site restoration strategies today are significantly more environmentally protective than past approaches. In some instances, these strategies actually enhance the environment and create economic benefits. The industry has been responding to the environmental challenges and treating site restoration as a critical operational activity. Specialized teams handle site restoration, 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.

Rigs-to-Reefs: 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. 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 topped and sent to the bottom of the ocean, providing several acres of living and feeding habitats for thousands of underwater species. The first planned rigs-to-reefs conversion took place in Florida in 1979. This approach saves the industry millions of dollars a year and yields economic benefits for States.

Oilfield Pits and Pads to Wildlife Habitats: 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 field 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: Southern 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 drill cuttings was found to be very similar to dredge spoil currently in use as a wetlands creation substrate.

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.

From Oil Fields to Housing: In looking at options for disposing of drill cuttings from its Colombia, South America operations, BP Amoco staff came up with a new answer: using the cuttings as a raw material for bricks. This simple idea has met a vital need in the local community, where building materials had been scarce and expensive. The approach 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.

OPERATIONS IN SENSITIVE ENVIRONMENTS

Alaska's North Slope: Logistical barriers, posed by extremely low temperatures, freezing and thawing of the tundra, and remote locations, once limited drilling in arctic environments. Operators today 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:

<u>Ice Pads and Roads</u>: 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.

<u>Low Impact Exploration Approaches</u>: 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 tracts. To protect the North Slope's fragile tundra, exploratory operations are now conducted exclusively during the winter.

<u>Advanced Drilling Technology</u>: 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 Prudhoe 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 rubbing 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 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 well drilled, drilling footprints, and waste volumes, they have benefited the environment as well.

<u>Reduced Production Pad Size</u>: 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. New production pads now are up to 70 percent smaller than the original Prudhoe Bay pads, and spacing between wellheads has been reduced dramatically. In addition, facilities are built more quickly than previous ones, further reducing construction costs and disturbances to the environment.

<u>Improved Methods for Site Restoration and Enhancement</u>: 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 Alaska Department of Fish and Game.

Wetlands, Coastal and Offshore: Growing national awareness of the environmental significance of wetland 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. Operators employ a variety of advanced drilling and production technologies to operate safely in sensitive wetland and coastal areas. In the wetlands of south Louisiana, for example, ARCO Oil and Gas Company 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.

In drilling an exploratory well in Malaquite Beach, near the Padre Island National Seashore on the Gulf Coast of Texas, Bright & Co. undertook extensive cooperative planning and regulatory compliance efforts with the U.S. Government 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 also minimized the possibility of harmful oil leaks. Because 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 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.

Offshore Operations: 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. 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, allow offshore operators to locate oil and gas resources far more accurately than only a 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, because of state-of-the-art subsalt imaging technology such as Full Tensor Gradient (FTG) imaging and marine magnetotelluric survey.

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. Nearly all Outer Continental Shelf operators are collaborating with the U.S. Government to implement Safety and Environmental Management Programs (SEMP)—voluntary, non-regulatory strategies designed to identify and reduced risks and occurrences of offshore accidents, injuries and spills. As a result, the commitment to safer and smarter operating practices has helped the offshore industry to practically eliminate oil spills from offshore platforms.

Advanced subsea drilling and completion technology also enable 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 seafloor 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 conditions and operational circumstances. Moreover, current measurement-while-drilling technology allows 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 control systems, and minimal sized umbilicals, are now able to connect remote subsea satellite wells to host production facilities tens of miles away.

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.

FUTURE CHALLENGES

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 facilitated by a flexible, responsive government regulatory and policy framework, can ensure a brighter tomorrow.

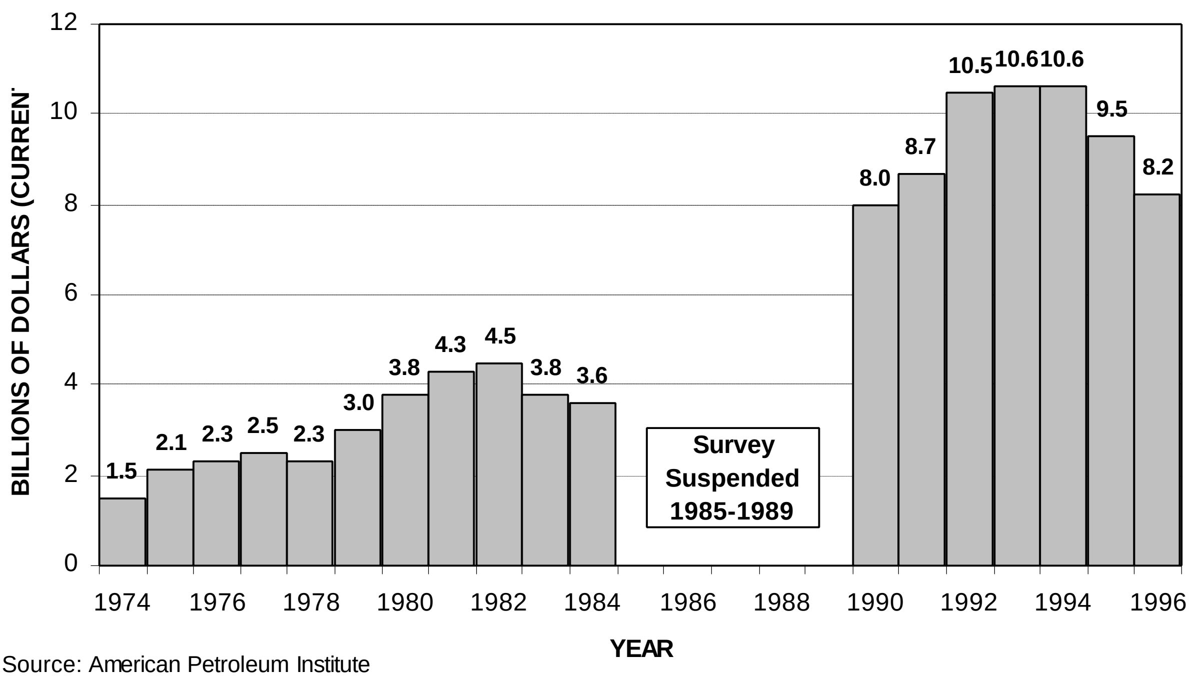
Concerns about global climate change are expected to drive reductions in greenhouse gas emissions associated with the production and use of fossil energy. Scientists cite such phenomena as the melting of the polar ice caps and increases in weather volatility as evidence that climate change is already underway. 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 exploration and production.

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

Ongoing technological progress will be essential in meeting the challenges of the 21st century. Further increases in E&P productivity will allow the industry to keep pace with the world's growing appetite for oil and gas. A competitive drive to drill faster and deeper will overcome the constraints of an increasingly more challenging resource base, both domestically and around the world. New approaches and technology will evolve to address future environmental challenges, particularly global climate change.

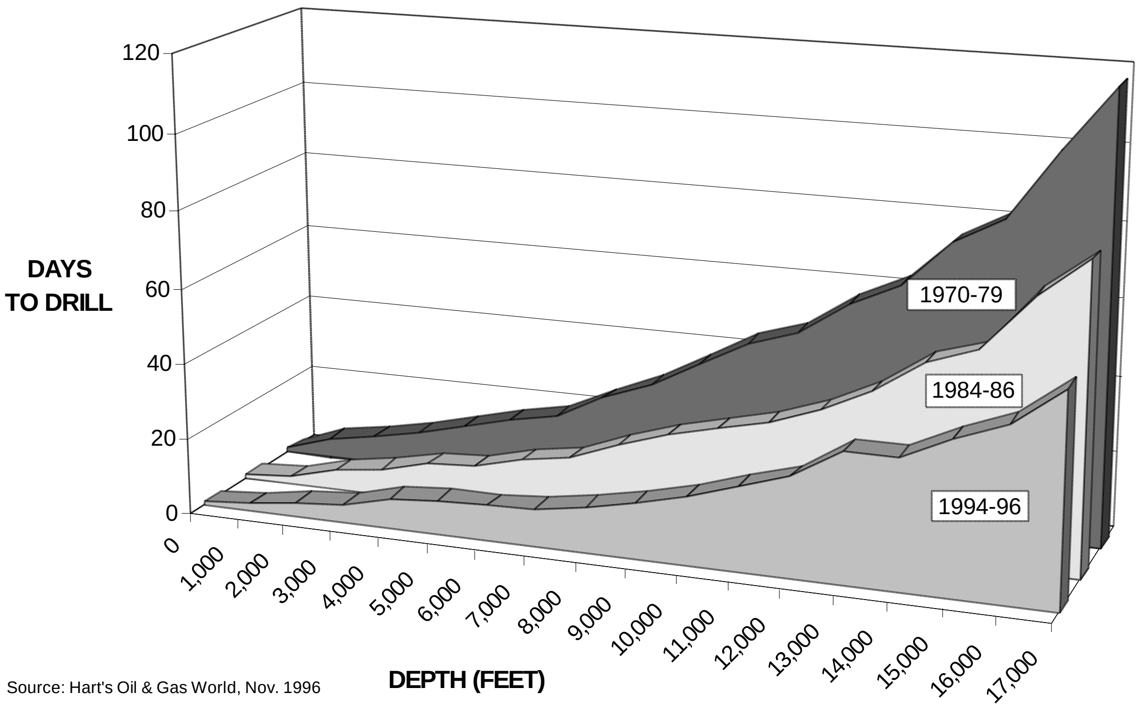
Greater awareness of the industry's achievements in environmental protection will provide the context for effective policy, and for informed decisionmaking by both the private and public sectors. The oil and gas industry will be challenged to continue extending the frontiers of technology. Progressively cleaner, less intrusive, and more efficient technology will be instrumental in enhancing environmental protection in the future.

FIGURE 1 - U.S. PETROLEUM INDUSTRY ENVIRONMENTAL COMPLIANCE EXPENDITURES



Source: American Petroleum Institute

FIGURE 2 - DECREASING DRILLING TIME



Source: Hart's Oil & Gas World, Nov. 1996