

# Historical Development of the Offshore Industry

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## 1 INTRODUCTION

The process for finding and developing oil and gas fields is sequential comprising three major stages: exploration, drilling, and production. Offshore engineering is required and has been applied throughout each of these stages, resulting in the industry's steady advance into deeper water and more challenging environments over the past 120 plus years.

Oil and natural gas was in high demand in the late 1800s due to heavy industries, such as railroads and the construction of homes, buildings, and chemical plants that used oil for fuel and lubrication. Construction techniques used on land and near-shore marine provided the initial step into shallow water. At each step into deeper water, engineering

design grew by applying fundamental principles to overcome increased current, wave, and storm activity, by developing new materials and standards, and by continuously improving safety systems. What follows is an overview of the major fixed and floating systems that enable the industry to find and develop hydrocarbon resources in some of the most remote and inhospitable regions of the earth's oceans.

## 2 EXPLORATION

To explore areas covered with water, geophysicists first adapted onshore geophysical equipment, sensor cables (streamers), and recording equipment, so that streamers could be towed behind a vessel of opportunity, giving birth to marine seismic acquisition. The industry developed air guns to hold and released high-pressure pulses of compressed air to "shoot" waves of sonic energy into the water and "illuminate" the rock formations below the seabed. Vessels of opportunity, used to tow the equipment, were eventually replaced with purpose-built vessels, designed for the special needs of marine seismic acquisition.

### 2.1 Paradigm shift: 2D to 3D datasets

From the late 1940s to 1980s, marine seismic was collected as two-dimensional (2D) data. A single vessel, towing a single streamer, produced an image similar to a geologic cross section, a "slice" through the water column and earth beneath. In the 1990s, advances in computer technology and vessel design increased towing capacity allowing marine seismic contractors to tow more than one streamer and to begin collecting "swaths" of data (Figure 1). Initially, this practice was used to improve the standard 2D image. However, competition quickly led to contractors towing four or more streamers and shooting surveys with multiple



**Figure 1.** Seismic vessels tow air guns and multi-streamer arrays to collect seismic data. (Reproduced with permission. © Petroleum Geo-Services, Inc, 2016.)

vessels. By spreading the streamers more widely behind the vessel, a three-dimensional (3D) volume of data was produced.

Seismic streamer control and vessel design improvements allowed surveys of different sizes and density to be gathered. Surveys could be tailored to the needs of regional exploration, as well as detailed field development. The resolution and detail of the survey is controlled by changing the shooting density (relative sensor spacing) and the lateral separation of the streamers during data collection.

These 3D datasets could be analyzed and viewed from any angle using specialized computer graphics and software, greatly enhancing an interpreter's understanding of the rock systems imaged. Now, the world beneath the seas was open and understandable as never before. Oil companies quickly invested in interpretation equipment (computers, software, and special display technology) and developed more prospects in deeper waters.

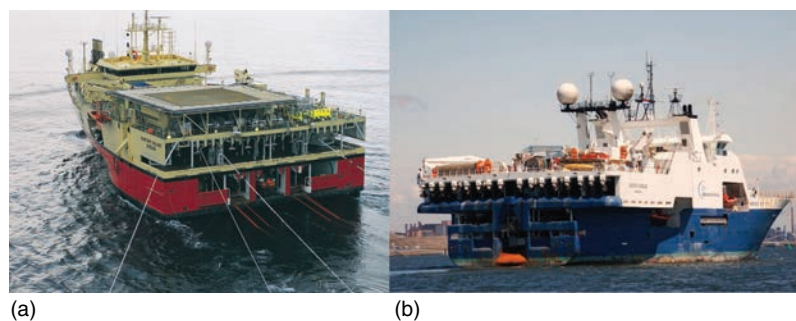
### 2.2 Seismic vessels

The shift from 2D to 3D seismic in the mid-1980s to early 1990s required increased towing capacity to pull multiple streamers. Streamers are deployed behind the vessel from large onboard reels and then spread (separated) from each other by vertical wings (hydrofoils) on either side of the streamer array. The existing 2D vessels of the day could tow up to 6 streamers with some limits on streamer length. But the

industry wanted more, so new larger vessels were designed by naval architects with innovative designs to accommodate towing up to 24 streamers.

A radical “delta-shaped” vessel was built by Petroleum Geo-Services (PGS) ASA in 1995 to provide a wide back deck for the large number of streamers it would tow (Figure 2). The Ramform™ design revolutionized seismic data collection, since the wide beam of the vessel provided more than double the internal space of a traditional 2D vessel. PGS added supercomputers and onboard processing of navigational data, as well as additional recording capacity, to capture the data stream from the sensor array. Onboard processing of the data allowed interpreters to view and work a dataset more quickly than ever before. The addition of satellite communication permitted data streaming to computing centers for final processing and distribution, reducing delivery times.

Intense competition to gather 3D seismic data led to the development of another vessel design advance in 1999, this time by WesternGeco (now part of Schlumberger). The new design created greater efficiency by adding a wide “wing” deck above a larger, efficient, trawler-style hull, thereby gaining the advantages of both traditional ship hulls and the wide sensor array deployment needed for 3D data collection. Larger engines and onboard electric generator sets allowed the vessel to be all-electric, eliminating traditional hydraulic fluid systems to operate streamer deployment and collection machinery. This saved weight, reduced complexity, and



**Figure 2.** PGS developed the delta-shaped Ramform™ seismic vessel (left) to tow multiple streamers for 3D seismic surveys, followed by Schlumberger's building of the *Geco Eagle* seismic vessel (right), which combined trawler ship design with improved wide seismic array deployment. (Reproduced with permission. © Petroleum Geo-Services, Inc/Western Geco, 2016.)

created a very wide, open back deck for hydrofoils, steamers, and air gun operations.

### 3 DRILLING RIGS

#### 3.1 Introduction

High demand in the late 1800s led the industry to seek new oil fields in the shallow waters off California. The first offshore drilling of wells originated in Summerland, California, in 1887 (Grosbard, 2012; AOGHS (American Oil & Gas Historical Society), 2014). H. L. Williams built piers out into the Santa Barbara Channel and drilled wells using wooden wharves and drilling towers constructed on the piers to protect workers and house drilling equipment (Figure 3). The first well drilled at Summerland Field was on a pier extending 300 feet seaward of the beach. Multiple wells were drilled after oil was discovered farther from shore; the most distant well was drilled on a pier built about 1200 feet out from land. The first offshore well in California proved there were commercially attractive volumes of oil in the seabed offshore, leading to the development of improved technologies that could operate in deeper waters.

The practice of building drilling towers on piers spread to Ohio in 1891, where productive wells were drilled in Ohio's Mercer County Reservoir (Grand Lake St. Marys). Other lakes in the United States (Caddo Lake, Louisiana) and overseas (Lake Maracaibo, Venezuela) were also tested and produced oil using simple free-standing platforms, based on the same construction techniques used for piers.

In 1936 the State of Louisiana sold its first oil and gas lease in the Gulf of Mexico (GOM) to Pure Oil Company in West Cameron Block 2. Pure modified the pier approach by building a wooden platform supported by timber pilings in 14 feet of water to drill the first oil well in the GOM. The well was started in 1937 and discovered oil in March

1938, opening Creole field over a salt dome just offshore Louisiana (Dobie, 1973).

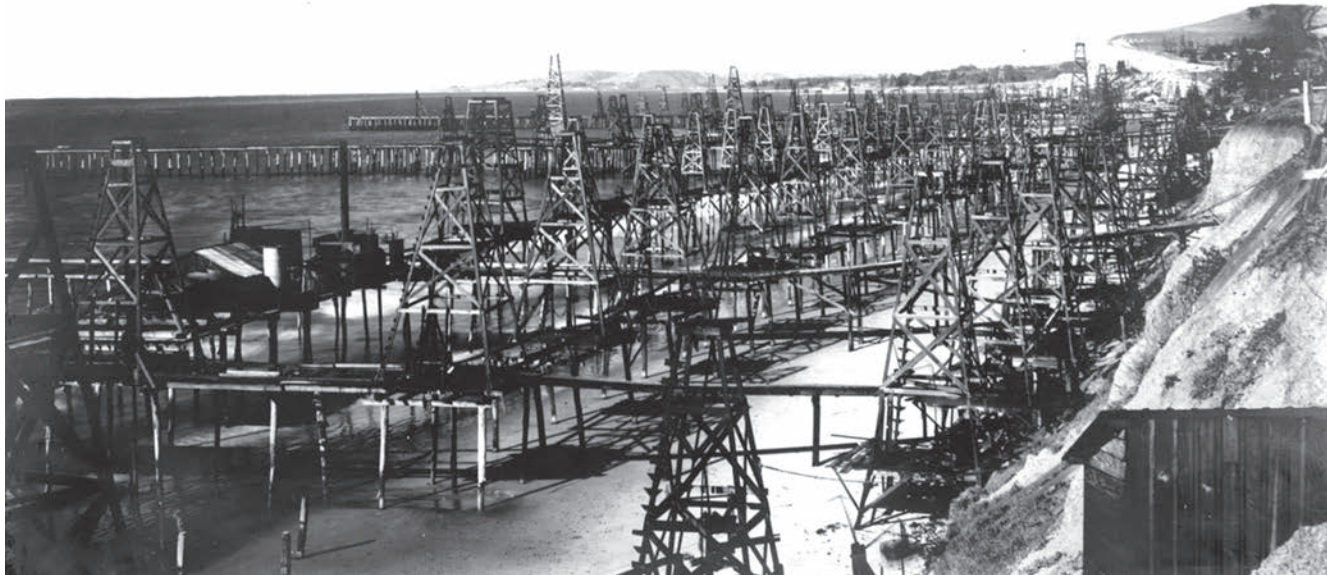
Offshore drilling continued using similar methods to drill in shallow water. In October 1947, Kerr-McGee stepped about 11 miles out into the GOM to drill offshore in 18 feet of water. Now known as *Anadarko Petroleum*, Kerr-McGee Oil Industries completed the Ship Shoal Block 32 well on November 14, 1947, yielding the first producing offshore oil well out of sight of land in the GOM (Figure 4).

Drilling and developing this well required the use of unproven techniques, which once proven were then used to develop resources further offshore. This evolution of technology is a process that the industry has used over the intervening years to advance into deeper water by applying existing technology and developing new technologies to address new challenges.

#### 3.2 Submersibles and inland barges

Offshore drilling rigs come in two fundamental types: bottom-supported and floaters. Most offshore drilling rigs used for exploration are known as *mobile offshore drilling units* (MODUs). As the industry moved into deeper water, it became uneconomic to build new, nonmoveable structures for each well, since many wells did not find oil (they were dry). The industry's engineers developed a solution. First, they used barges (drilling barges or submersibles) secured with pilings (posted) at the corners and ballasted onto the seabed. These vessels could carry a permanent drilling system including a steel tower (derrick) and were moveable and suitable for shallow water. Numerous exploratory wells could be drilled with these submersible barges, allowing companies to reserve platform building for those wells that produced oil.

Drilling barges are sufficient for shallow water such as lakes, swamps, rivers, and canals. They are typically smaller, floating vessels that are moved from place to place by



**Figure 3.** The first offshore drilling used land drilling techniques staged from wooden piers and towers, built into the Santa Barbara Channel off California. (Reproduced from [https://en.wikipedia.org/wiki/Summerland,\\_California#/media/File:Oil\\_wells\\_just\\_offshore\\_at\\_Summerland,\\_California,\\_c.1915.jpg](https://en.wikipedia.org/wiki/Summerland,_California#/media/File:Oil_wells_just_offshore_at_Summerland,_California,_c.1915.jpg). Public Domain.)



**Figure 4.** Kerr-McGee drilled in 18 feet of water using a drilling tender, *Frank Phillips*, a converted US Navy barge. (Photo Courtesy of Kerr-McGee.)

tugboats. Drilling barges are unable to withstand strong currents or waves in large, open-water areas.

### 3.3 Jackups

There were several hulls modified to be jackup drilling rigs in the early 1950s. Zapata Off-Shore's *Scorpion* was the

first purpose-built offshore jackup rig. This concept was developed by R. G. LeTourneau in 1953 when he came up with an idea to safely drill oil and gas offshore by creating a drilling vessel that could withstand all weather conditions (Drilling Contractor, 2005). The key was to build a vessel that could be quickly moved to the drill site and stabilized before drilling. A structure of lattice-style support legs lowered to the sea floor solved the problem (Figure 5).

LeTourneau proposed his idea to George H. W. Bush, who was head of Zapata Off-Shore Company. The idea was accepted, and construction on the first jackup rig began in late 1954 at LeTourneau's shipyard on the shores of the Mississippi River at Vicksburg, USA. The completed project cost about \$3 million.

On March 20, 1956, *Scorpion* was christened, and the 140-foot rig was towed to a location offshore Port Aransas, Texas where it drilled its first well for Standard Oil Company of Texas. LeTourneau jackups quickly became very popular, because they were the only rigs on the Gulf Coast that could tolerate windy and disruptive weather conditions.

The industry settled on a three-legged system as the most efficient and stable for drilling. Jackups are towed to a location with the legs elevated. While the hull floats, the legs are lowered to the sea bottom using an electric rack and pinion or hydraulic jacking system. The hull is raised on the legs or "jacked" up high above the water surface to provide a safe air



**Figure 5.** The first jackup rig, *Scorpion*, was built for Zapata Offshore Company for use in the Gulf of Mexico. (Reproduced with permission. © Rowan Companies.)

gap during stormy weather. This air gap allows large waves to pass under the jackup without damaging the hull.

Continuous improvements have led to larger deck areas, longer legs for drilling in deeper water, and multideck hulls for personnel accommodations and storage of drilling equipment and consumables. Jackups can now drill in water depths of over 500-foot deep, reaching across most of the world's continental shelves, and can drill to depths of 40,000 feet or more into the seafloor.

Advantages of jackup rigs include stable work platforms, lower capital cost than floating rigs, and the versatility to work over a production platform (fixed structure) in open water. Most jackups can be upgraded with improved drilling equipment but are limited by their deck load and seaworthiness. Early jackups were designed for a service life of 12–15 years, but with improved technology and proper maintenance, they can remain operable for more than 35 years.

The two common types of jackup rigs are the mat slot (MS) and independent cantilever (IC). The MS jackup has a bottom plate (mat) attached to its legs. Both the hull and mat have a rectangular cutout (slot) on one side. The slot fits around small fixed platforms, so that the drilling system can be positioned over the wellheads on the platform. Once positioned around the platform, the MS rig's legs are jacked down together, so that the mat supports the rig on the seabed. MS jackup rigs are limited to about 250 feet of water, are particularly useful in areas having unconsolidated (soft) seafloor conditions, and tow slower than other rigs.

The IC rig has become the standard jackup because of its versatility and is the largest bottom-supported rig type. The hull does not have a slot and the legs move independently

(Figure 6). An IC rig's legs are supported by “spud cans” at the bottom of each leg. After the legs are jacked down, seawater is pumped into tanks in the hull, adding weight to force the legs into the bottom sediment. This loading process is repeated until the legs stop sinking into the ocean floor and the jackup is stable.

To cantilever over a platform, the hull has a set of rails over which the drilling tower and system rests. Once positioned next to a platform, the legs are jacked down to support the rig and the drilling system is extended using the rails, away from the main hull, and over the platform. This allows the IC jackup to service wells on fixed platforms of any size.

The type of jackup rig used depends on the work to be done, rig availability, water depth, seafloor conditions, and metocean and weather conditions expected.

### 3.4 Semisubmersibles

Semisubmersible rigs (semis) are floating MODUs that can drill in deep water up to 12,000 feet or more (Figure 7). This rig type is a column-stabilized vessel, which is transparent to much wave energy, minimizing motions due to forces on the vessel. Semis float on large horizontal pontoons with large vertical columns (legs) connecting to a hull that is held above the water. Over the development history of these rigs, the number of legs has changed with the designs: 3, 4, 5, 6, and 8-legged semisubmersibles have been built. The present trend is to build robust 4-legged semis, reserving 6-legged semis for harsh environments.

Semis have ballasting systems in the pontoon hulls to provide stability when on a drilling location. Moored semi designs depend on a set of 6–12 large anchors attached to chains and ropes of wire or polyester to hold the semi in place. Other semi designs use automated dynamic positioning (DP) systems to keep the semi in place. These systems ensure that the vessel is secure enough to maintain position in heavy seas and storms.

The first semi, *Blue Water Rig No. 1*, was developed by Shell in 1961 by converting a submersible rig, which was used for drilling in shallow water, into a floating unit. It was built on pontoons with four columns, one at each corner of the vessel, supporting a deck and drilling tower. Originally intended to be towed and set on the sea bottom, the vessel was stable under tow with partially ballasted pontoons, so Shell and the Blue Water Drilling Company decided to drill with the vessel while it floated, thus creating a new class of drilling rig, while extending the water depths in which the rig could operate.

The first purpose-built semi was the *Ocean Driller*, a “V”-shaped, three-column vessel built in 1963 in New Orleans, Louisiana, by Ocean Drilling & Exploration



**Figure 6.** The *Joe Douglas*, an independent leg cantilever jackup built in 2011, can drill in 350 feet of water. (Reproduced with permission. © Rowan Companies.)



**Figure 7.** Modern high-specification semisubmersible rigs can drill in 12,000 feet or more of water to depths of 40,000 feet into the earth. (Reproduced with permission. © Diamond Offshore, 2016.)

Company (ODECO). It was built to operate and drill in up to 600 feet of water and was active until 1992 when it was retired. The vessel cost US\$3 million to build and had a hull 355 × 210 × 125 feet in size with a 140-foot derrick in the center of the “V”-shaped hull. It was conventionally moored using anchors and chains.

Semis have been built in seven major construction cycles or generations. With each generation, semis’ size and capacity has increased, so that they can work in deeper

water and more challenging environments. A semi has a drilling derrick located at the middle of its deck over a moon pool, which extends through the vessel to the open sea. This allows the drill pipe to extend through the vessel through the water and into the seabed. As semis’ water depth ratings increased, a change in positioning systems was needed to improve station keeping ability. Mooring with anchor and chain was replaced by DP systems as rigs moved into water depths beyond 3500 feet.

DP systems keep the vessel centered over the drill site using 4–8 electrically driven propellers (thrusters). Computers are used to monitor the hull's position, using global satellite positioning equipment and sensors placed on the seafloor, and to measure environmental forces impacting the vessel. Through a complex algorithm, the DP system calculates positional adjustments and actuates individual thrusters to keep the semi centered directly above the drill site at all times.

### 3.5 Drillships

A drillship has a drilling derrick over a moon pool similar to a semi but has a ship-shaped hull. Drillships are generally self-propelled, so they can mobilize more quickly than semis and are often used for drilling operations in very remote locations and in very deep water.

In 1955, Robert F. Bauer of Global Marine designed the first drillship, the *CUSS I*, named for the partners Continental, Union, Shell, and Superior. This was a conversion of a surplus Navy YF barge. By 1957, it had drilled in 400 feet of water. *CUSS II* or *Glomar* was Global Marine's first major drillship. It cost around US\$4.5 million and was completed in 1962. Weighing 5500 tons, it was almost twice the size of *CUSS I*.

Later that year, The Offshore Company decided to create a larger drillship that would feature an anchor mooring system using a turret system, which allowed the hull to weather vane around the stationary drill floor. Named *Discoverer I*, it was built without engines and was towed to the drill site. Around 1961, Global Marine began a new drillship era by ordering self-propelled drillships that could drill wells to 20,000 feet in water depths of 600 feet. Most modern drillships use DP to maintain their location over the drillsite (Figure 8).

As the industry moved into deeper water and sought new reserves in more remote ocean depths, the need for drillships has grown. New vessels continue to be added to the fleet and provide naval engineers with the challenge of creating space for additional equipment, workrooms for equipment service and repair, and additional capacity for drilling in ever deeper water. Some new drillships are being designed to carry two blowout preventers (BOP), so that an immediate replacement is available if needed. Along with the extra BOP, additional workspace is required to service a failed BOP. Dual derricks are becoming more common to perform drill pipe make-up/break-up operations on one derrick, while drilling is taking place on the other derrick. The most recent designs have a 20,000-psi well control system and a high crane capacity and can set back more drill pipe than earlier vessels for drilling in more than 12,000 feet of water (Offshore, 2014).

## 4 PRODUCTION

### 4.1 Introduction

After exploration locates a prospective area and drilling discovers oil, the production process begins. Production extracts hydrocarbons from the earth and separates the mixture of liquid hydrocarbons, gas, water, and solids flowing from the well for delivery to shore. Constituents that cannot be sold are removed, leaving liquid hydrocarbon and gas that are sent to shore for processing and sale. Unusable components are disposed in an environmentally correct manner. Production sites normally include hydrocarbons flowing from multiple wells.

Producing oil and gas from below the sea has undergone tremendous change since the first offshore wells were drilled. Connecting a producing well to land over the top of a pier is a relatively simple plumbing task. Once a well is drilled beyond the reach of land, pipe must be laid on the seabed to shore, or the produced oil must be stored and offloaded (lightered) to a tanker vessel for transport to shore. Natural gas cannot be stored at the site of production but must be used as fuel on the platform, sent to shore by pipeline, reinjected, or burned (flared).

Wells completed offshore are controlled by Christmas trees (a series of valves) either on top of a surface facility or on the seabed. Dry trees are accessible on the top of a platform or on the deck of a floating production system (FPS); each tree connects to a well at the mudline through production casing in a fixed riser (pipe that transports the produced fluids). Subsea wells require in-water (wet) trees for pressure control. These trees are secured on the wellhead at the seabed and connect to an FPS or fixed platform by flowlines and risers.

### 4.2 Offshore Pipelines

Subsea pipelines were created in the early 1940s out of necessity as a logistical support for the World War 2 effort to fuel allied troops in France after the D-Day invasion. The technology applied by the British in Operation Pipelines Under The Ocean (PLUTO) evolved from that used to lay underwater communication cables across the Atlantic Ocean. Both cable construction techniques and cable-lay vessels were modified to meet the war need.

The first subsea pipelines laid were formed from 2-in. diameter lead pipe that was wrapped in several protective layers and armored with steel. The pipeline was flexible like telegraph cabling and was spooled onto large 30-foot diameter drums for transport. The pipeline was then played out from the drums during installation. In December 1942,



**Figure 8.** New drillsips can carry dual towers, two BOPs, and additional workspace as standard equipment. (Reproduced with permission. © Rowan Companies.)

a trial was conducted by laying a 30-mile pipeline across the Bristol Channel to connect Swansea and Ilfracombe. The trial was a success and the decision was made to expand the pipeline to 3-in. diameter (76 mm) for the connection across the English Channel. The cost of materials and limited quantities of lead forced manufacturers to replace lead pipe with steel tubing. Much of the steel used in the pipeline came from the United States.

The subsea pipeline eliminated the need for tanker vessels and provided a secure fuel delivery capability that was weather independent. Fuel was pumped from the Isle of Wight to Cherbourg, France, within 2 months of the invasion. Twenty subsea pipelines were eventually laid from England to France across the English Channel to deliver fuel to the fighting forces.

It is generally accepted that early offshore pipelines to deliver oil and gas from offshore wells to shore were first deployed in significant quantity along the US GOM coastline as production moved from onshore to offshore beginning in the late 1940s.

Offshore pipelines have since evolved from shallow water to deep water and from relatively benign to harsh environments. The following summarizes a number of developments that have allowed offshore pipelines to be installed (called *pipelay*) in water depths approaching 10,000 feet in most non-Arctic areas worldwide. Beyond 10,000 feet and ice prone areas represent today's frontier challenge to offshore pipelines.

### 4.2.1 Fixed structures

From the legacy of wooden piers and small fixed wooden structures in shallow water, the industry has designed ever larger bottom-supported steel structures (platforms) to produce oil and gas from the continental shelves. These structures (jackets) are generally built of steel with a lattice structure having multiple, cross-braced legs. They are secured to the seabed by piles, driven through the hollow legs into the soft bottom soils. The jacket supports the deck (topsides) where wellheads, processing equipment, helipad, and crew quarters reside. Fixed platforms are suitable for installation in water depths to about 1400 feet, but the majority of platforms are in less than 300-foot water depths. A variant of the fixed platform, the compliant tower, has been used in over 1700-foot water depth in Chevron's Petronius field in the GOM.

Shell Oil Company designed the tallest, pile-supported, fixed-steel platform in the world in 1985. The Bullwinkle platform is 1736-foot tall from seabed to flare boom and is set in GOM Green Canyon Block 65 in 1353 feet of water (Skyscraperpage.com, 2014) (Figure 9).

The total cost of the platform was US\$500 million. Holding 60 well slots, the platform's structural weight is over 77,000 tons. Initial processing capacity of the platform was 59,000 barrels of oil per day and 100 million cubic feet of gas per day. Bullwinkle is also the processing hub for a number of other fields in the GOM.





**Figure 9.** The Bullwinkle jacket was towed (a) to its location and installed so the topsides (b) could be set on the jacket in 1353 feet of water in the Gulf of Mexico. (Reproduced with permission. © Shell, 2016.)

Another fixed platform type is the gravity-based structure or GBS, developed originally for use in the North Sea. The steel-reinforced concrete structures were constructed in the deep fjords of Norway by building consecutive rings on top of one another until the structure reached its designed size and shape. The structure was then towed to its intended location and ballasted with iron ore, settling it onto the seabed. No piles were needed to secure the structure; the structure's weight and gravity were sufficient to keep it in place. The first GBS was built and installed for Ekofisk field in the North Sea and weighed 215,000 tons (Veldman and Lagers, 1997). It was installed in 1973 in 230 feet of water and included a large concrete tank for oil storage.

#### 4.2.2 Floating structures

Floating structures come in several forms from rectangular, pontoon-supported vessels to large vertical cylinders moored to the seabed, to ship-shaped vessels for gathering and processing oil and gas. Most FPSs have production modules that are built onshore or near shore before being towed to their intended location. The deck and topside modules are frequently constructed separately and mated to the hull, after it is launched (Figure 10).

Tension leg platforms (TLPs) are vertically secured floating systems with buoyancy that exceeds the weight of the structures (Kak, 2009). They are usually placed in water depths between 1000 and 5000 feet.

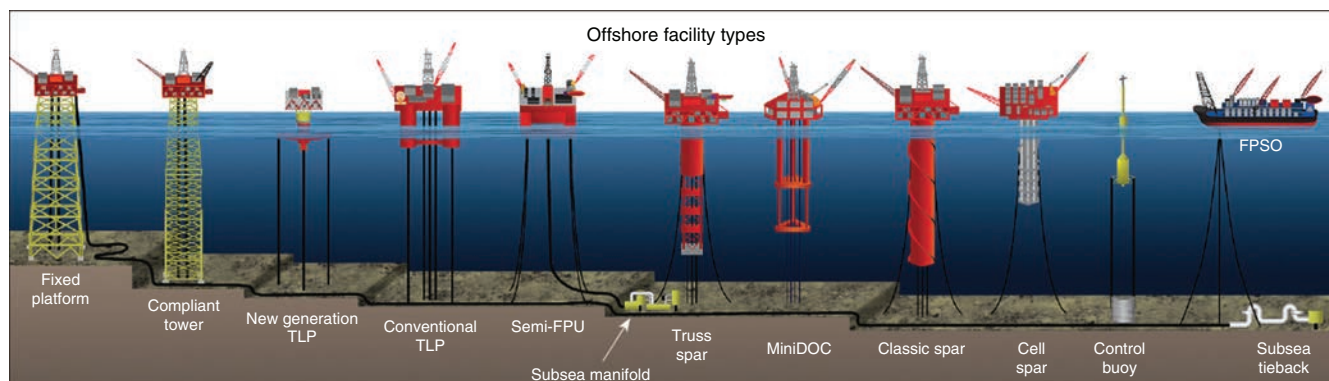
TLPs are connected to the seabed by rigid pipes (tendons) that act as mooring legs. The TLP hull is ballasted down into the water and then the tendons are connected to the hull, which are connected to the seafloor by piles. The hull is then deballasted, which puts the tendons in tension, limiting the vertical movement (heave) that the vessel experiences

and also keeping the platform on location. Advantages of using TLPs include the ability to support dry tree wells, easy accessibility for maintaining riser systems, and the ability to weather major storms without disconnecting from producing wells.

The first TLP was developed for the Hutton field in the North Sea in 1984. Conoco Company engineered the system for a water depth of 485 feet. This structure consisted of six columns connected at the bases by rectangular pontoons; the column tops were connected by boxed structures.

The hull and deck of the structure were mated in the Moray Firth in 1984 and then towed out to UK Blocks 211/27 and 211/28. Originally designed with a service life of up to 25 years, the Hutton TLP was decommissioned in 2008. Most TLPs have been installed in the GOM, but they have also been used in West Africa, the North Sea, Brazil, and Indonesia.

Spars are FPSs that are cylindrical in form. They come in many sizes and configurations depending on metocean conditions and the processing modules needed to produce the field. Early spars were vertical solid-wall cylinders on which a deck and processing modules were mounted. Later versions were a combination of a solid-wall cylinder with a truss section beneath. This design permitted a larger deck, due to the structure's reduced weight, compared to a solid-wall form of the same dimension. The combination design includes heave plates, which help reduce vertical motions. All spars are located in the GOM except for Kikeh in the South China Sea off Malaysia and another planned for Aasta Hansteen in the North Sea off Norway. They have been used in water depths ranging from 1900 to 7800 feet. The deepest spar was installed in 2010 at Perdido field in the GOM in 7817 feet of water.



**Figure 10.** Modern offshore drilling structures include (from left to right) conventional fixed platform, compliant tower, vertically moored minimal tension leg platform, conventional tension leg platform, semisubmersible floating production unit, truss spar, MiniDOC spar, classic spar, cell spar, control buoy, and floating production storage and offloading facility. (Reproduced with permission. © Wood Group Kenny, 2016.)

Semisubmersible drilling rigs have occasionally been transformed into FPS, but they are also frequently purpose-built for use as floating production platforms. By replacing the drilling equipment with process equipment and pumps, oil and gas from subsea wells can be processed and sent to shore by pipeline. This choice is less expensive than a new-build TLP or spar, because older semis can be repurposed economically and converted quickly to production mode. Because semis are easily moved, they are an economical choice for producing several smaller fields in sequence. Semi FPSs have been used around the world, including very deep water in the GOM and Brazil. The deepest is Independence Hub in the GOM in 7920 feet of water.

Ship-shaped floating platforms are the most common FPS form because of their flexibility. Commonly referred to as *floating production, storage, and offloading* (FPSO) vessels, they are secured for station keeping with mooring lines or occasionally with DP systems. FPSOs have production systems on the deck, store produced oil in the vessel's tanks, and can offload the oil to shuttle tankers, which transport the oil to refineries. The ship-shape vessel can be spread-moored in one heading or pivot (weathervane) around a turret, where all the mooring lines, flexible production risers, and umbilicals come together from wells on the seabed and where export pipelines also connect. Where the weather is mild, such as offshore West Africa, an FPSO can be spread-moored without using a turret. Risers and umbilicals are then connected to the hull of the FPSO.

Turrets can either be internal to the FPSO or float as an external buoy that connects to the FPSO by an articulating boom. A few FPSOs have a disconnectable turret, which

allows the FPSO to separate from the production/export system and move away when extreme weather approaches.

About half of the current FPSO fleet was constructed by converting commercial tankers, including very large crude carriers (VLCCs), into production systems. The repurposed tankers are reengineered and reinforced to carry processing systems and storage, ranging from several hundred thousand barrels to over 2 million barrels of crude oil. Natural gas produced with the oil is sent through a dedicated pipeline to shore, reinjected into formations below the seabed, used for fuel on the FPSO, or flared. FPSOs operate in all the major offshore producing areas of the world. The deepest location is in the Cascade–Chinook field in the GOM in 8200 feet of water.

#### 4.2.3 Subsea systems

A subsea system is the array of equipment placed on the seafloor to facilitate safe hydrocarbon production to a host facility, which might be a platform, FPS, or a shore base. Subsea systems can be traced back to 1943 in Lake Erie, USA, where the first subsea completion took place in approximately 30 feet of water. That well used a land-type tree that required diver intervention for installation, maintenance, and flowline connections.

Cameron built the first subsea Christmas tree in 1961 for installation on the first GOM subsea producer, a Shell well in about 50 feet of water. The first diverless subsea well was completed in 1967. By 1971, subsea wells were completed in 220 feet of water at Ekofisk Field, developing the first North Sea subsea system. By 1978, 140 subsea systems were active worldwide and now they number in the thousands.

Subsea wells can often be brought into production faster to an existing host than by building a new fixed or floating

platform. Wells on the seafloor can be placed beyond the effective drilling reach of existing platforms and allow additional production, if the host facility has no spare well slots. When tiebacks to existing surface facilities are available, investment in expensive new facilities such as fixed platforms and FPSs can be bypassed. If the flowlines of a deepwater well are tied back to a structure in shallower water, less expensive infrastructure can result. Disadvantages of subsea wells include higher installed costs per well and higher intervention costs, when compared to dry trees on surface facilities. Reduced flow rates or expensive interventions in subsea wells can force early well shut-ins, leaving unproduced oil in the reservoir, because the well reached its economic limit.

Subsea well technology developed from the mid-1950s to mid-1970s as companies drilled in deeper waters. As wells were being drilled further away from host facilities, valves were improved and wet, remote-controlled satellite trees were developed, as were trees that were housed in one-atmosphere systems (dry chambers) at the same pressure as at sea level. Lockheed developed these systems and the transfer bells needed to access them in the 1970s. They developed single-well chambers as well as dry manifold chambers holding production manifolds. Personnel were moved from the surface to the dry chamber by a transfer capsule that was lowered from the surface and set on top of the dry chamber, where it was sealed and locked. Personnel could then move into the chamber and work as required for initial installation and ongoing operations. Dry chamber systems were used in the GOM and offshore Brazil but had limited usage because the transfer system was expensive to maintain and the chambers became too expensive for deeper waters due to increased hydrostatic pressure.

Initially, subsea wells were installed and maintained by divers. As the industry moved into deeper depths, remotely operated vehicles (ROV) were developed in the 1970s to work beyond normal diving depths for humans and to improve working flexibility with subsea systems.

Large maintenance systems were tried in the GOM and the North Sea in the 1970s and 1980s, such as the Shell/Exxon Cormorant field that had the Underwater Manifold Centre (UMC). Wells were drilled through a template that supported a manifold placed in the center. The maintenance vehicle moved on a track and could access the wet subsea trees and the manifold. Over time, ROVs eliminated the need for these larger maintenance vehicles.

ROVs and the tooling they use to work underwater have become the primary equipment for subsea installation and intervention. They serve multiple roles including platform and pipeline inspection, surveys, drilling and construction support, debris removal, platform cleaning, subsea installation and maintenance support, and object location and recovery. Today, ROVs have improved gyroscopic controls

and excellent communication systems. They are equipped with 200–300 horsepower systems to perform installation, maintenance, troubleshooting, and repair of subsea equipment in up to 15,000 feet of water.

When the need for templates was no longer a concern and improved subsea measurement and navigation was available, clustered well systems were developed. They were first used in shallow water in the North Sea in the late 1970s. These system designs were later applied offshore Norway, Brazil, and the GOM in the mid-1980s. Because of their flexibility, clustered well systems are still used today. The wells can be placed in optimal locations to develop the reservoir and can be connected by flowlines to a subsea manifold, so that multiple wells can flow back to the host through a shared flowline.

Early remote-controlled valves came about from equipment developed for BOPs. However, the size and cost of remote-controlled valves, along with the discovery that stacked valves could not withstand horizontal forces during installation, became an issue. Block trees overcome this problem because the valves are machined into a single forging. Early trees (termed a *vertical tree*) were designed to use guidelines for installation and had vertical bores for the production to flow through. The well was drilled, casing strings were set, and then the tubing string was landed in the wellhead, where plugs were set in the tubing. The BOP was pulled and then the subsea tree was landed. If the well required a workover, the tree had to be removed.

The through-bore tree was developed to overcome complications with downhole safety valves and other downhole issues. The tubing was landed in the tree below the valves. This was a vertical tree that required large master valves. The advantage of this tree design was that the completion could be pulled through the bore without removing the tree. Because of the difficulty of designing larger master valves, this tree design had little usage. A new design was developed with the valves offset from the main bore. This *horizontal tree* replaced the through-bore tree, because it has no valves in the vertical bore.

The key difference between a vertical and horizontal tree is in the installation process. The vertical tree's well is drilled and completed, including the production tubing, through a drilling riser and BOP. After the well is completed, the BOP and riser are recovered and the tree is installed on the well. For a horizontal tree, the well is drilled and suspended without tubing, the BOP and riser are recovered, and the tree is run at that time or later. After the subsea tree is landed on the well, the BOP and riser are installed on top of the tree. The well is completed by installing the tubing and downhole hardware, and then the BOP and riser are pulled back to the drilling rig. Depending on the project, either tree can be used. If the well is expected to need significant workover during

its life, the horizontal tree is normally preferred. One other major advance with subsea trees was developed for deeper water. Guidelines became difficult to install for deepwater drilling at the time global positioning was being developed. This resulted in guidelineless systems for BOPs and subsea trees, which is now the common method used for rigs in deeper water and with all rigs using DP.

Umbilicals used today are multiline assemblies that allow complex subsea systems to be controlled and operated. They include thermoplastic and steel hydraulic fluid and chemical supply lines, electrical control and communication cables, and fiber optic cables. Early umbilicals were comprised of thermoplastic hydraulic hoses for subsea control systems over short distances of a few miles. These thermoplastic hoses worked well in most applications but not in deep-water situations where the fluids had a lower specific gravity than water, such as gas injection lines. If pressure was lost, the hose collapsed. Other problems occurred with methanol and other chemicals that can migrate through the thermoplastic hose. Steel tubes solve both of these problems and are commonly used today. In addition, high collapse resistance (HCR) thermoplastic hoses were developed for deepwater.

Flowlines are used to transport produced fluids from the subsea tree to the host facility. These can be made of steel pipe or of a composite of various materials called *flexible* flowlines. Risers are the section of the flowline that transports produced fluids from the seafloor to the surface and can be the same pipe as the flowline. For an FPS, risers are in a dynamic environment due to currents and the motions of the FPS. Steel catenary risers (SCR) can also be used in deeper water and accommodate dynamic applications. Flowlines and risers are used intrafield as opposed to pipelines, which are normally larger in diameter and export oil and gas from a field to the shore facility.

Today, subsea well systems are used around the world. They can take less than 2 years to start up and can be designed for most any reservoir configuration. Currently, subsea trees are used to produce oil from over 40 miles from a host facility and gas from up to 90 miles, and subsea wells are producing in almost 10,000 foot water depth with up to 15,000 psi shut-in pressure. These limits continue to be expanded into deeper water and at higher production pressures.

## 5 SPECIALTY VESSELS

The challenges of offshore construction, logistics, and operations have led the industry's naval architects to develop specialty vessels of many types. The seismic vessels explained earlier are but one example of the many vessels created to accomplish important tasks on and in the water to support offshore exploration and production.

Semis and drillships with anchor and chain mooring systems require the services of anchor handling tug supply (AHTS) vessels. AHTS are larger than port tugs and have the capacity to transport and set very large anchors used to secure drilling rigs and FPS units on location. When they are not setting anchors and chain, AHTS serve as supply vessels.

Offshore construction requires a number of specialty vessels to install and decommission production facilities and structures, both fixed and floating. These include heavy transport vessels for moving rigs, jackets, topsides, FPSs, and equipment between continental regions; heavy lift vessels with massive cranes to place topsides and equipment packages on jackets and spars; diving support vessels (DSVs) to support and house dive systems and divers to perform underwater work; and pipelay vessels to install steel pipe, flexible pipe, and umbilicals (Figure 11).

Pipelay vessels are used to install the pipelines that bring produced hydrocarbons to land for processing. Workers in the vessels weld sections of pipe together, perform X-ray weld inspection, and add various coatings to the pipe before the pipeline leaves the vessel's "firing line" and goes over the "stinger," a suspended support structure on the stern of the vessel, as the pipe is lowered to the seabed. Other pipelay vessels carry out "reel lay" operations. For these vessels, steel pipe is welded together onshore and then spooled on to a large reel on the vessel at a shore base. The vessel then transits to the installation site and lowers the pipeline to the seafloor using the large reel. Flexible pipe was developed to install flowlines in deep water (Figure 12).

Several developments allowed offshore pipelines to move from shallow to deep water and increase pipelay productivity. Pipelay technique evolved from welding individual pipe joints horizontally (S-lay) to welding pipe joints vertically (J-lay), and then to reeling. Reeling pipe onto a large spool aboard the pipelay vessel allowed pipe to be welded into a flowline onshore rather than offshore, improving project efficiency. Reeled pipe has certain diameter and length restrictions.

Pipelay vessels evolved from anchored mooring to DP to keep the vessel on location while welding joints together and then placing the pipeline on the seabed. Automatic welding was developed to increase pipelay speed over manual welding. As pipelines were built for deeper water depths, tensioners grew in load capacity to restrain the pipe onboard the pipelay vessel during pipelay in both S-lay mode and J-lay mode. Winches also improved increasing in load and wire length capacity for laying down and recovering pipe during construction.

Double jointing (welding single 40-foot pipe lengths into 80-foot lengths either onshore or onboard the pipelay vessel)



**Figure 11.** The offshore oil and gas industry uses many specialty vessels, such as this heavy lift vessel, for moving production modules, rigs, and other major equipment to offshore locations. (Reproduced with permission. © Dockwise, 2016.)



**Figure 12.** Flowlines and smaller pipelines are lowered to the seabed using reeled pipelay vessels. (Reproduced with permission. © Technip, 2016.)

increased pipelay productivity over single jointing in S-lay mode. Quad jointing has similarly been used in J-lay mode.

Shallow water pipelay depended on divers to perform the underwater work necessary to lay, connect, and test offshore pipelines before they were put into use. ROVs and mechanical subsea tie-in connectors were developed to reach beyond the depth limitations of divers (600 feet in saturation diving and 1000 feet in atmospheric dive suits).

Other developments allowed offshore pipelay to move into harsh environments. First generation flat bottom barges were used to lay smaller diameter pipelines in the GOM. They evolved into larger second generation barges, self-propelled ship-shaped vessels, and third generation semisubmersible vessels to install the larger diameter trunk lines necessary to handle high volume oil and gas production in the North Sea.

## 14 General

| Pipelay Vessel Item           | First Generation  | Second Generation | Third Generation                        | Fourth Generation   |
|-------------------------------|-------------------|-------------------|---|---|
| Vessel hull                   | Flat bottom barge | Ship shape        | Ship shape or semisubmersible           | Ship shape or semi  |
| Propulsion                    | Towed             | Self-propelled    | Self-propelled                          | Self-propelled  |
| Station keeping               | Anchored          | Anchored          | DP                                      | DP  |
| Lay mode                      | S-lay             | S-lay             | S-lay or J-lay (through vertical tower) | S-lay and J-lay (through vertical tower)                  |
| Jointing                      | Single joint      | Single joint      | Double joint                            | Quad or reeled  |
| Pipe                          | Rigid             | Rigid             | Rigid                                   | Rigid or flexible   |
| Pipe diameter (incl. coating) | Up to 36"         | Up to 48"         | Up to 60"                               | Up to 60"/18" reeled                                      |
| Welding                       | Manual            | Manual or auto    | Auto                                    | Auto or reeled  |
| Subsea support                | Divers            | Divers            | ROVs                                    | ROVs  |
| Water depth (m)               | 100               | 200               | 300                                     | 3000  |
| Tension (t)                   | 100               | 200               | Up to 1000                              | Up to 600 S-lay<br>Up to 800 reel lay<br>Up to 2000 J-lay |
| Jointing                      | Single            | Single            | Double                                  | Reeled  |
| Developed                     | 1960s             | 1970s             | 1980s                                   | 2000s   |
| Examples                      | Iroquois          | —                 | Castoro Sei<br>Solitaire                | Aegir<br>Borealis<br>Deep energy<br>Lewek Constellation   |

Delivery of the pipe from shore to the pipelay vessel (called *pipehaul*) evolved from using towed barges with transfer of individual pipe segments by crane into the pipelay vessel's hold to faster and larger DP vessels with offshore transfer of large reels by crane. DP allows the pipehaul vessel to maintain position alongside the pipelay vessel during pipe transfer to the pipelay vessel and to keep pace with pipelay progress during the transfer operation.

Fourth generation vessels have now been deployed with vertical lay systems and vertical reels or carousels that allow installation of flowlines, risers, and control umbilicals from the subsea wellhead to floating production platforms and export risers in deep water. Examples of current state-of-the-art pipelay vessels are the Solitaire (S-lay), Aegir (J-lay), and Lewek Constellation (reel lay).

While offshore construction vessels are primarily used only when a project is underway during the installation phase, there is another class of specialty vessel that supports ongoing offshore operations. Platform supply vessels (PSVs) transport goods and personnel to and from offshore oil platforms and drilling rigs. Their cargo tanks carry needed supplies such as drilling mud, cement, diesel fuel, water, and chemicals used for drilling and production processes. Depending on vessel deck area, they can carry deck cargos above and bulk cargo below deck. Most PSVs are built for a particular job. Some have firefighting capabilities to

manage platform fires, while others have oil containment and recovery equipment to control and capture oil spills.

A relatively new class of specialty vessel, the multiservice vessel (MSV), has been designed to place equipment on the seabed, including the installation of flexible pipe for flowlines and risers, as well as umbilicals. They also house ROVs and provide surface space from which to direct ROV operations for subsea installation, maintenance, and decommissioning work. MSVs have operational flexibility and lower cost compared to hiring a drilling rig or large pipelay vessel to do the work (Figure 13).

## 6 CONCLUSION

At every stage of the industry's march into deeper water to find and develop oil and gas reserves, offshore engineers and naval architects have developed new approaches to solve the problems associated with offshore oil and gas operations: subsea trees to control wells at the seabed, flowlines, and pipelines to transport hydrocarbons; umbilicals to deliver power and chemicals to keep the wells flowing; ROVs for installation and servicing of deepwater constellations; and fixed platforms and FPSs on the ocean's surface to gather and process the produced fluids.



**Figure 13.** Multiservice vessels have operational flexibility to perform many subsea service operations. (Reproduced with permission. © EMAS, 2016.)

Every new oil or gas field discovered offshore presents a unique set of challenges that must be solved to bring the production to market. Progress is generally incremental and is illustrated by the industry's history of development as it moved first to deeper water on the continental shelf and then to open ocean conditions beyond the shelf. Major technology leaps like that from bottom-supported structures to floating structures have occurred regularly and demonstrate the industry's flexibility and ingenuity in overcoming the widening operating sphere as the offshore industry has moved from shallow to deeper water and from benign to harsh environments.

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## GLOSSARY

|           |   |
|-----------|---|
| Drilling  | The process of creating an opening into the earth (a well) through which hydrocarbons can be extracted. |
| Drillship | A ship-shaped MODU designed for extended-stay, remote, deep water operations.                           |

|                 |   |
|-----------------|---|
| FPSO            | Floating production storage offloading vessel, a ship-shaped production system for deepwater operations.    |
| Jackup          | A MODU supported on legs that extend through the water column and rest upon the seabed.                     |
| MODU            | Mobile offshore drilling unit.  |
| Platform        | A fixed or floating structure from which hydrocarbons are produced.   |
| Production      | The process of controlled hydrocarbon extraction from drilled wells.  |
| Seismic         | The process of imaging the earth's subsurface using artificially induced acoustic waves.                    |
| Semisubmersible | A deepwater MODU that floats on pontoons and whose hull is supported by 4 or more legs.                     |
| Submersible     | A shallow-water MODU whose hull rests directly on the seabed.   |
| Subsea system   | The array of equipment placed on the seafloor to facilitate safe hydrocarbon production to a host facility. |
| Subsea tree     | A stacked series of high pressure valves used to control the flow of hydrocarbons from a deepwater well.    |

|           |  |
|-----------|--|
| TLP       | Tension leg platform, a floating production platform attached to the seabed by very long steel-tubes (tenons).         |
| Umbilical | A long bundle of electrical and hydraulic connecting an FPSO and subsea system used to operate complex subsea systems. |
| Vessel    | The general term for any ship or MODU used in offshore oil and gas operations.   |

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