To the Bottom of the Sea

by José M. Roesset

Offshore structures have been built in more than 3,000 feet of water. How much deeper can the technology be pushed?

SLIM FILMS

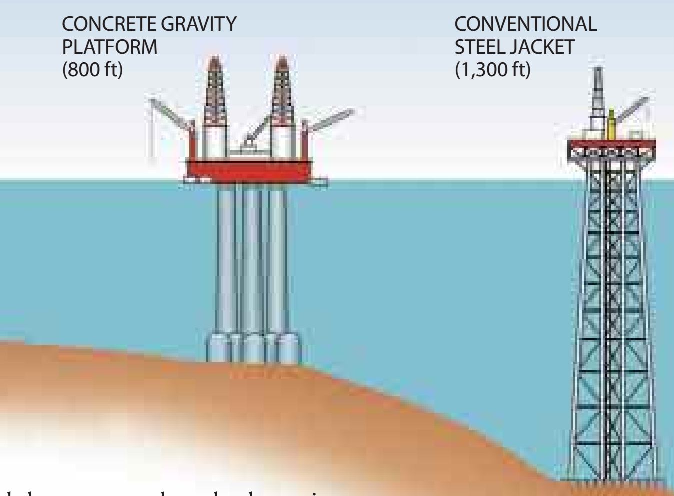
Oil reserves on land and on the continental shelf have become scarcer and more difficult to extract. Meanwhile the worldwide demand for gas and petroleum continues to grow almost linearly. It is not surprising that oil exploration and production have moved into deeper and deeper waters.

In just 50 years the offshore industry has built increasingly impressive platforms to extend oil production from just 20 feet of water to more than 3,000 feet (915 meters). Indeed, the excitement and challenge of structural engineering—once associated with tall buildings, large dams and long-span bridges—are currently in the offshore area. And for depths exceeding a mile, the industry is looking at new solutions, including subsea systems built directly on the ocean floor. With continued innovation, the extraction of oil from water depths of almost two miles will become a reality.

Oil production near water was already taking place in the 1870s in the Caspian Sea at Baku and in the 1880s near Santa Barbara, Calif. But it was not until 1947 that the first steel platform was erected offshore—out of sight of land—in 20 feet of water off the Louisiana coast. In the following years the design and construction of such facilities were based on engineering techniques developed for land structures. To account for unknowns and uncertainties with respect to environmental forces (the ocean waves, for example), soil conditions and the behavior of the materials used, engineers had to overdesign the platforms, making them heavier and stronger than necessary. Even so, the water depths of the structures

FLOATING CITY: The tension leg platform is a new type of offshore structure that could reach depths of 6,000 feet.

DEEPER DEPTHS: The illustration at the right gives the current maximum depths for five types of offshore structures. Not shown is the subsea system (6,000 feet), which is installed directly on the sea bottom with long pipes connecting to the shore or to an existing platform in shallower water. By making steel jackets more pliant and by securing them with guys, mooring lines or deep piles, engineers have extended such towers to 1,800 feet, and further improvements could increase that to 3,000 feet. Some experts believe that tension leg platforms and spars could be built in up to 6,000 feet of water and that modified tankers and subsea systems could be pushed to more than 10,000 feet.



have increased steadily and quickly, from 100 feet in 1955 to more than 1,300 feet in 1988 (Shell's Bullwinkle platform in the Gulf of Mexico).

All these projects were steel jackets—structures that rely on a frame of metal trusses for support. For shallow waters, the platforms were fabricated as a single unit and carried on a barge to the desired location, where the unit was launched into the ocean. A crane or derrick on another barge then picked up the structure and placed it vertically on the sea bottom. Piles were driven through the legs to the desired depth, and the deck units were welded into place. For such offshore platforms, the piles were the main structural elements and the jacket provided the needed bracing.

But as the water depth increased and the jackets got larger, hoisting them upright became unwieldy. One solution was to fabricate and install the jacket in multiple parts—a strategy used in 1978 by Shell to construct the Cognac platform in more than 1,000 feet of water in the Gulf of Mexico.

In the North Sea the much harsher environmental conditions, the stiffer soils on the sea bottom and the familiarity of European countries with concrete construction led to concrete gravity structures as an alternative or a complement to conventional steel jackets. Instead of pile foundations, these behemoths rely more on their substantial weight and large base diameter for their stability. The massive base, which also serves as storage for petroleum between tanker pickups, is usually built in a dock and towed to a protected deeper-water location, where the construction of the legs takes place. The deck is sometimes installed there as well, and the completed structure is then towed to the installation site.

Like skyscrapers and bridges, an offshore platform must withstand gravity (a structure's own dead weight could, for example, cause it to collapse on itself), wind and—depending on its location—ice, snow and even earthquakes. But deep-sea structures must also endure waves and currents, and it is these hydrodynamic forces that make such projects different from most other civil engineering efforts.

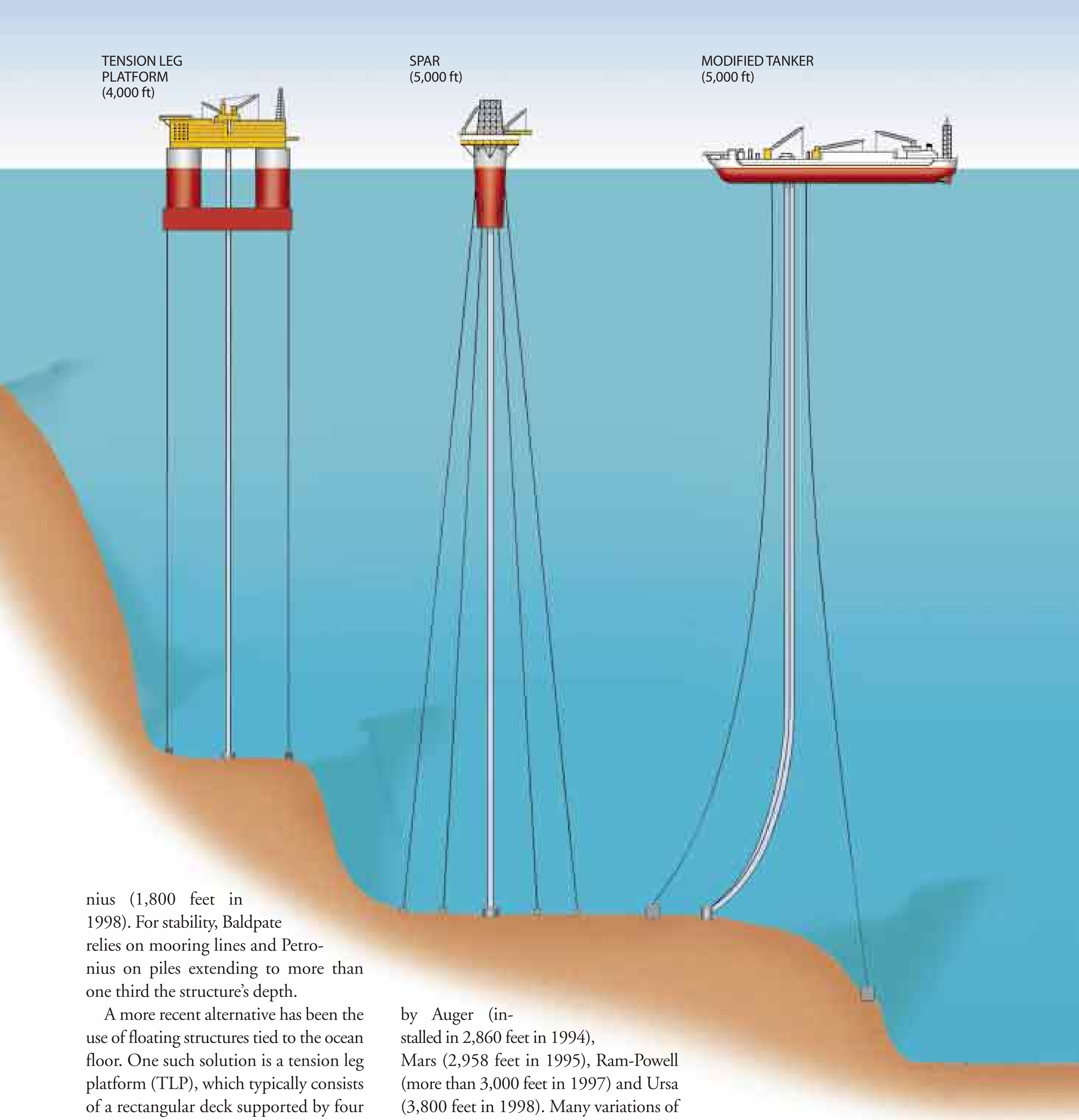
Waves and currents affect offshore structures differently. The action of waves is concentrated near the water surface, and the forces associated with them dissipate rapidly with depth. Current forces, on the other hand, subside much more slowly. Thus, although wave forces may be more significant for traditional jackets in shallow and intermediate waters, the relative importance of currents grows with greater depths. In the Gulf of Mexico, strong loop currents and the subeddies they spawn, as well as recently detected currents at great depths, are a major consideration.

To determine the wave and current forces requires knowledge of the water particle velocities and accelerations as well as the motions of the main structural elements and other basic components, including the pipes, risers, mooring lines and tethers. Obviously, the loads vary with time, so the accurate prediction of how the structure will react to them requires, in principle, complex dynamic analyses.

In the past, engineers typically neglected dynamic effects when designing shallow-water steel jackets. This omission was acceptable because the structures were very rigid against the dynamic forces. In engineering parlance, the natural period of a steel jacket in shallow waters is about one second or less. (In other words, the structure would have a tendency to vibrate with the beats spaced roughly one second apart, just as a guitar string of a specific length and material will emit a note of a certain pitch.) The period of the design waves, on the other hand, is normally around eight to 14 seconds, depending on the part of the world where the platform is installed.

But construction in deeper waters has led to taller—and inherently less stiff—structures that are much more susceptible to dynamic effects such as those caused by waves. For instance, the natural period of Shell's Cognac platform was reported to be roughly four seconds. For greater depths, the natural period of conventional steel jackets would approach that of the waves, and thus the dynamic effects would become amplified through resonance. (Think of a child soaring higher and higher on a swing because her parent pushes her in synchronicity with her motion.)

Because building a very rigid structure in deep water would be prohibitively expensive, engineers chose a different solution: making the platforms more flexible so that their periods far exceeded those of the waves. This approach led to Exxon's Lena (built in some 1,000 feet of water in 1983), Amerada Hess's Baldpate (1,700 feet in 1997) and Texaco's Petro-



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nius (1,800 feet in 1998). For stability, Baldpate relies on mooring lines and Petronius on piles extending to more than one third the structure's depth.

A more recent alternative has been the use of floating structures tied to the ocean floor. One such solution is a tension leg platform (TLP), which typically consists of a rectangular deck supported by four columns at the corners. Below the water surface, pontoons connect the columns, and four bunches of multiple vertical tendons, one for each column, secure the entire assembly to the sea bottom. The buoyancy of the structure creates tension in the tendons, and the structure behaves as an upside-down pendulum. TLPs have played an important role in the deep waters of the Gulf of Mexico, as evidenced by Auger (installed in 2,860 feet in 1994), Mars (2,958 feet in 1995), Ram-Powell (more than 3,000 feet in 1997) and Ursa (3,800 feet in 1998). Many variations of the classical TLP with different sizes and numbers of legs or tether bunches have been proposed and used recently, such as in British-Borneo's Morpeth field (1,700 feet in 1998).

Another variation is the spar concept, which consists of a cylindrical hull anchored with mooring lines that radiate from the center of the floating structure. Two spars have been installed in the Gulf of Mexico: Oryx's Neptune (1,900 feet in 1997) and Chevron's Genesis (2,600 feet in 1998), with several others under design or construction. Still another option is to use a semisubmersible structure (referred to as a floating production system) that has a hull like a TLP's but is held in place with catenary mooring lines. Also, modified tankers (called floating production storage and offloading systems) secured to the sea bottom with mooring lines are being used in many parts of the world but not in the Gulf of Mexico.

The new structures are very pliant, with natural periods much longer than those of ocean waves. Such flexibility, however, leads to other potential problems. Engineers must consider that a structure—particularly when it is limber—can vibrate at frequencies higher than the one associated with its natural period (just as overblowing into a flute results in higher notes). For TLPs, spars and other buoyant platforms, various nonlinear effects must be investigated.

Vibrations can also be caused by vortex shedding, which occurs when waves and current move around an object, spawning vortices that can make the body undulate [*see illustration on opposite page*]. Even small waves cause periodic movements that can contribute to fatigue failure, similar to the way a metal paper clip will eventually snap if a part of it is bent back and forth repeatedly.

To study such effects, researchers must develop more accurate methodologies to compute the nonlinear wave kinematics, hydrodynamic forces and structural responses. Much has been accomplished recently in these fields, but numerous problems require further study.

In addition to computational analyses, scale models in wave tanks have been used to study structures that were later installed at great depths in the Gulf of Mexico and in the North Sea. Similar to wind-tunnel tests for aircraft, such experiments helped to validate proposed designs by yielding results that were then compared with analytical predictions. Tests of North Sea platforms led to the discovery of previously unknown phenomena, such as ringing and springing of TLPs, in which nonlinear effects cause the structure to vibrate vertically. Yet even model tests are limited in their ability to determine the true behavior of a platform in the ocean. Researchers are currently developing computer simulations that fully take into account nonlinear hydrodynamics to complement the wave-tank experiments.

A factor that must be considered in such analyses is damping—the ability of a structure to dissipate energy while vibrating, thus minimizing the effects of dynamic forces. But damping for offshore platforms is normally very small; it is mainly associated with vortex shedding around the hull, tethers and mooring lines. These effects are difficult to reproduce in lab experiments and to incorporate in computer models. Although numerical solutions are under development, much work remains before they can be validated and incorporated into wave-tank simulations.

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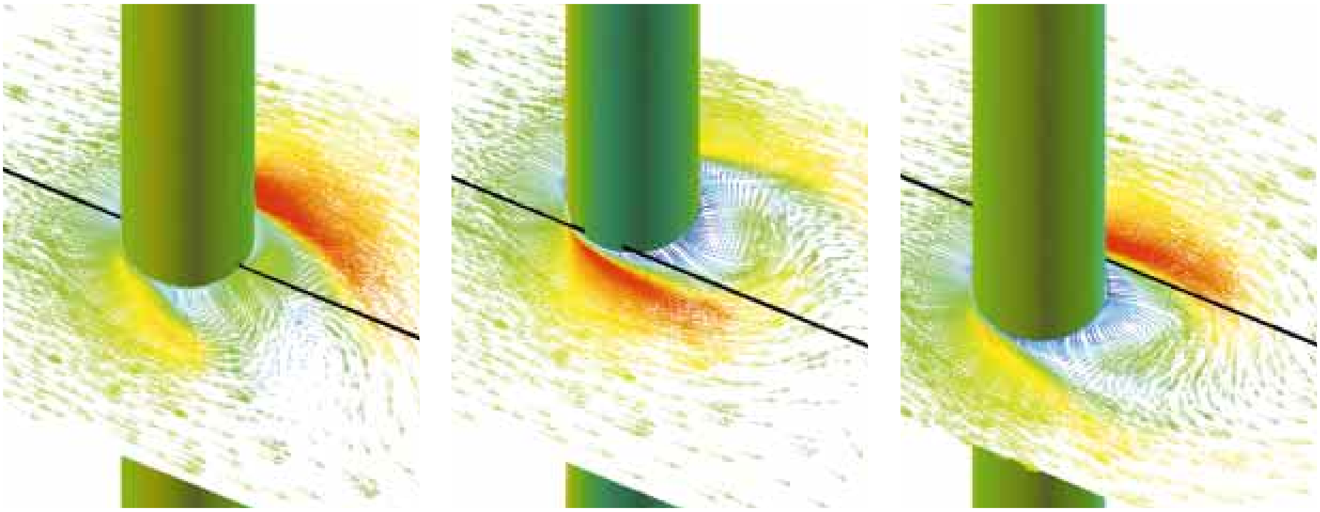
Most of the structural solutions for deep water consist of a large floating hull attached to the sea bottom by either vertical tethers or mooring lines, or both. They essentially consist of a combination of large-diameter bodies (hull), for which diffraction effects are important, and long slender members (tethers, mooring lines and pipes), for which drag (friction from moving water) must be considered. Although analysis of these different components is usually performed separately, an accurate prediction of the behavior of the complete platform requires the coupled analyses of all the components.

One approach for building TLPs and other deepwater floating platforms is to use composite materials that are resistant to corrosion and fatigue failure. These materials can be tailored to specific stiffnesses and strengths, resulting in weight reductions that then lead to greater overall economy. For one thing, a hull that is lighter can be made smaller with the resulting structure still buoyant even though it displaces less water. The size decrease has an advantage: waves will have less surface area to push on, and the structure will thus require less extensive mooring systems and anchor piles for stability. In fact, every pound reduction in weight of the hull of a TLP can ultimately bring down the total cost of the platform by $4 to $5.

Phenolic materials have already been used for the floor gratings, stairs, partitions and even bearing walls of TLPs, saving millions of dollars. More substantial cost reductions could be achieved if the tethers, mooring lines and risers (vertical pipes that transport the petroleum products up from the well) could also be made of composites consisting of a resin matrix with glass or carbon fibers, or a combination of both.

The main obstacle is a lack of knowledge about the long-term underwater behavior of these materials. Much research remains to be done to determine their aging and degradation, among other effects. The impracticality of having to wait 30 or 50 years to gain the necessary experience before using the new materials has motivated the development of instrumentation and nondestructive evaluation techniques that can monitor their performance as they are being used underwater. This capability is crucial because a composite pipe, for example, can suffer significant internal damage and deterioration before any external symptoms become visible.

Because of the difficulties of constructing offshore platforms in deep water, an increasingly popular alternative has been to install the well control equipment—called "Christmas trees" for historic reasons (on land the pipes and valves were stacked and resembled Christmas trees)—directly on the ocean floor. Such systems rely on long pipelines that connect to the shore or to existing platforms in shallower water. Examples include Petrobras's Marlim project off the coast of Brazil and Shell's Mensa in the



KARL W. SCHULZ AND JOHN KALLINDERIS *Offshore Technology Research Center*

A RIVER RUNS AROUND IT: When a fluid flows around an object, it can spawn alternating vortices (*shown in red, from left to right*). This phenomenon, called vortex shedding, can cause the object to undulate (the black line is stationary). The motion could then become amplified through resonance, leading to potential problems.

Gulf of Mexico, which was installed in 5,400 feet of water.

But the technology to pump mixed products (fluids as well as solids and gas) from a deepwater well needs additional investigation. One option is to separate the different components directly on the seabed. The success of such systems will depend on the development of equipment, including manifolds, control systems, actuators and meters, that can perform reliably at great depths.

The petroleum industry has already been considering the possibility of drilling in water as deep as 10,000 feet—nearly two miles. The task is daunting, given the extreme conditions. For starters, at a depth of 10,000 feet the water pressure is more than two tons per square inch, greater than 300 times the atmospheric pressure. Other complications include the potential presence of geohazards such as overpressured layers of sand that, when drilled through, erode the support around the casing, making further operations impossible. Additionally, at 10,000 feet the use of a drilling riser becomes problematic because of the pressures caused by the long mud columns inside the pipe. An alternative currently being explored is riserless operation, but the behavior of an unprotected rotating string for drilling under the combined action of waves and currents and the associated vortex-induced vibrations is largely unknown.

Additional research is also needed to maintain the position of the drilling vessel, particularly under strong winds and waves. To study such issues, Conoco recently deployed a new drill ship, the *Deepwater Pathfinder,* that boasts important innovations, including the use of satellite signals and six high-powered thrusters to maintain the vessel's position to within an average of less than seven feet without an anchor.

Of course, as drilling moves farther offshore, the potential for accidents continues to be a concern, and preventing such mishaps and mitigating their impact on the environment should they occur requires basic research in several specific areas. For example, to determine the effects of a blowout in very deep waters, scientists have been incorporating knowledge of ocean currents and other conditions into computer-simulation models to predict accurately the path of the oil and the extent of the spill. Furthermore, some of the most serious accidents, including the Piper Alpha disaster of 1988 and the *Exxon Valdez* incident of 1989, have highlighted the need to consider various human factors. Effective solutions will depend on cooperation between industry, research organizations, certification agencies (such as the American Bureau of Shipping) and regulatory bodies (the Minerals Management Service in the U.S., for instance).

In 1994 the daily production from deepwater drilling in the Gulf of Mexico was less than 100,000 barrels. By 1996 that figure had increased to 275,000, and it is expected to exceed one million by the end of 1999. This dramatic success in the Gulf of Mexico represents just the initial phase, and efforts will also intensify in other areas, including off the coasts of Brazil and West Africa. But this anticipated expansion—Marathon Oil recently announced an important find at 7,200 feet in the Gulf of Mexico—cannot occur without continued engineering innovation.

The technology needed for the safe production of oil in up to 3,000 feet of water is currently available, and the industry is able to reach water depths of 5,000 feet without any major foreseeable problems. Greater depths, though, will require no small amount of research and development, both at the basic and applied levels, to overcome a number of technical hurdles. SA

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JOSÉ M. ROESSET is director of the Offshore Technology Research Center, which is jointly operated by Texas A&M University and the University of Texas at Austin.